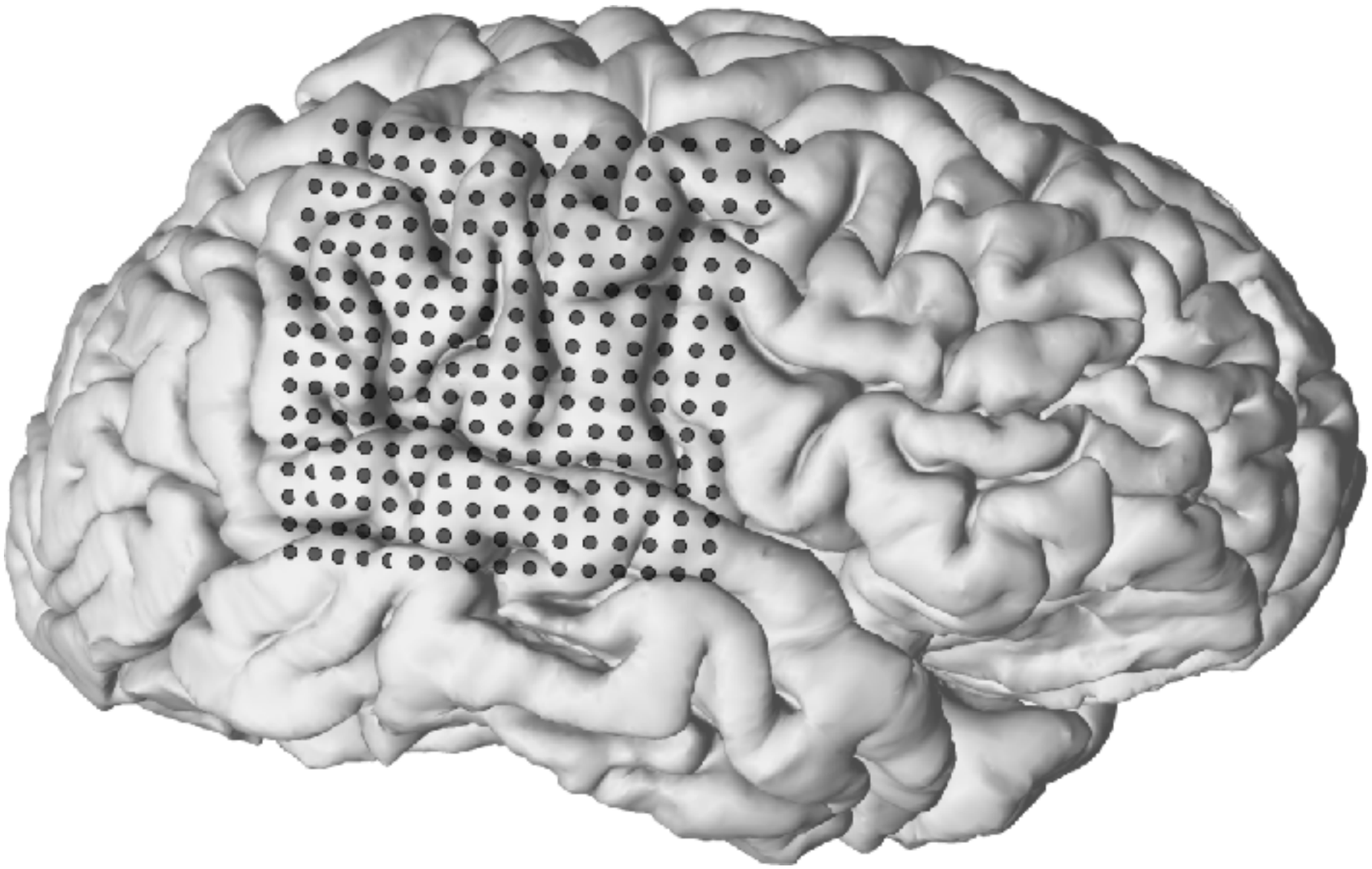
University of California
San Francisco

Graduate Program in
Bioengineering
UCSF
UC Berkeley

Chang Lab



Using ECoG to understand the representation of vocal pitch in humans

Ben Dichter, Jonathan Breshears, Matthew Leonard, Claire Tang, Edward Chang

Vocal pitch is an important feature of speech

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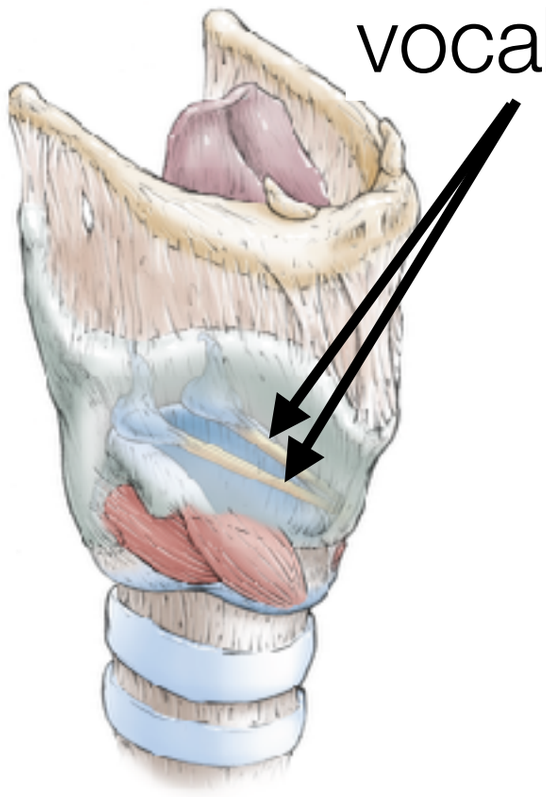
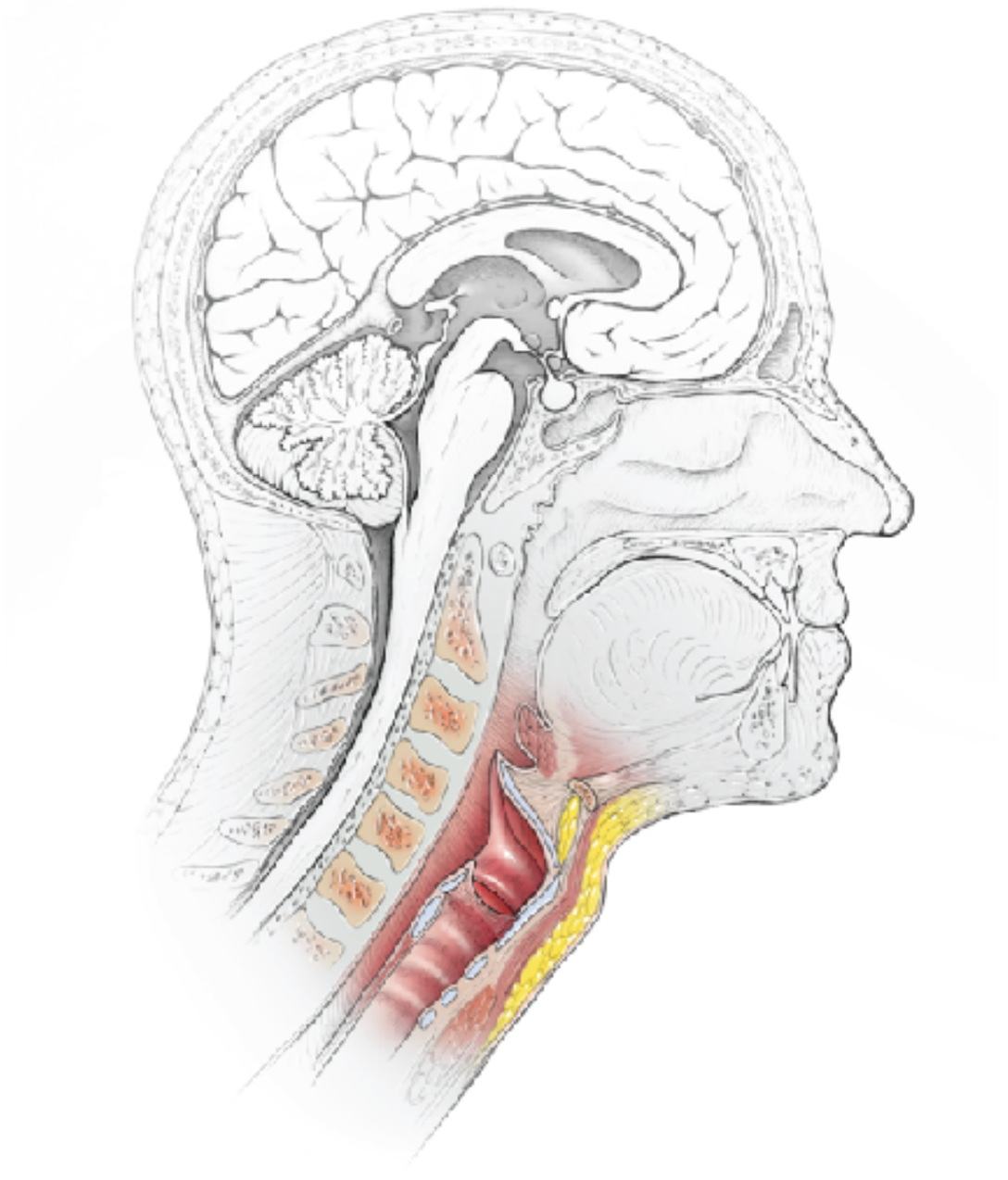
  - In English: excitement, doubt, sarcasm, emphasis, question, clause structure
  - In tonal languages, pitch carries lexical information
- Humans have more **flexible control** than other primates
  - Difference due to brain, not body (Fitch et al., 2016; Jurgens, 2002)
  - Hypothesized to be a **key evolutionary step** toward speech (Brown et al., 2008; Pasinski, 2016; Hickok, 2016)

Pitch is controlled by the larynx





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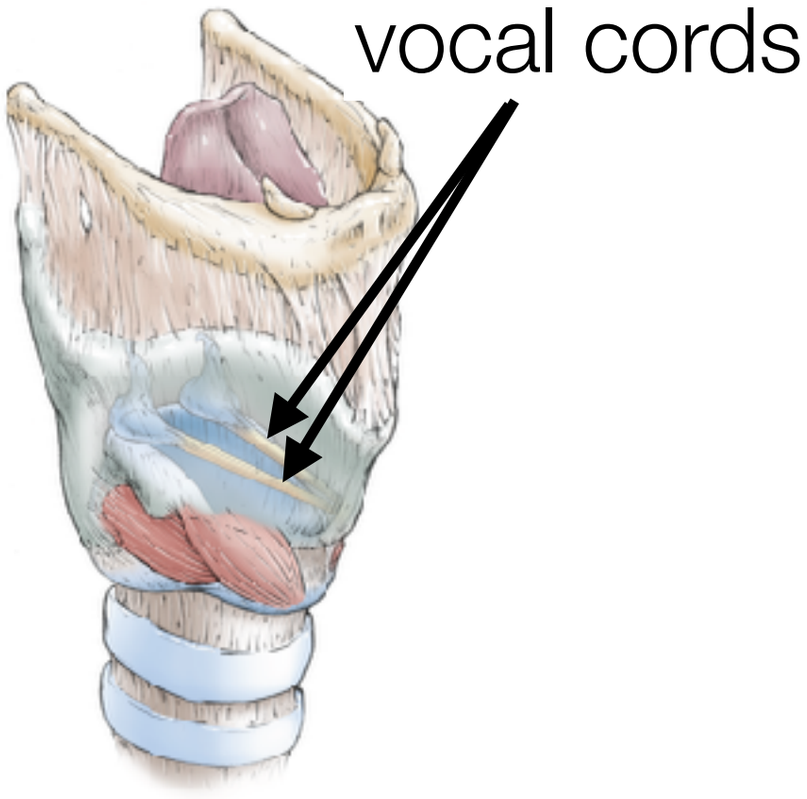

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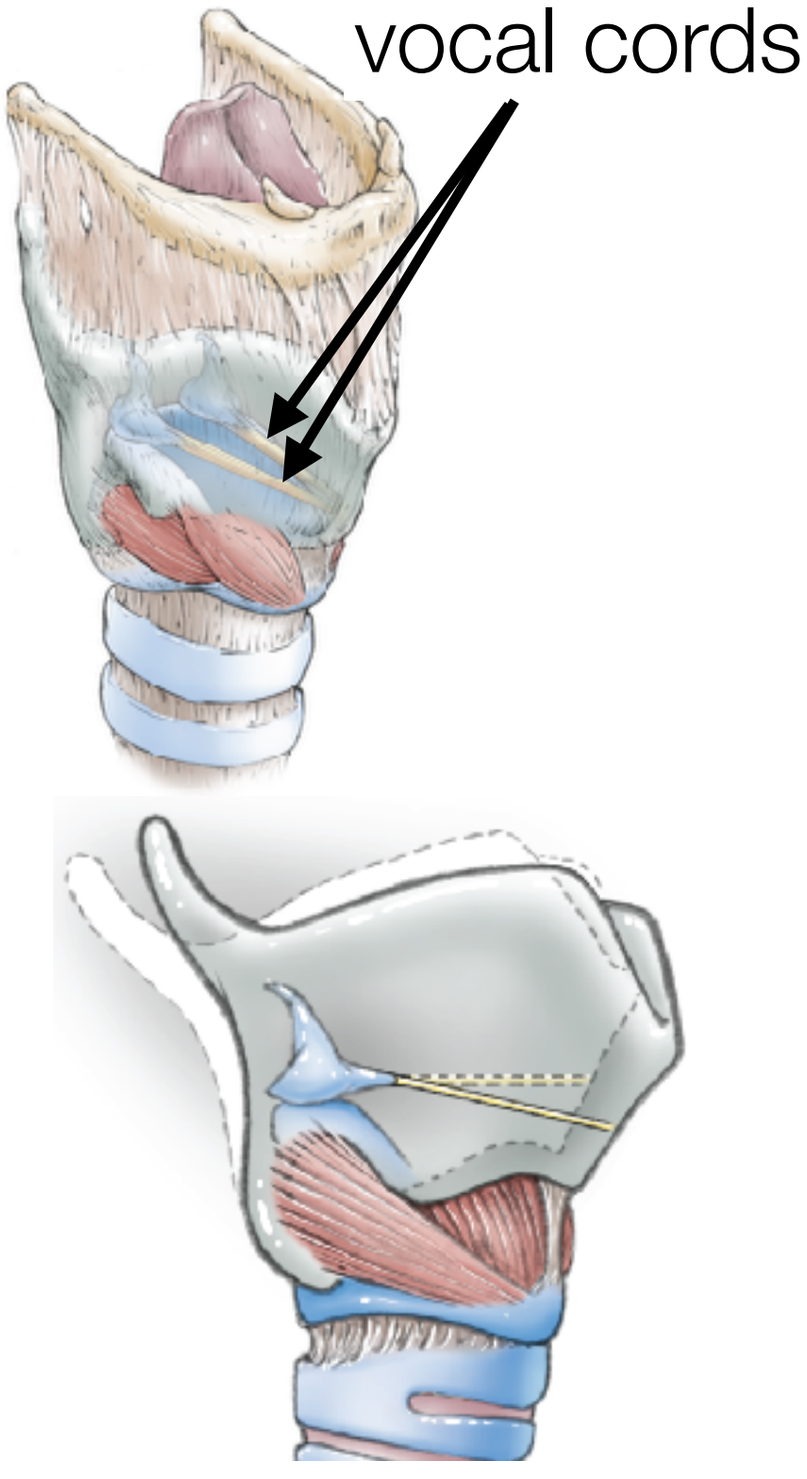

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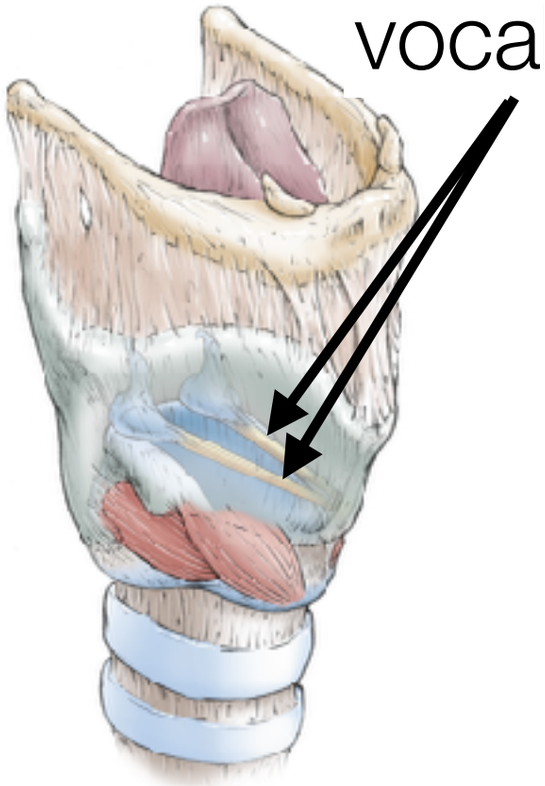

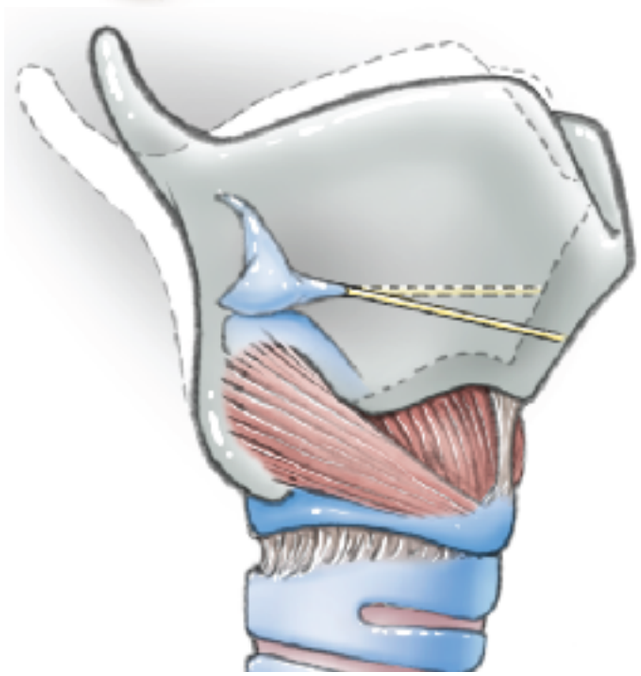

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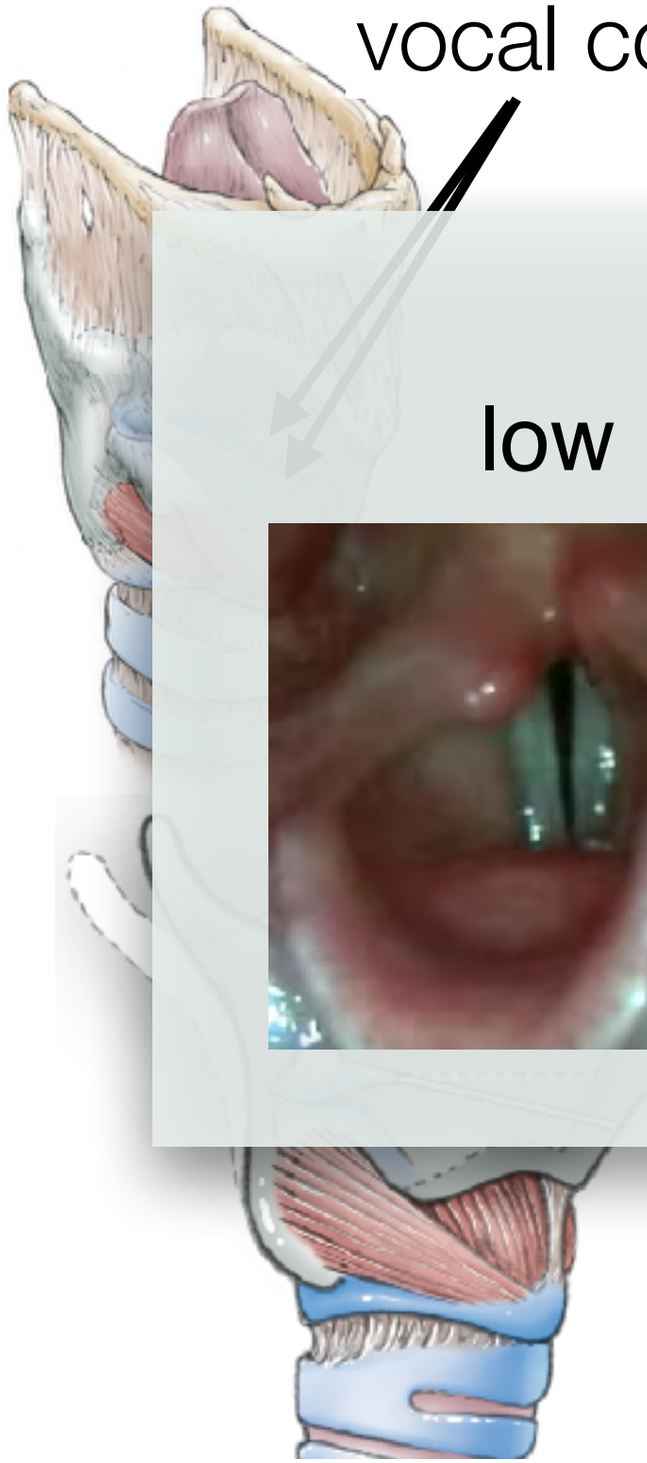
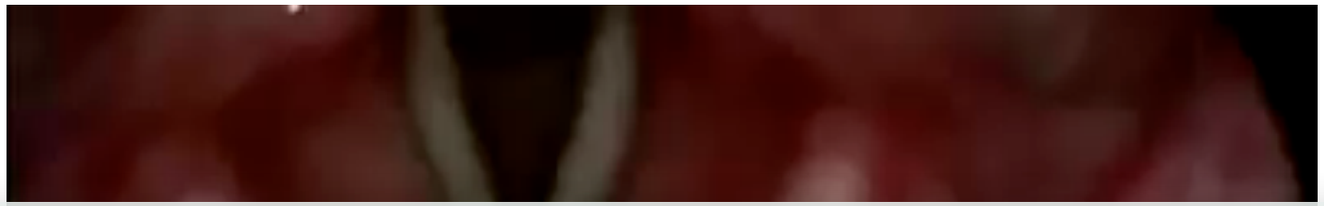




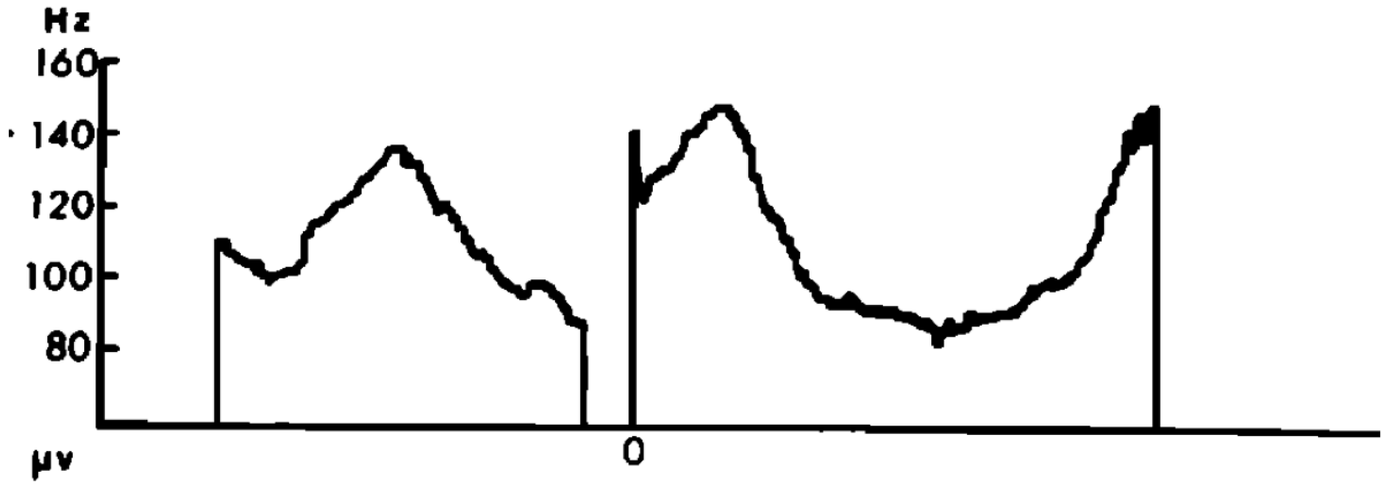
low

mid

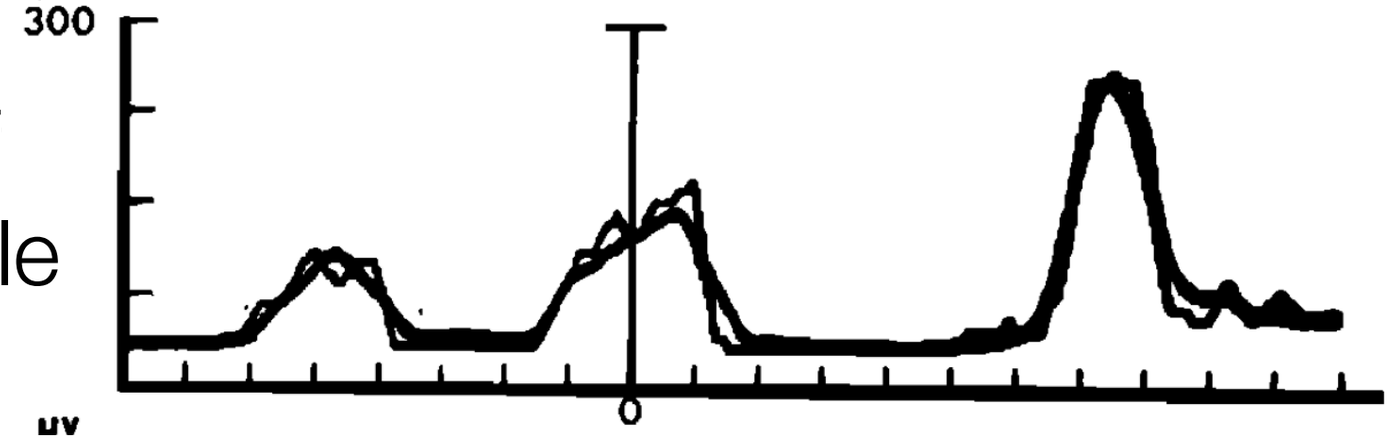
high

Muscular control of pitch

Pitch



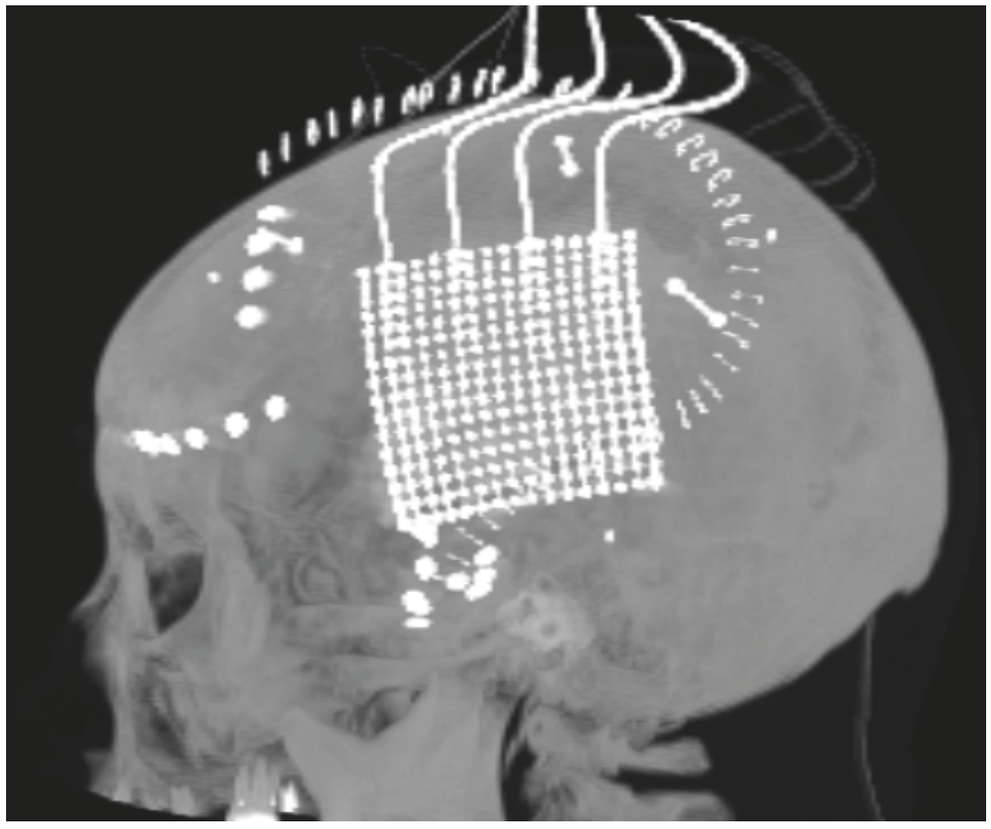
EMG of CT muscle



(Collier 1974)

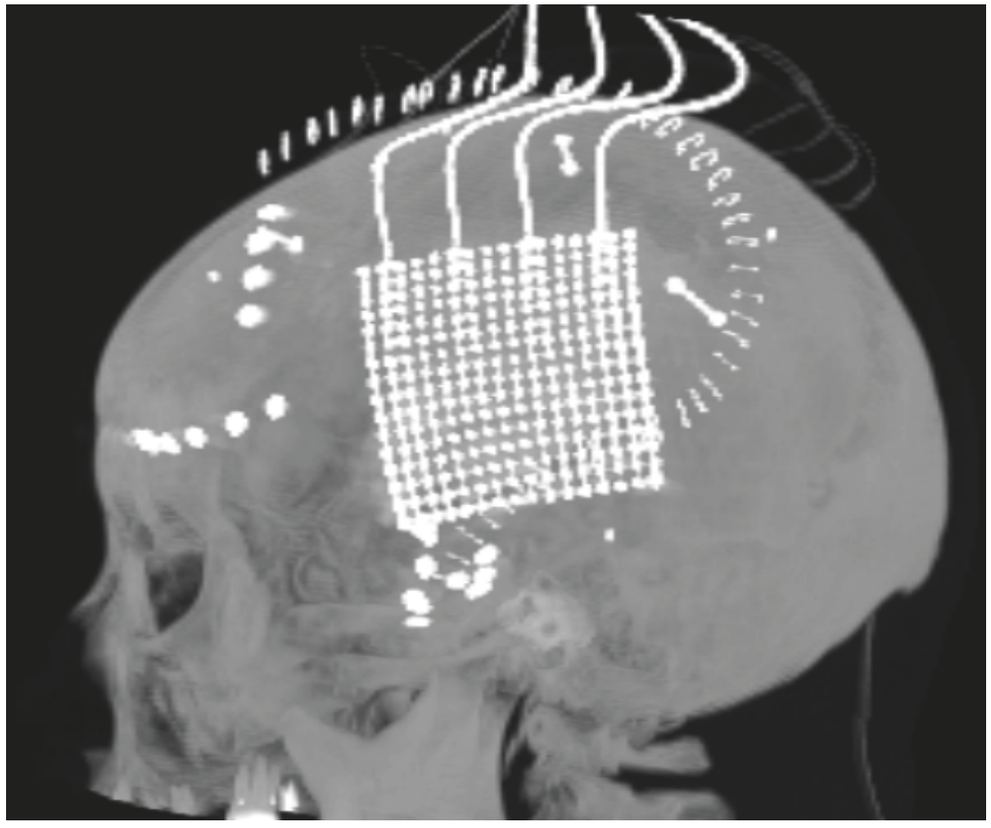
The cricothyroid (CT) muscle stretches the vocal folds and increases vocal pitch

Electrocorticography (ECoG)



Electrocorticography (ECoG)

- Surgical treatment for epilepsy



Electrocorticography (ECoG)

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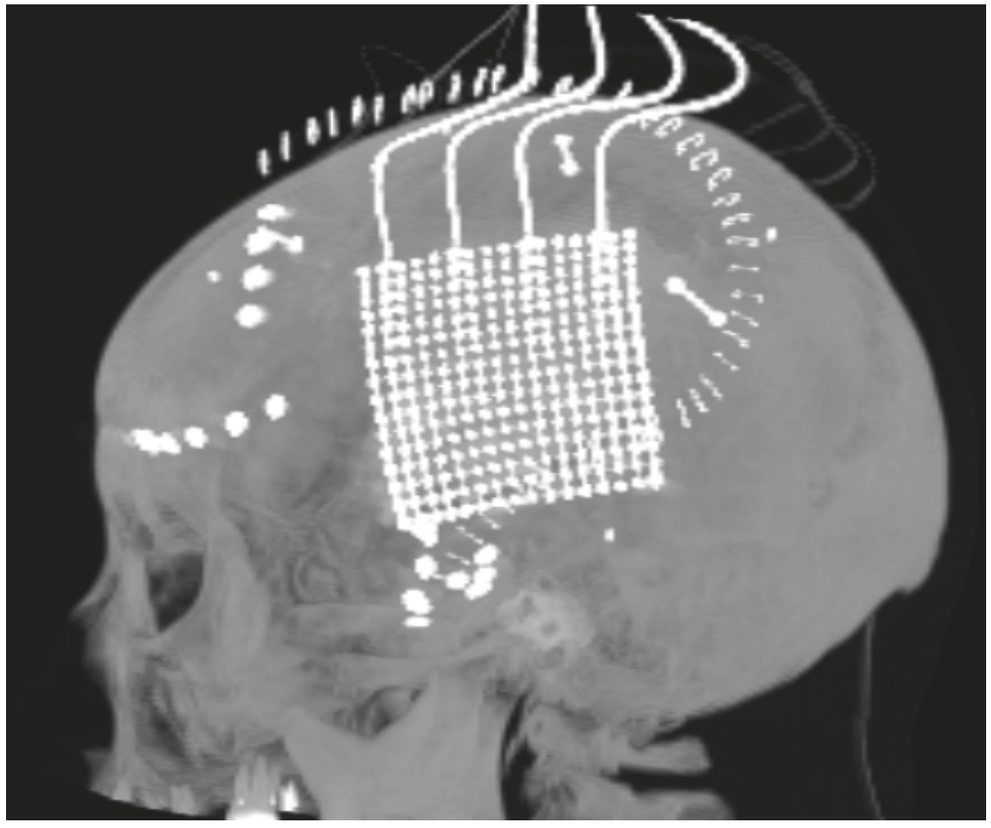
- 256+ electrodes



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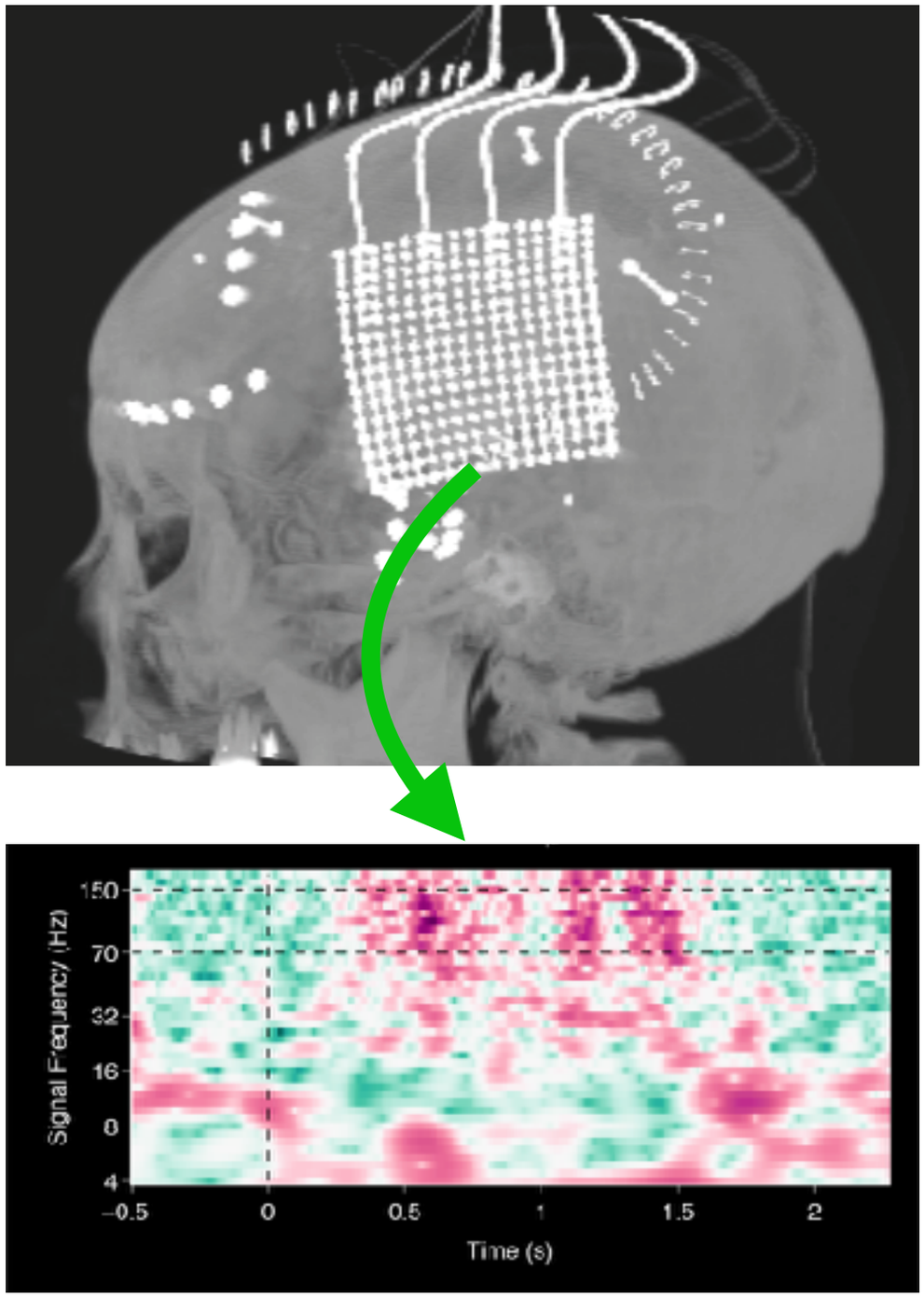

Electrocorticography (ECoG)

- Surgical treatment for epilepsy
- 256+ electrodes
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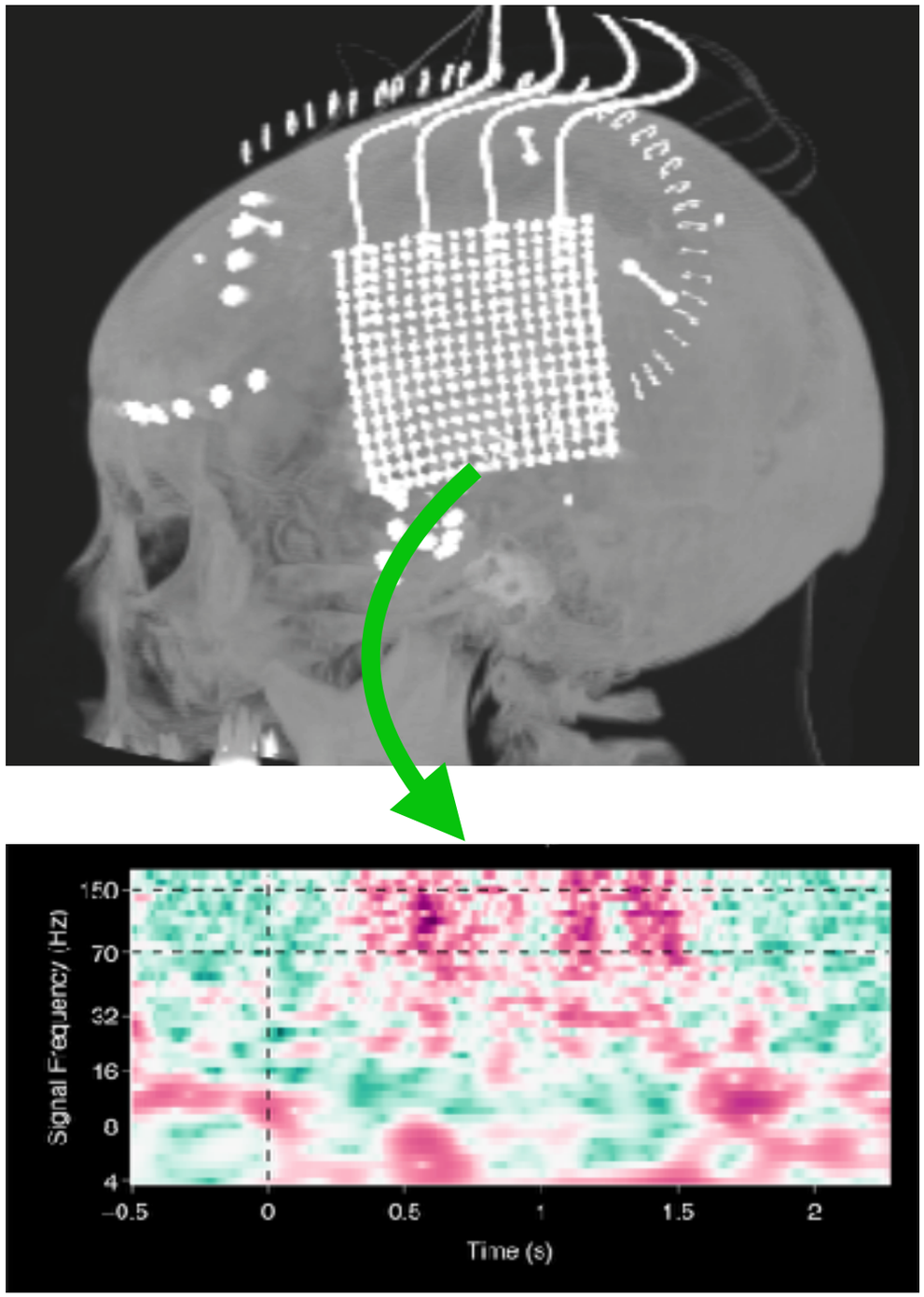
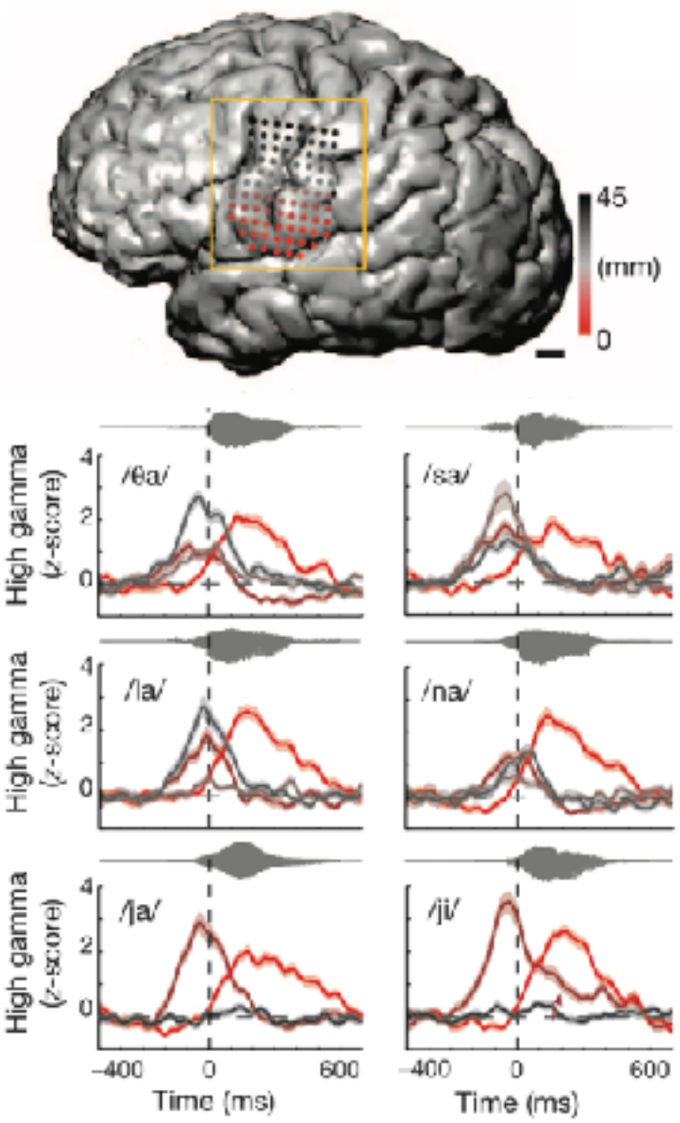
- Very good temporal resolution



Previous work: ECoG activity related to **articulators**

vSMC = M1 + S1



(Bouchard et al., *Nature*, 2015)

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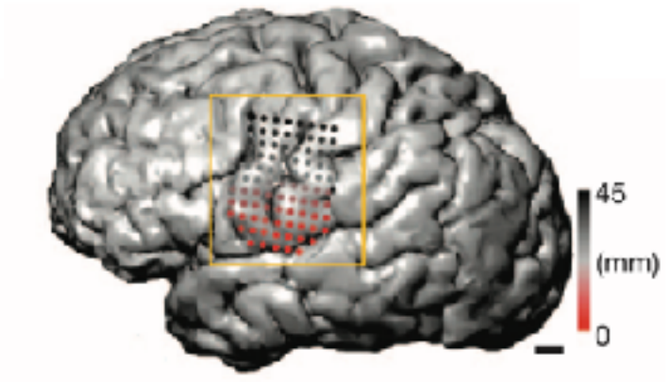

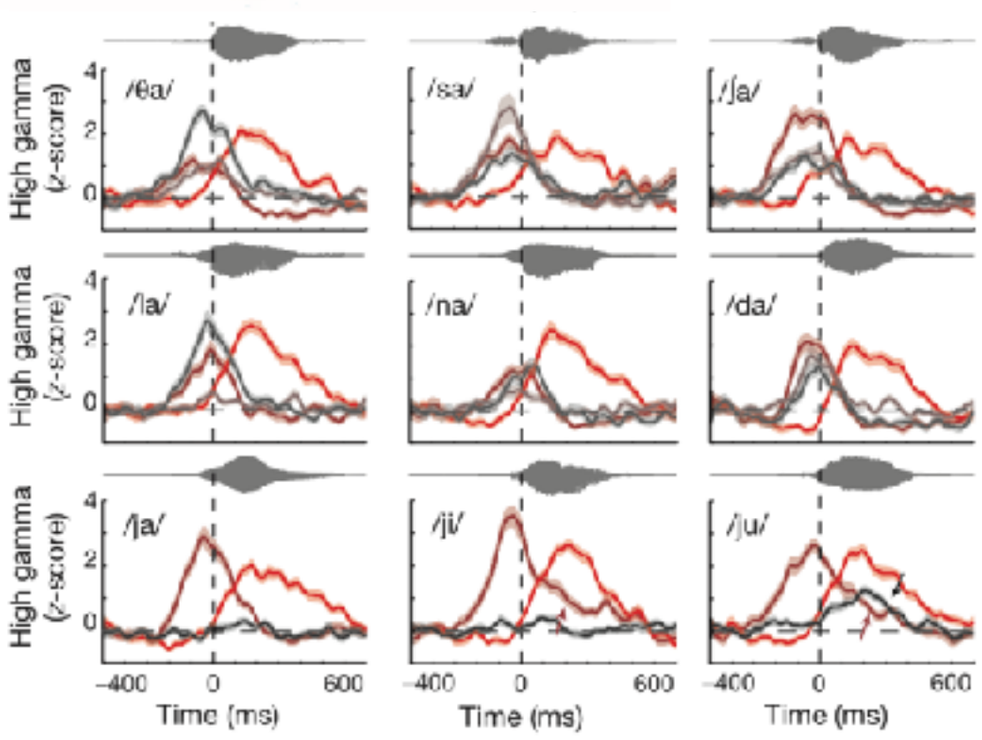

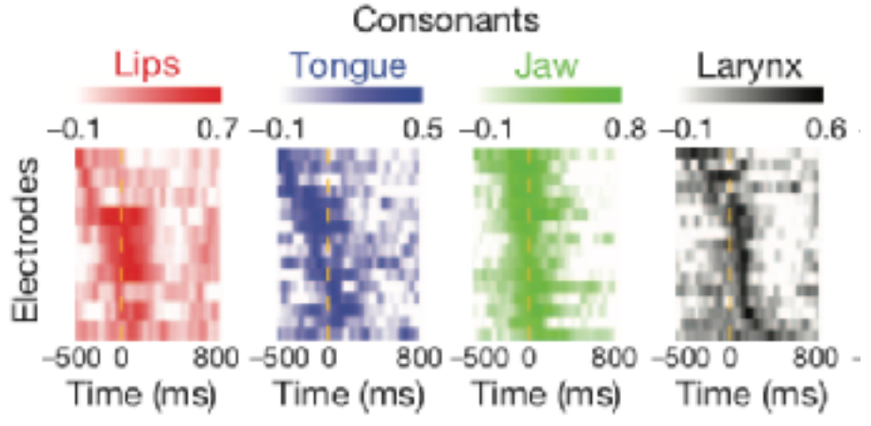

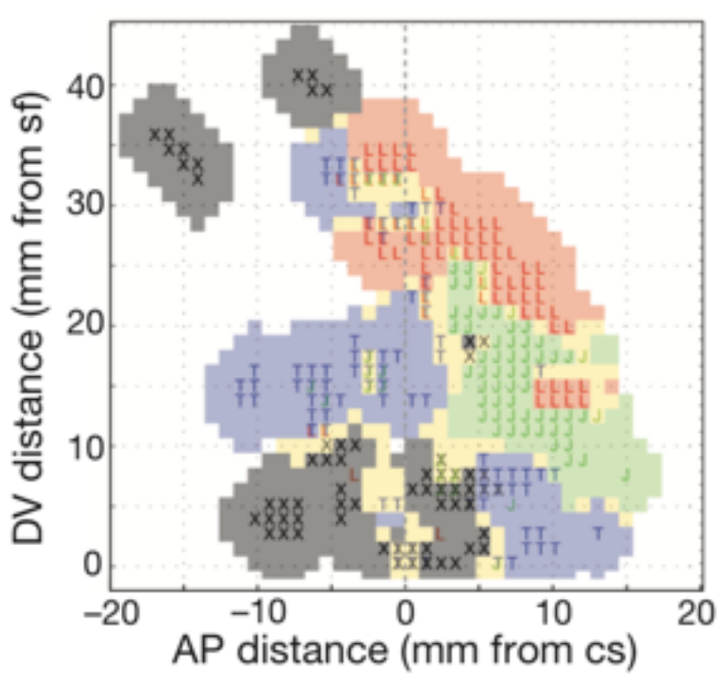

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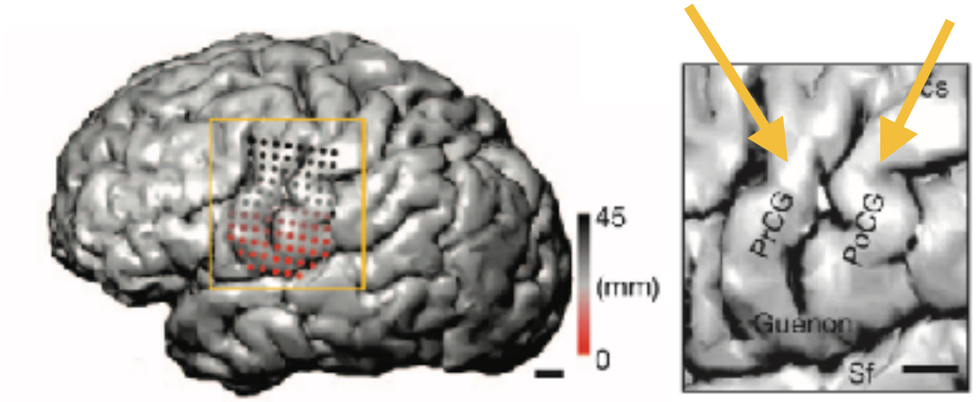

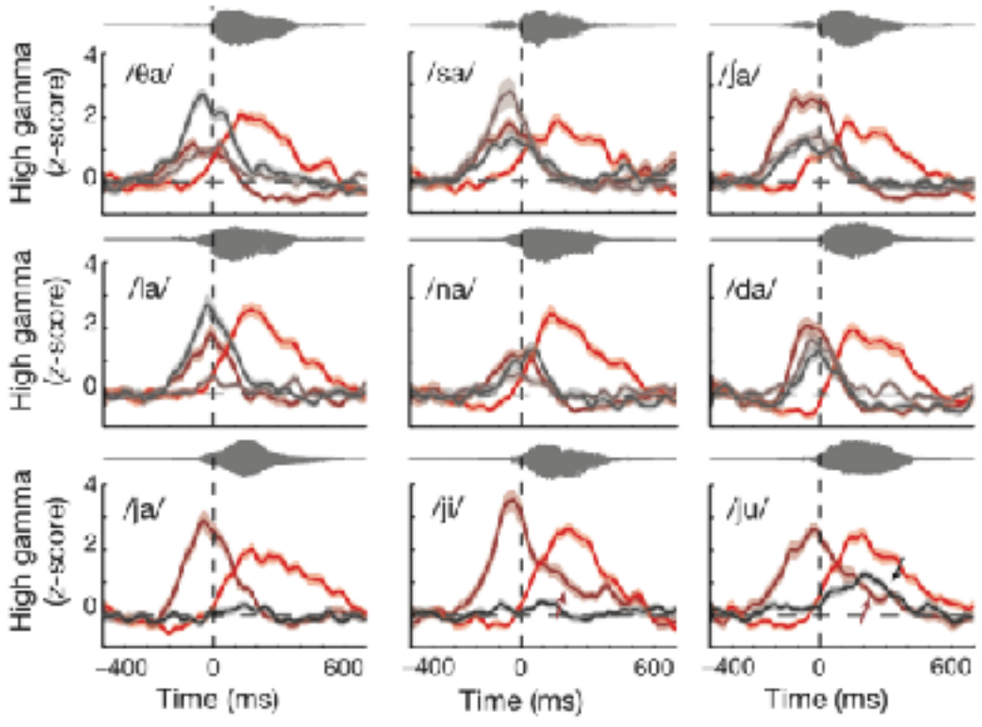

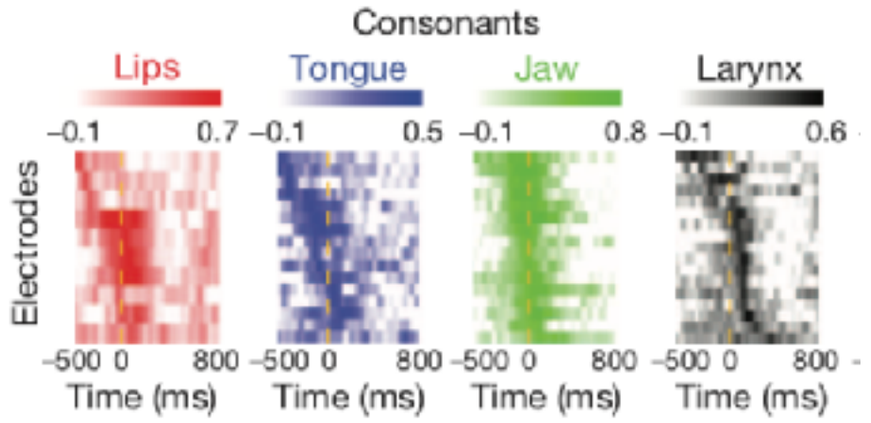

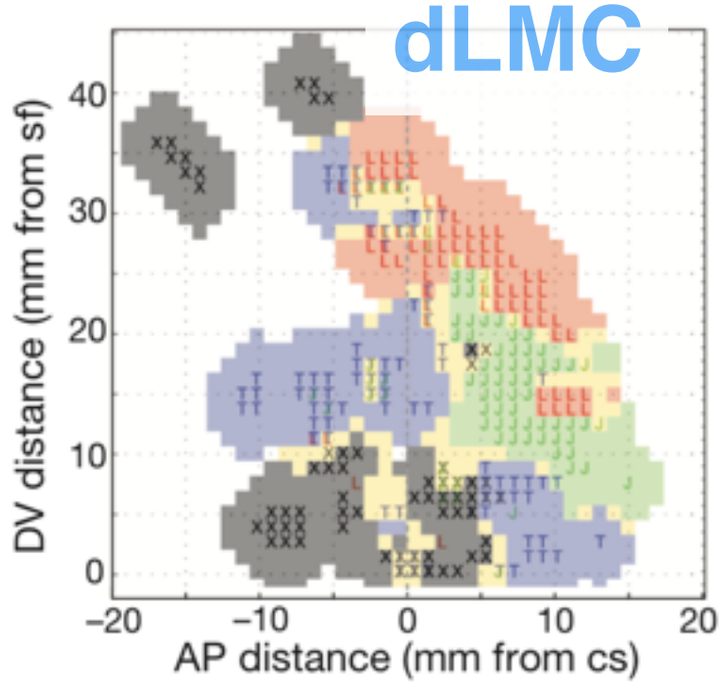

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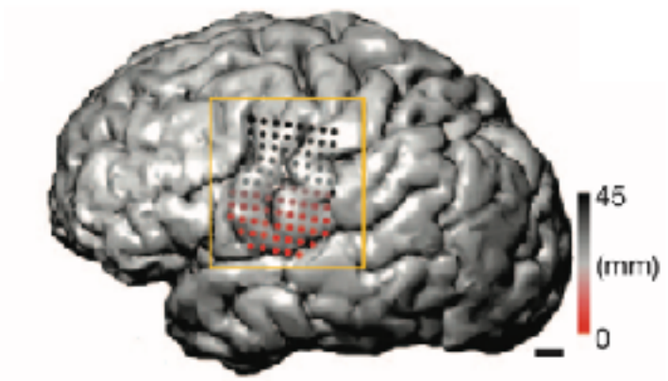

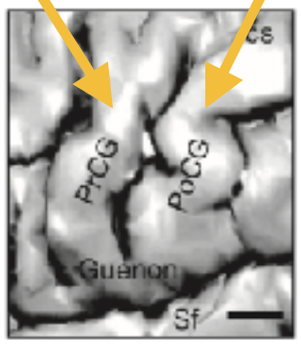

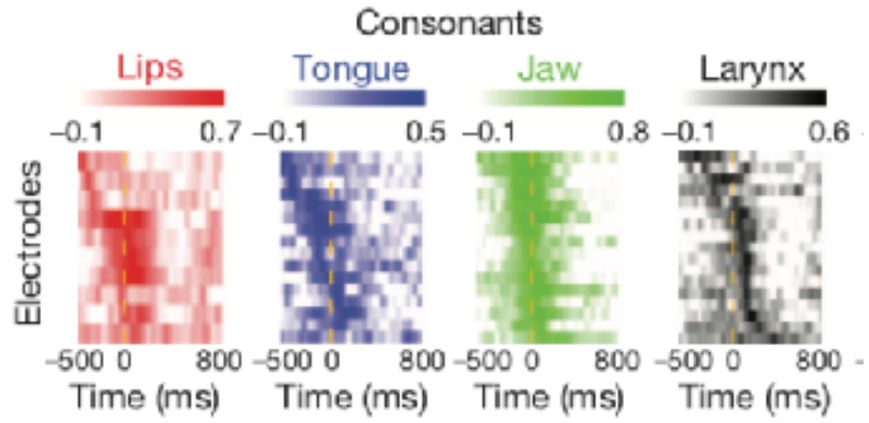

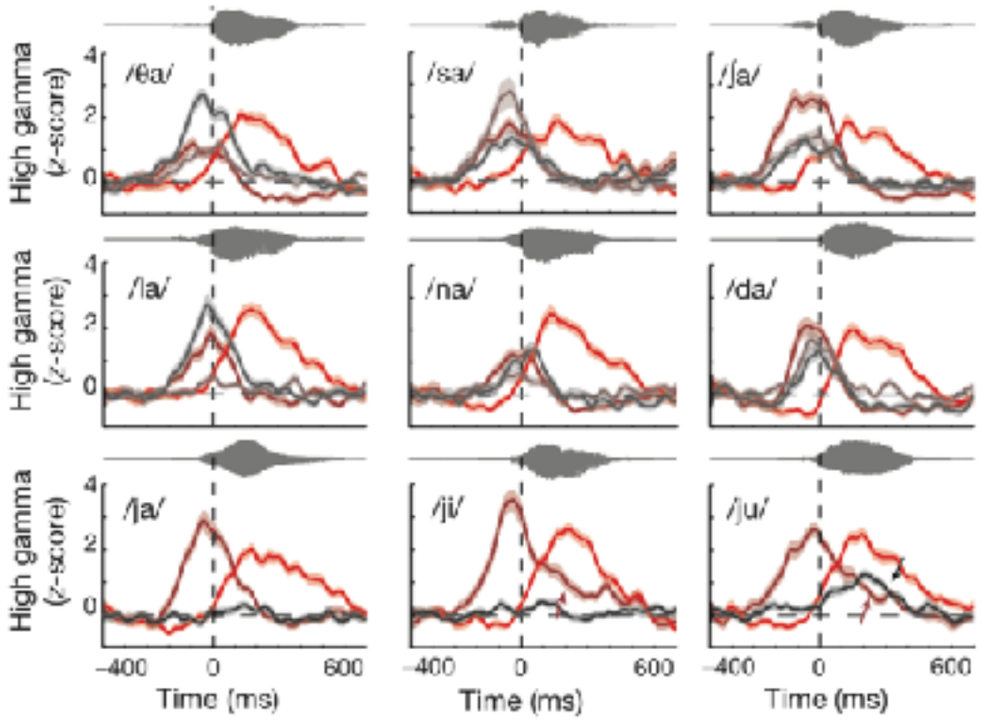

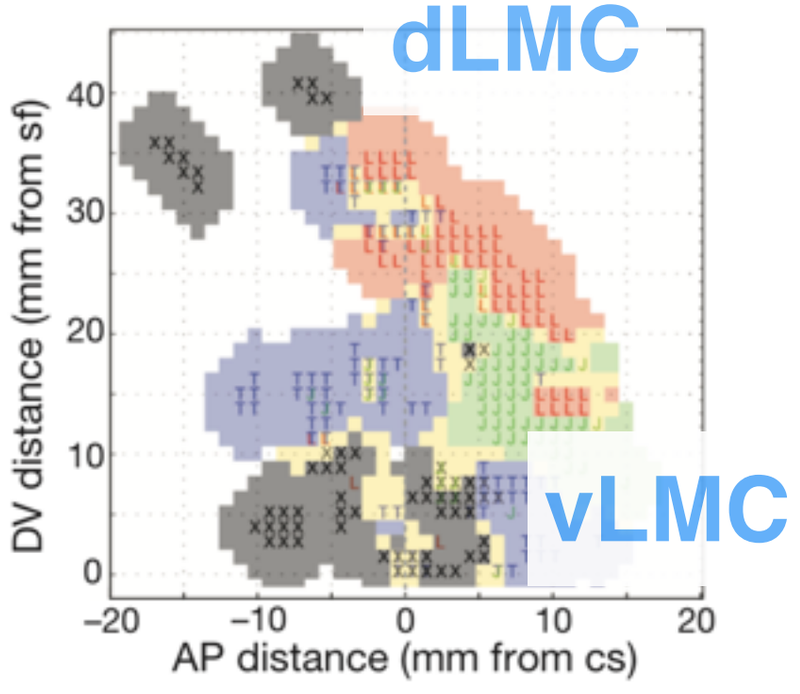

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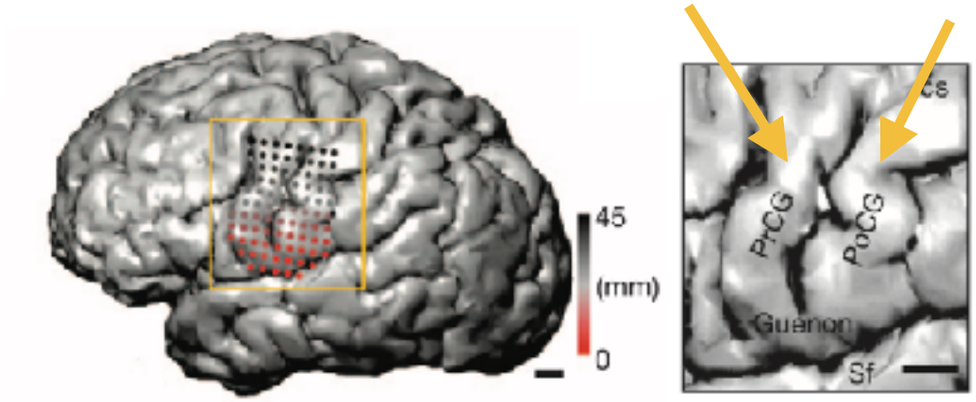
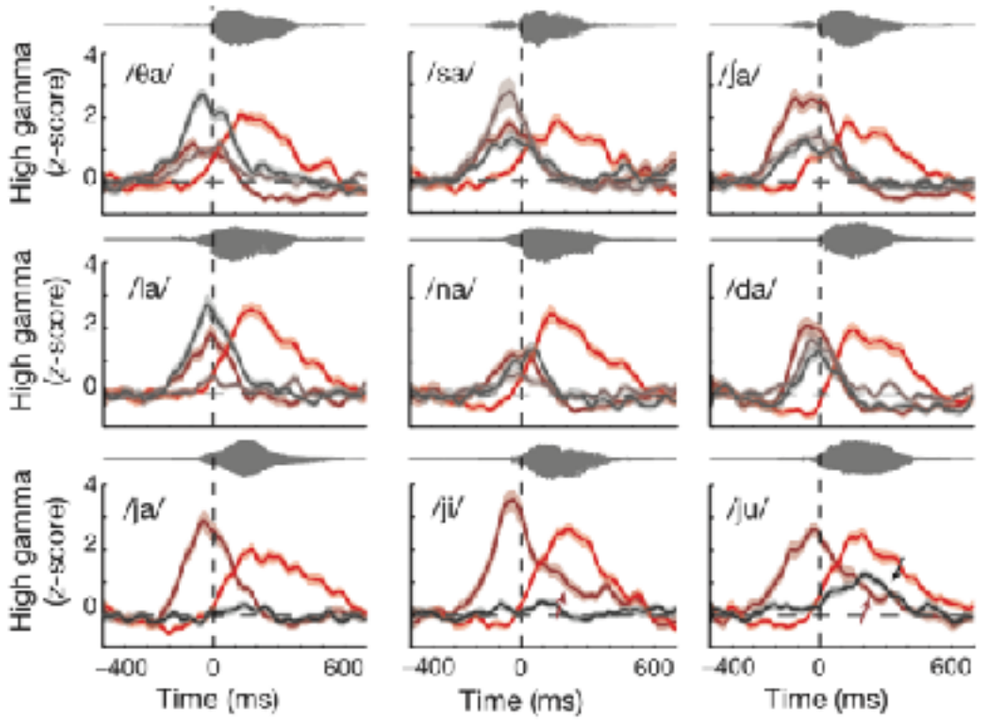
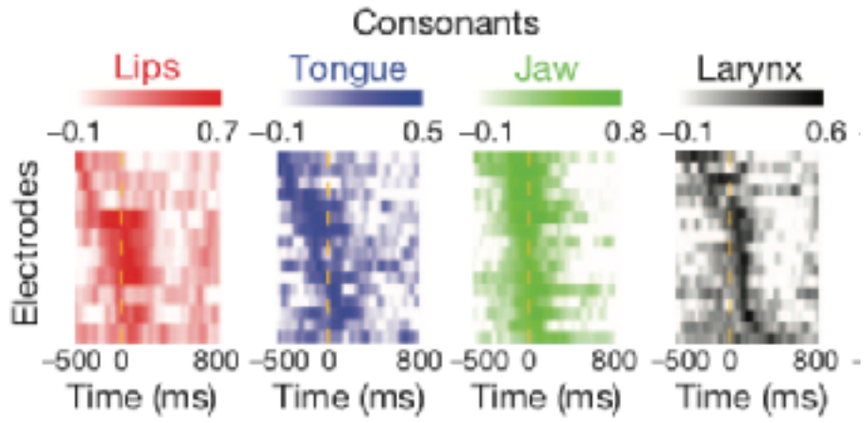
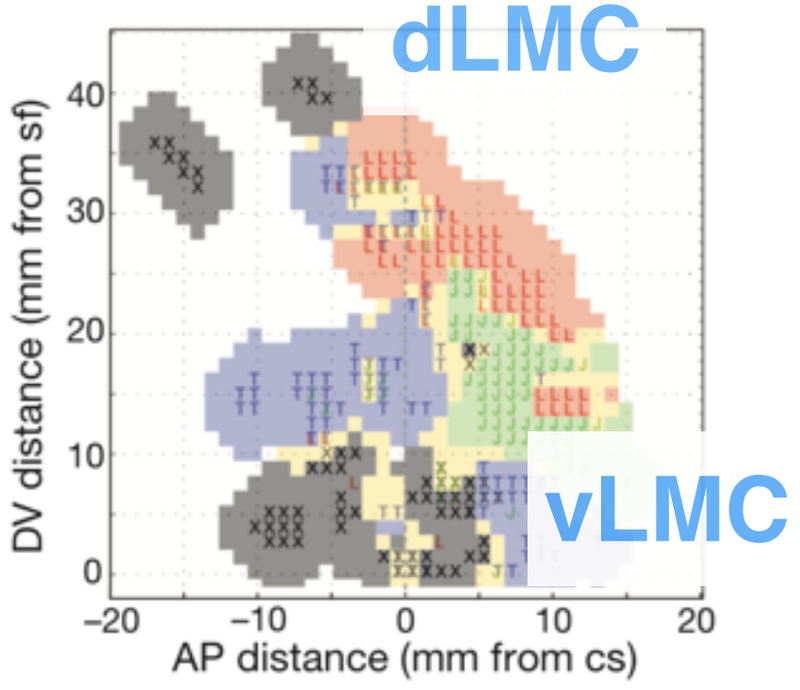




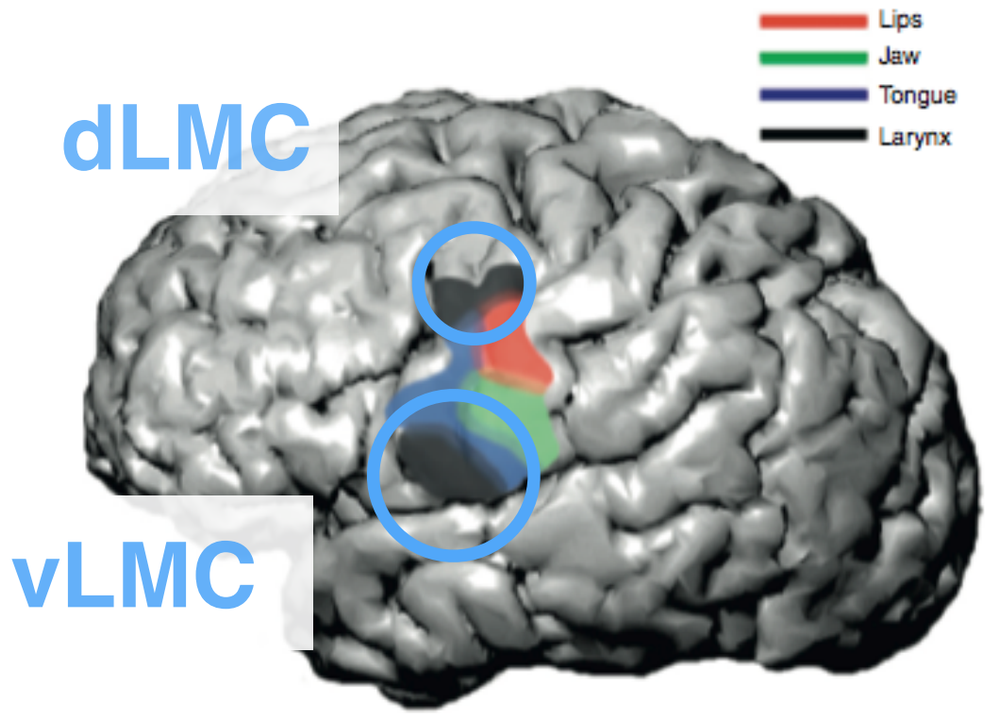




Larynx is voicing only

(Bouchard et al., *Nature*, 2015)

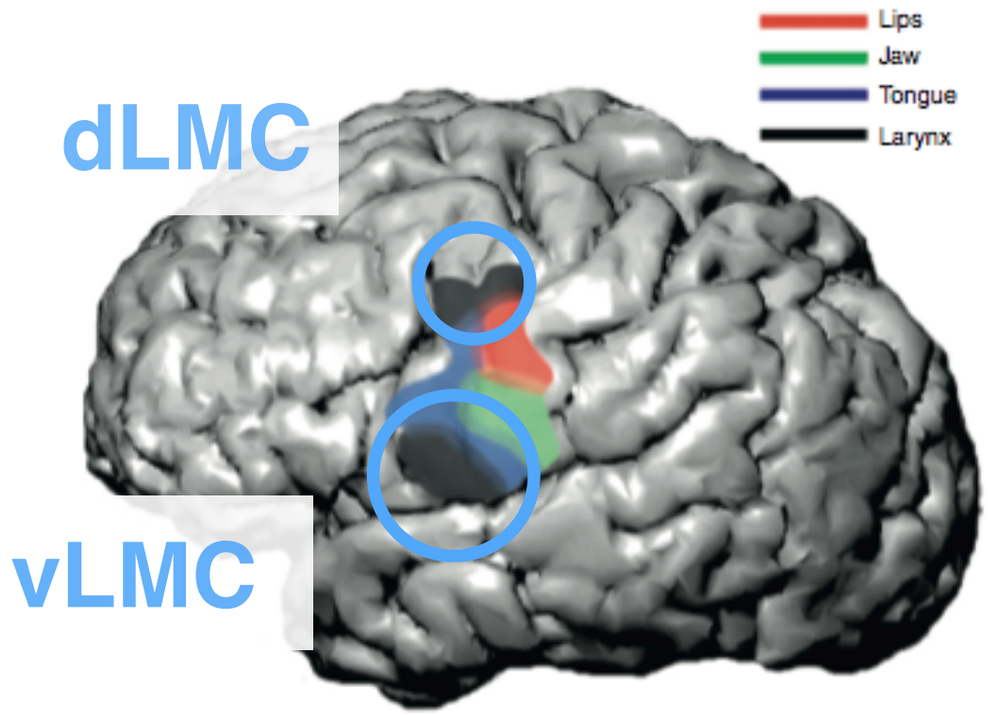
Cortical representation of larynx



Conant 2014 review

Cortical representation of larynx

- dLMC and vLMC active in voicing



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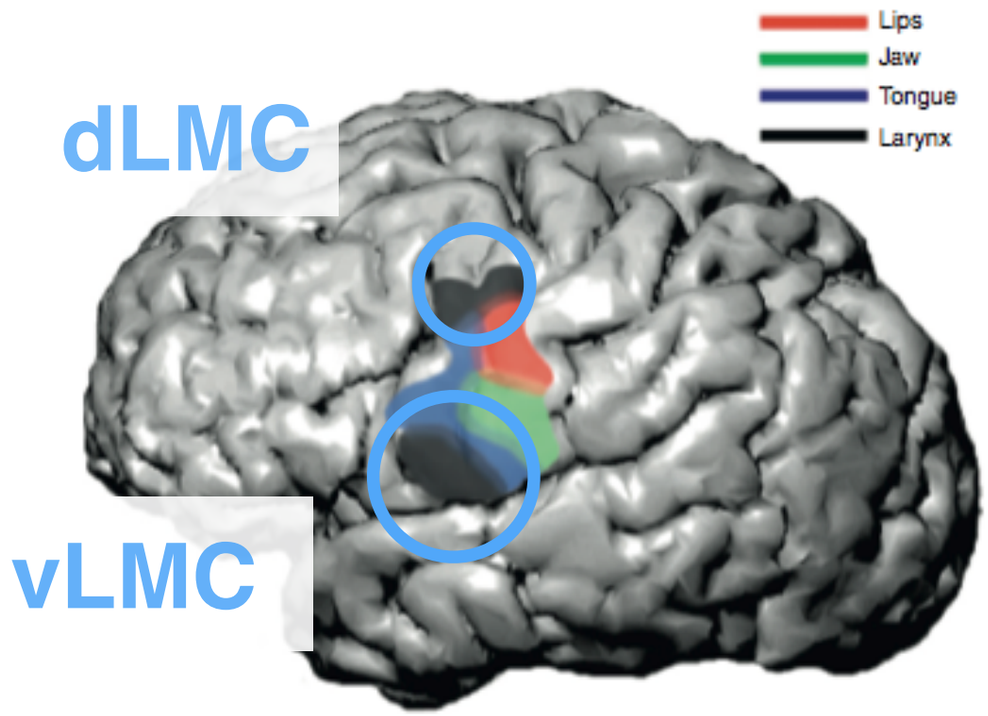

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- dLMC and vLMC active in voicing
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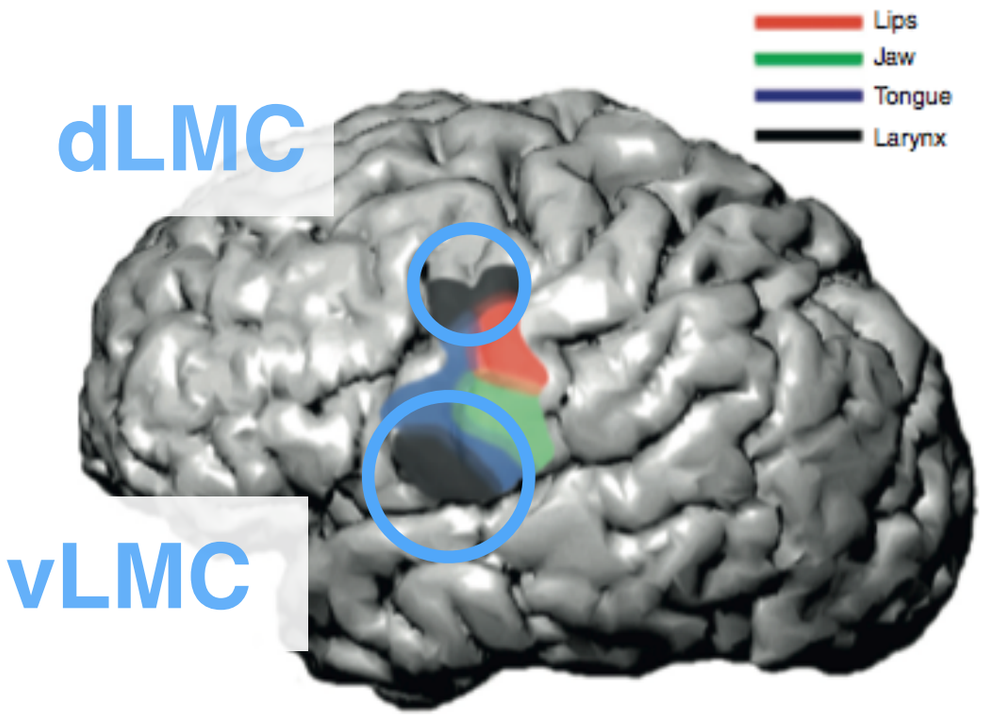
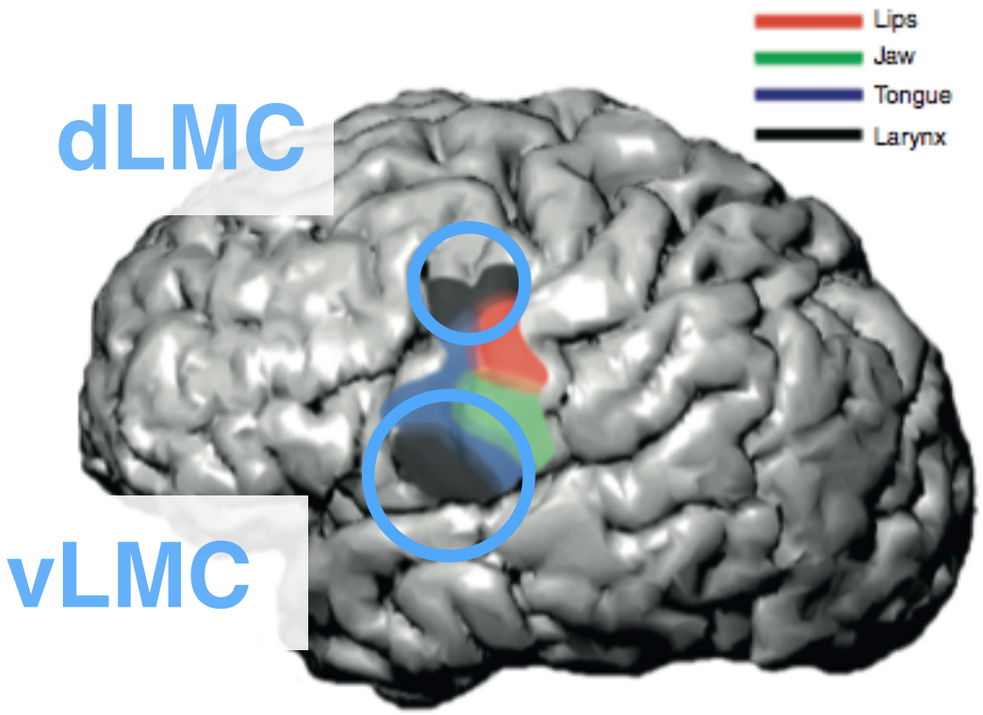


Conant 2014 review

Cortical representation of larynx

- dLMC and vLMC active in voicing
- vLMC found in non-human primates but dLMC unique to humans among primates
- Tuning for pitch has not yet been identified
- We hypothesize that there is an explicit encoding of pitch in dLMC



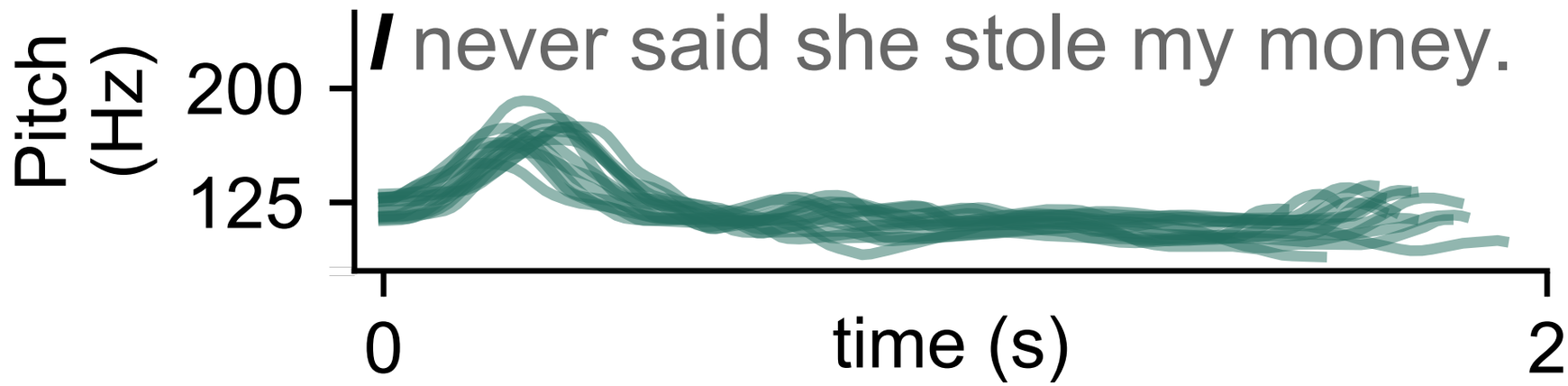
Conant 2014 review

Contrastive emphasis task: vocal pitch encoding

I never said she stole my money.

(Cell, *in press*)

Contrastive emphasis task: vocal pitch encoding



(Cell, *in press*)

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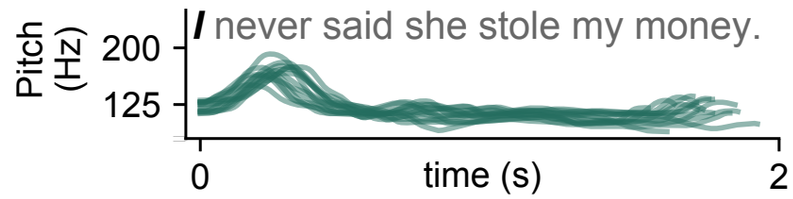

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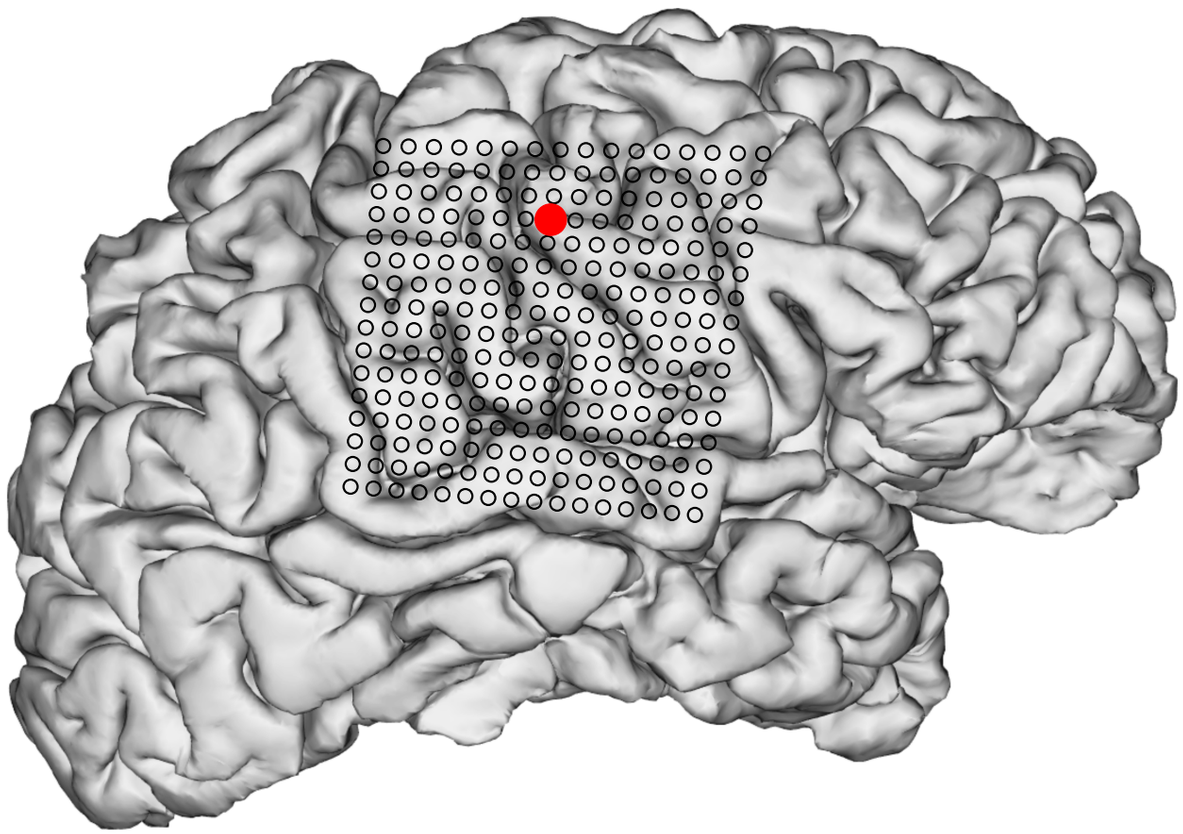
ECoG



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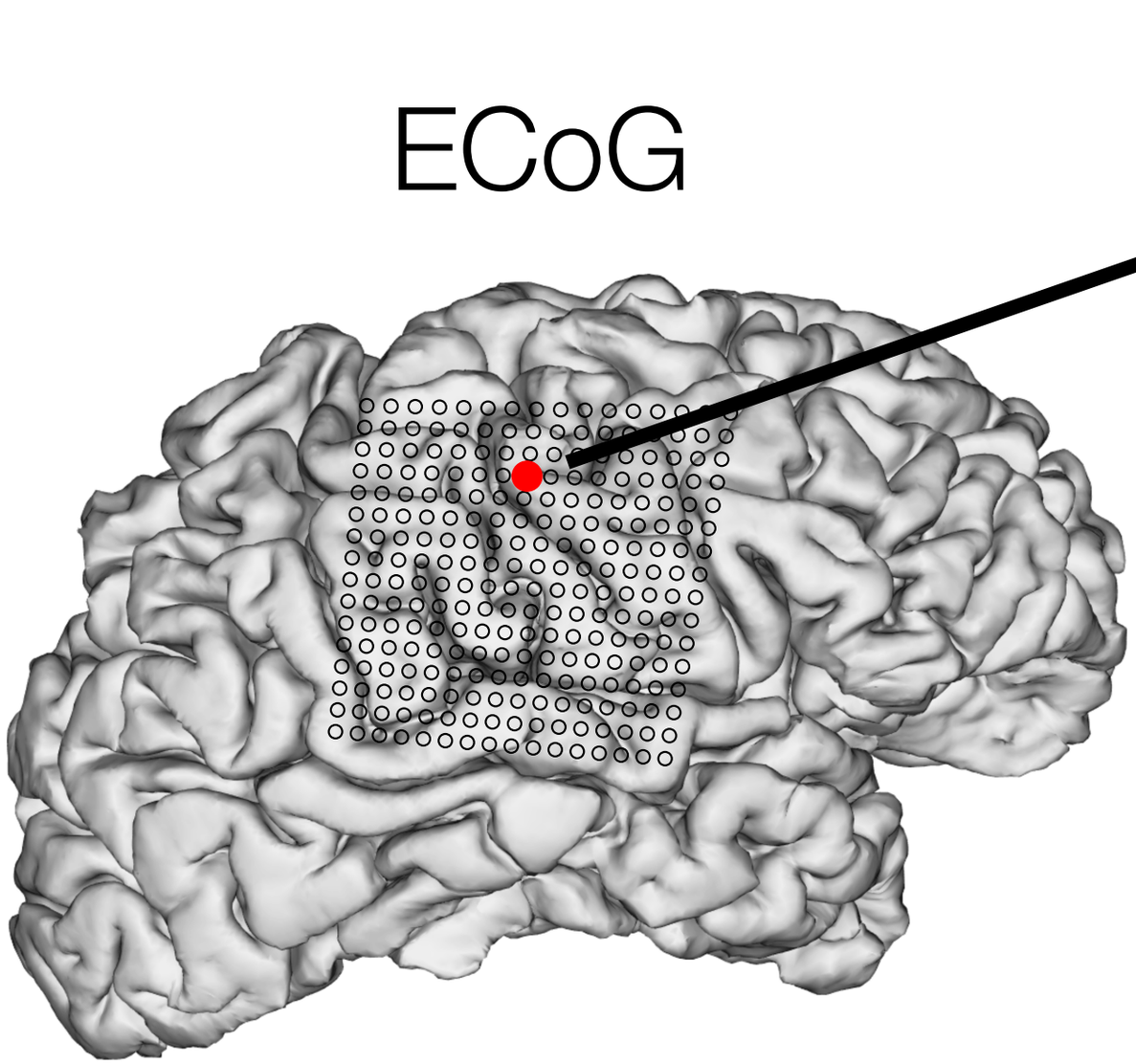

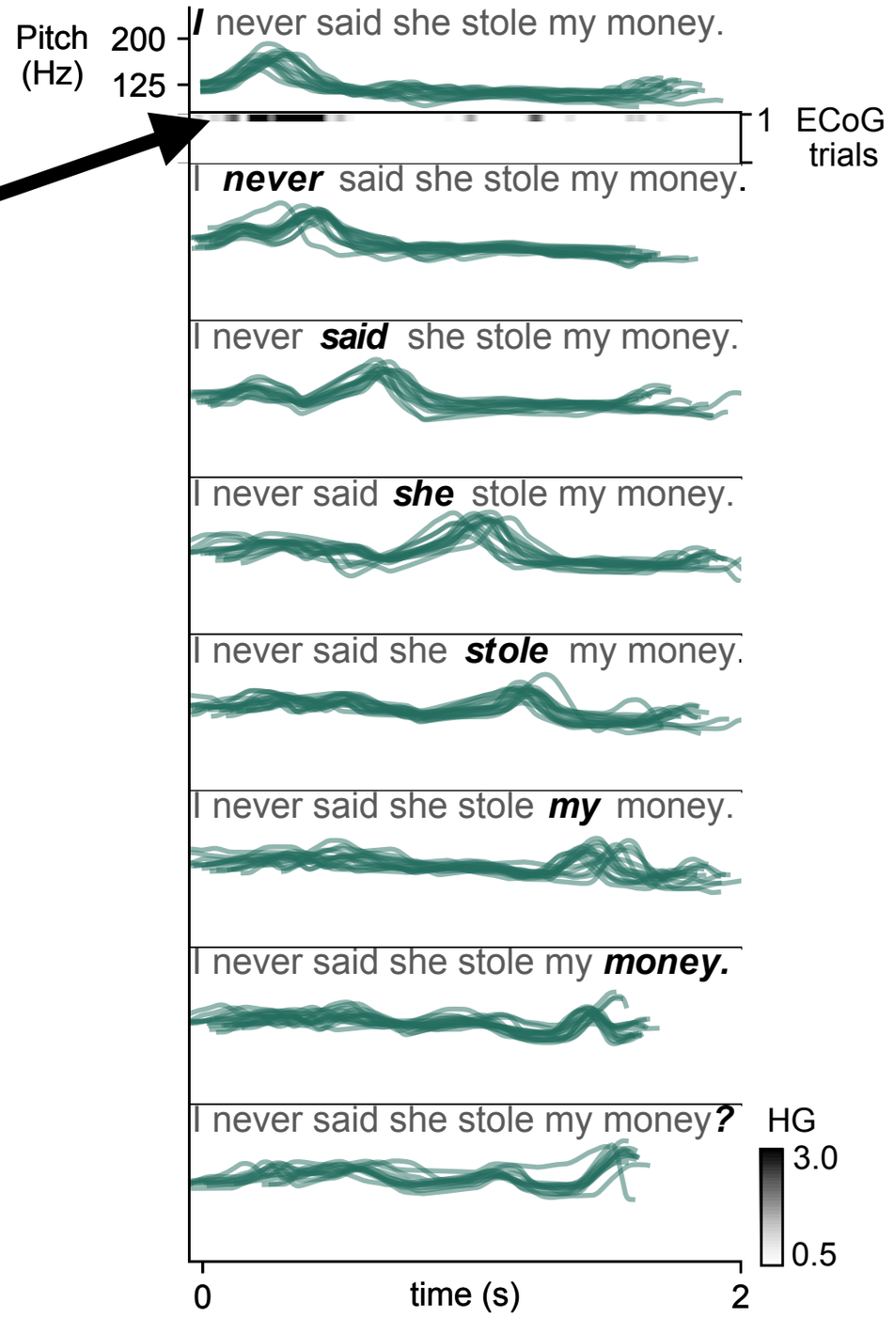

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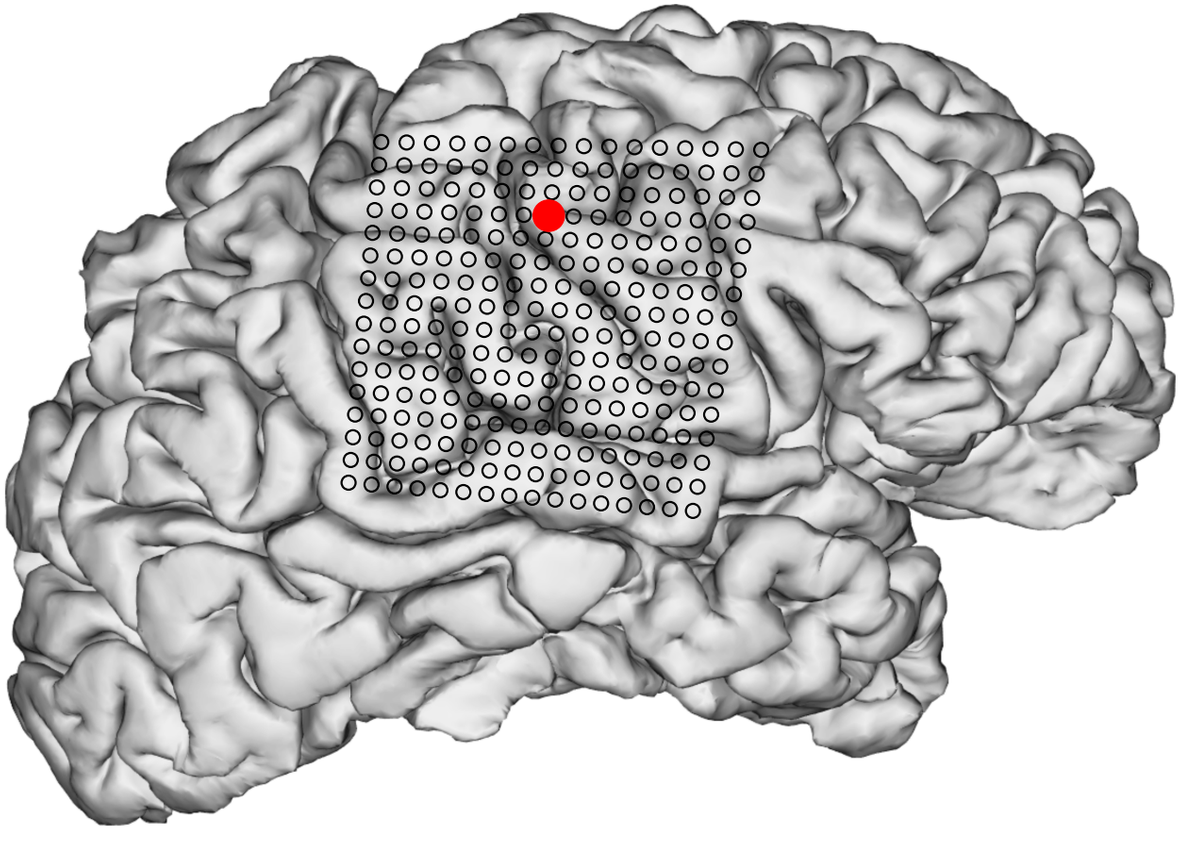
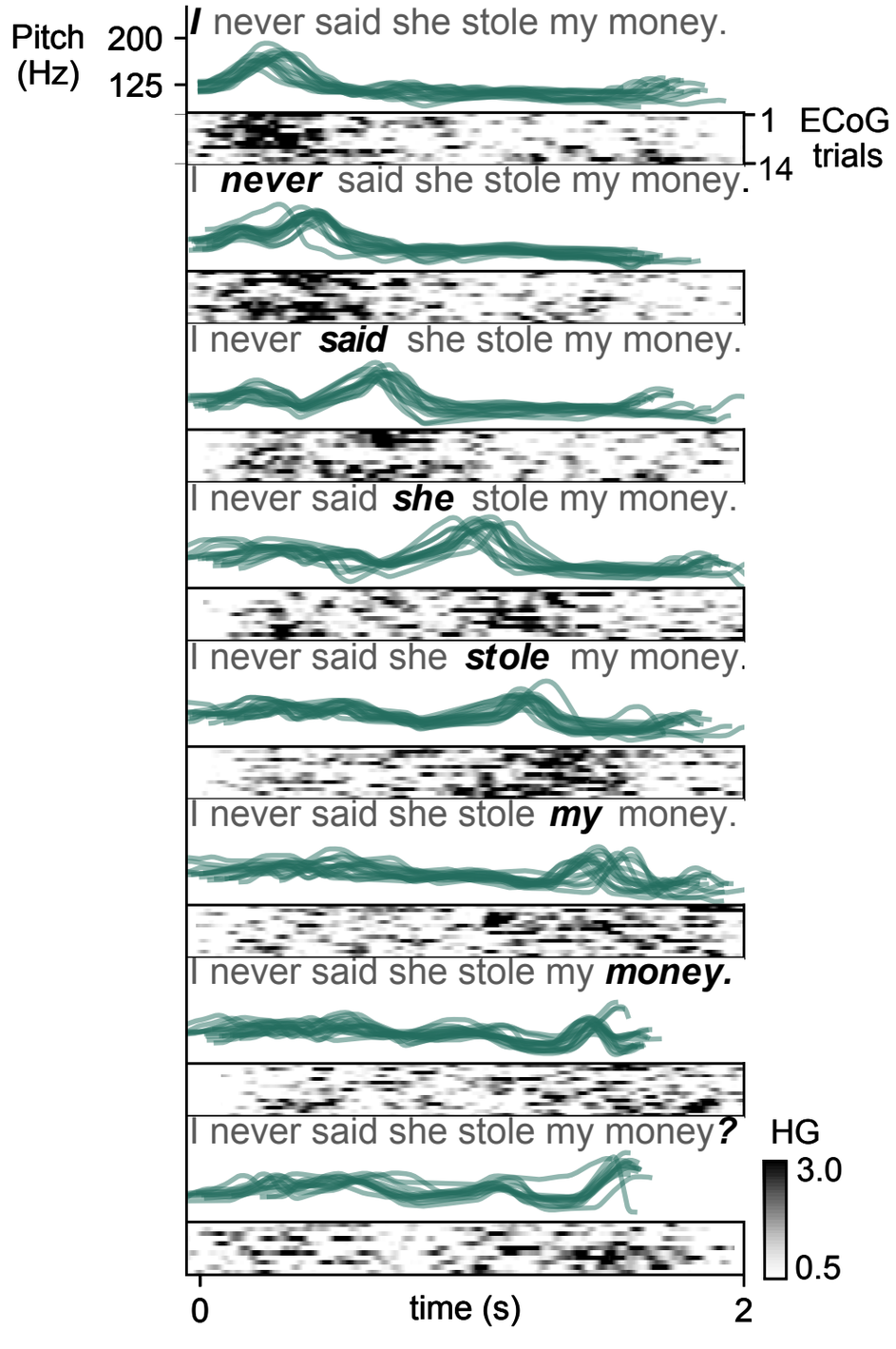
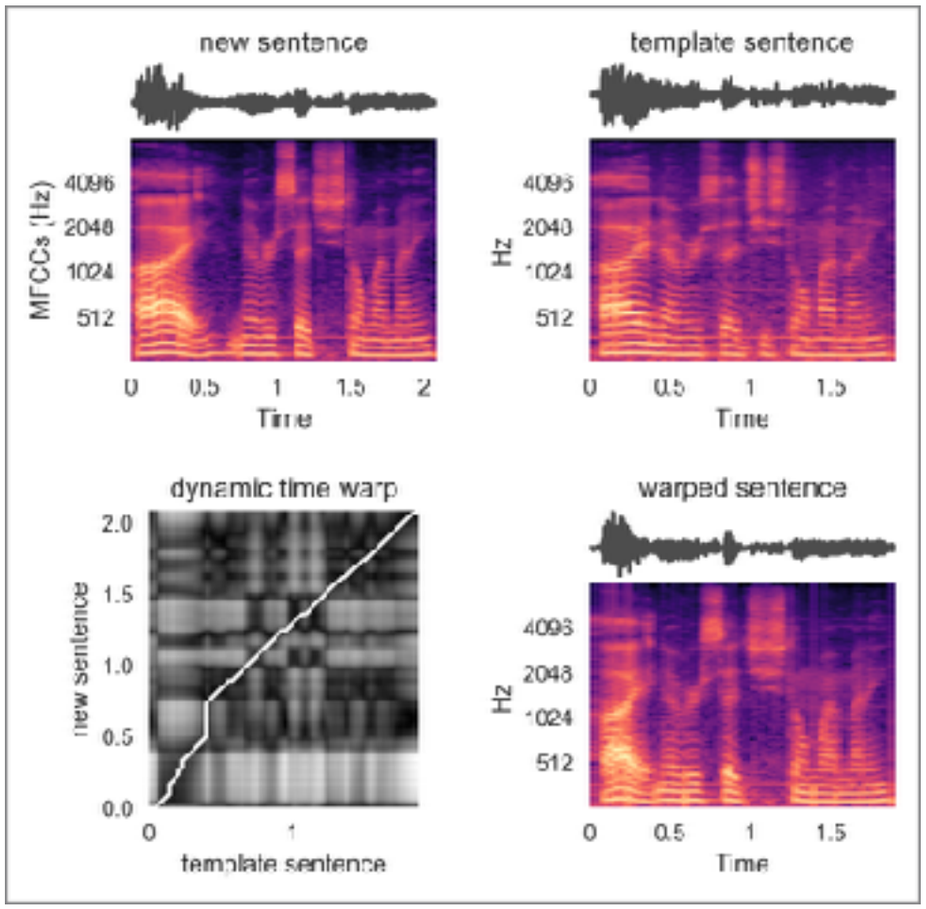




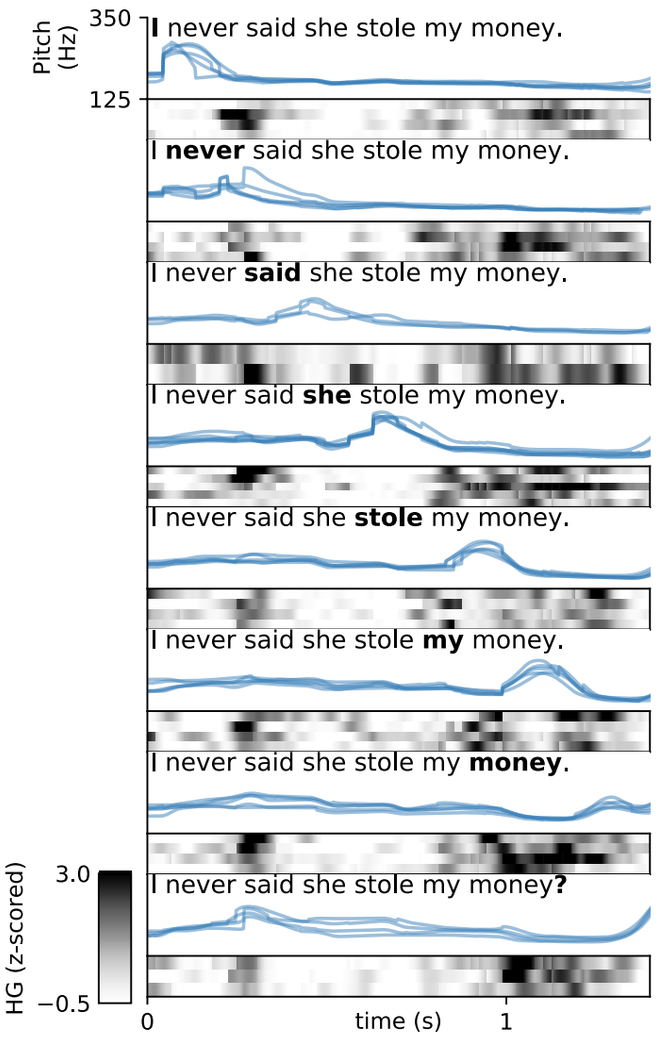
(Cell, *in press*)

Articulators: dynamic time warping

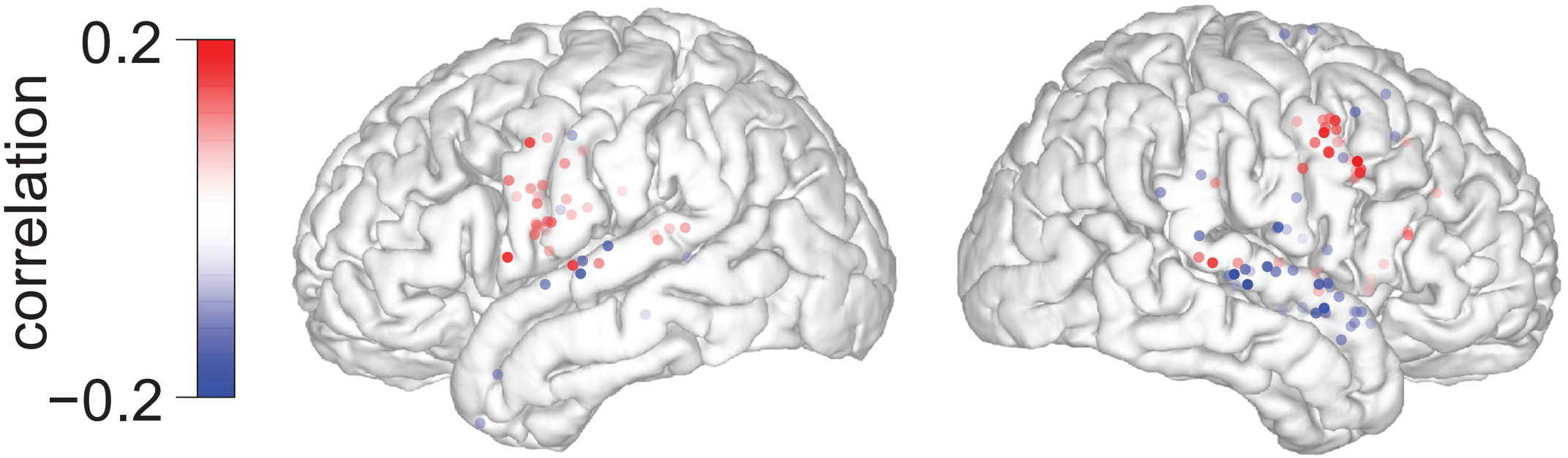
before warping



after warping

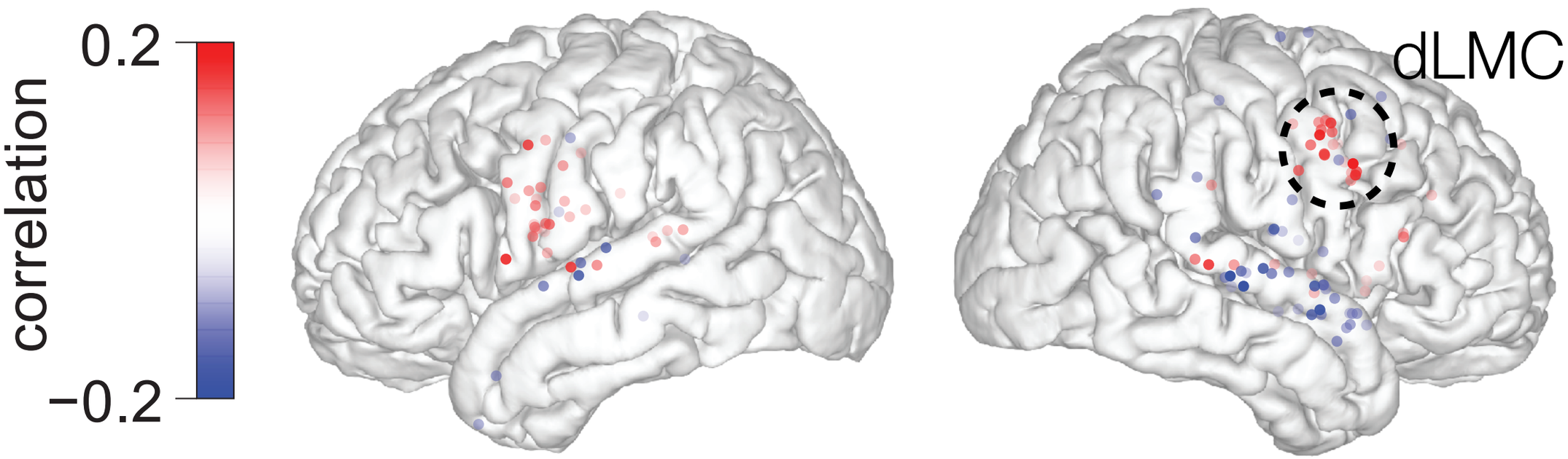


Pitch encoding in dLMC across subjects



12 subjects

Pitch encoding in dLMC across subjects



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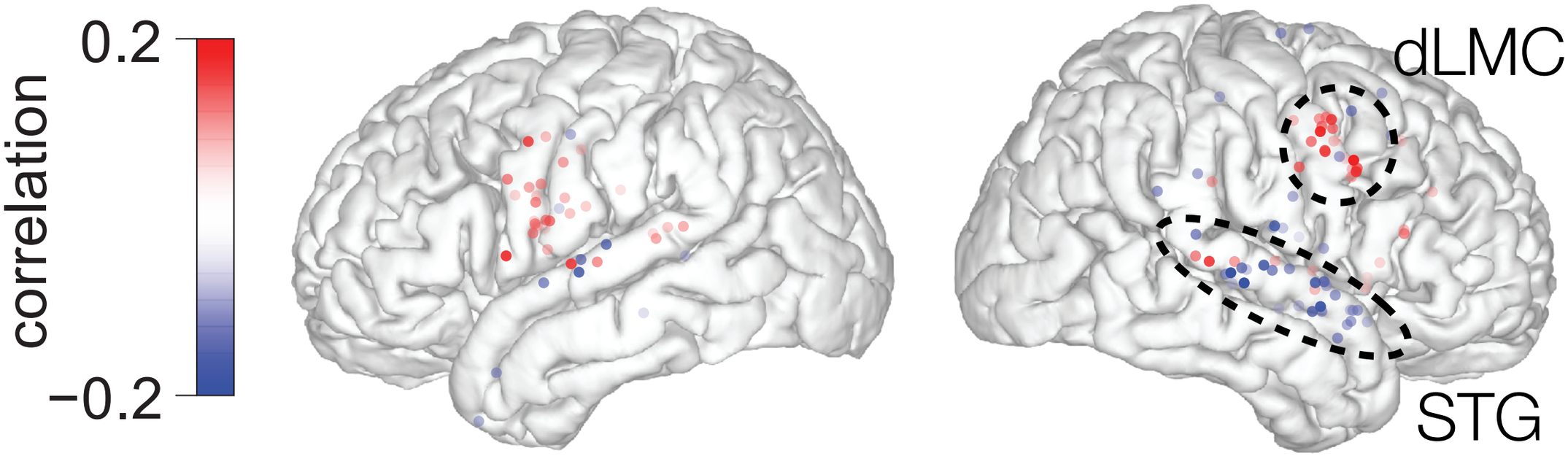

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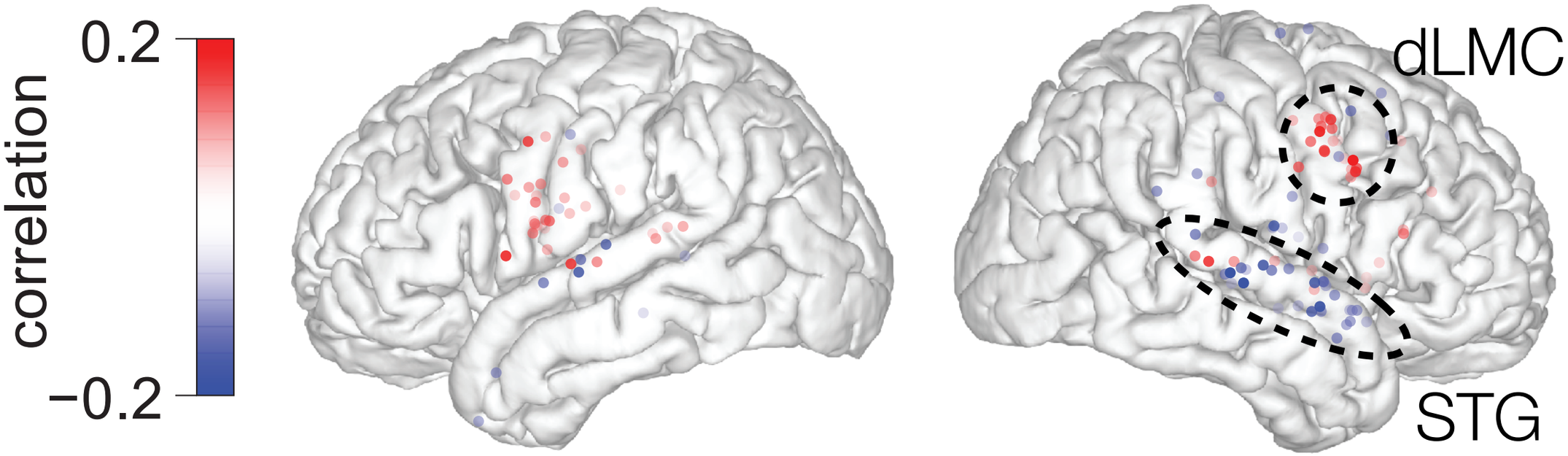
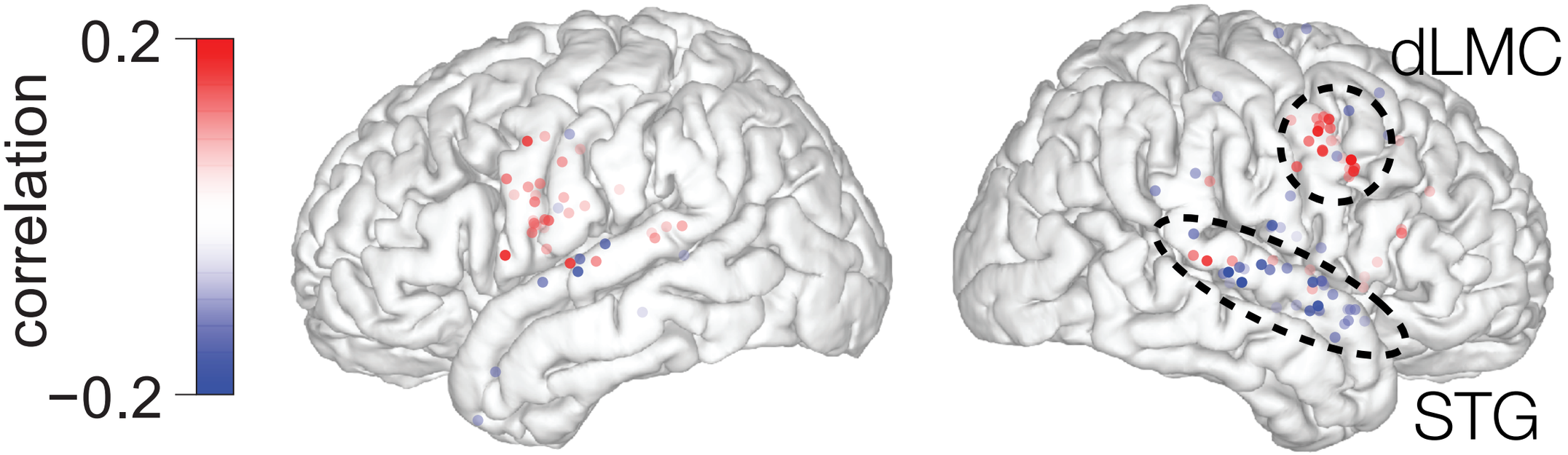


12 subjects

Findings:

Pitch encoding in dLMC across subjects

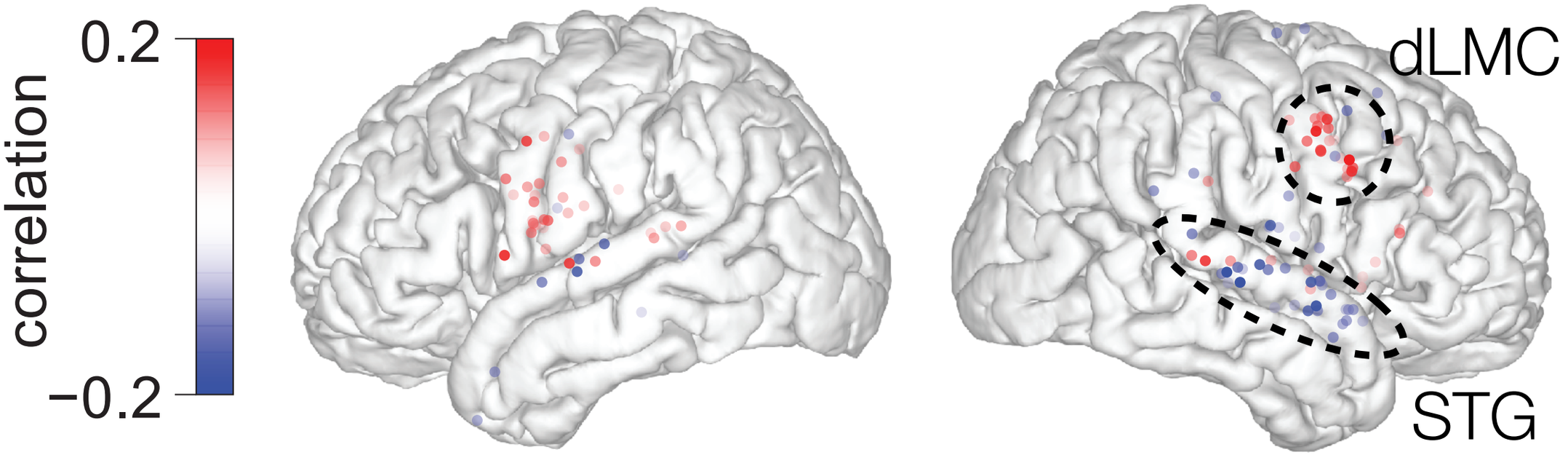


12 subjects

Findings:

- In dLMC, higher pitch has higher activation

Pitch encoding in dLMC across subjects

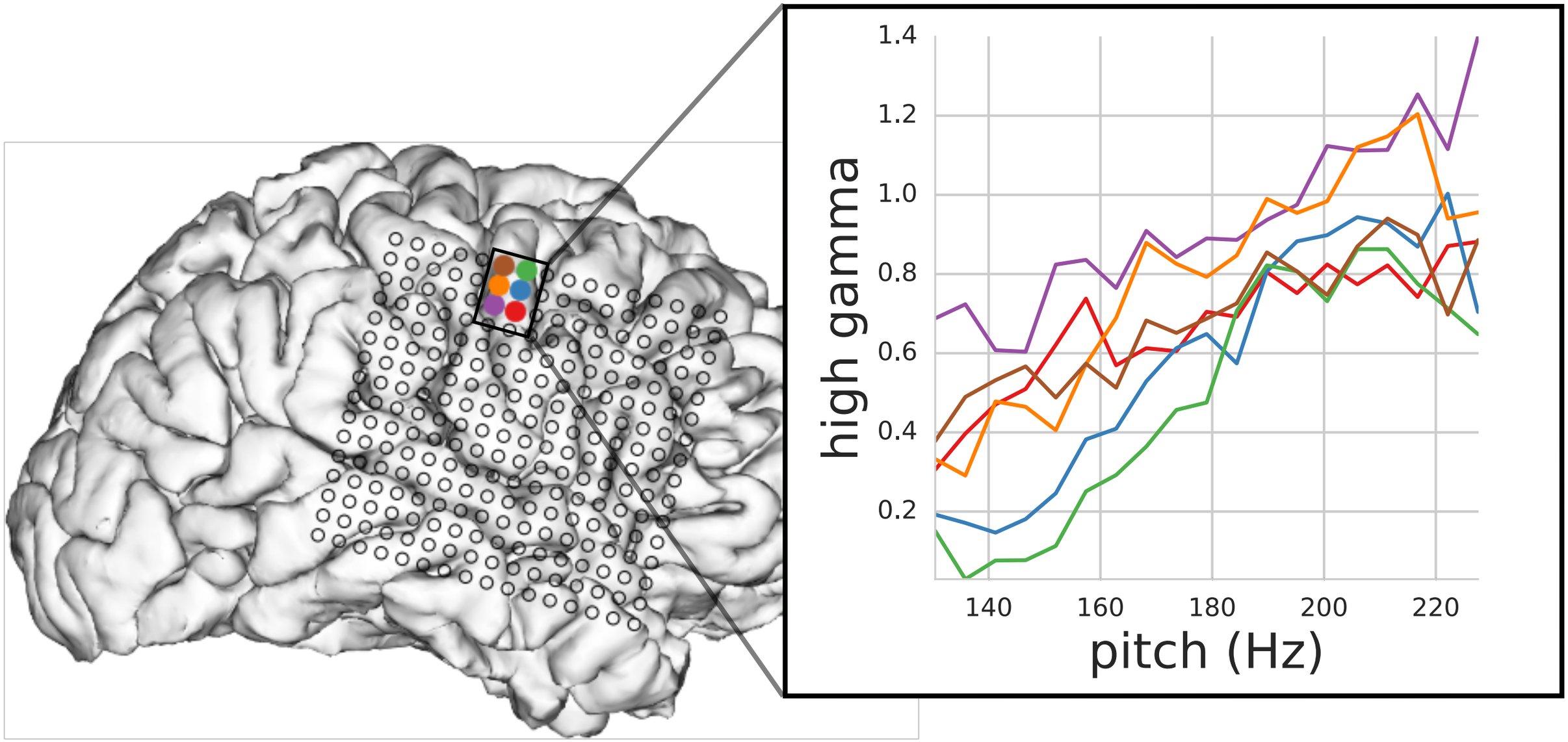


12 subjects

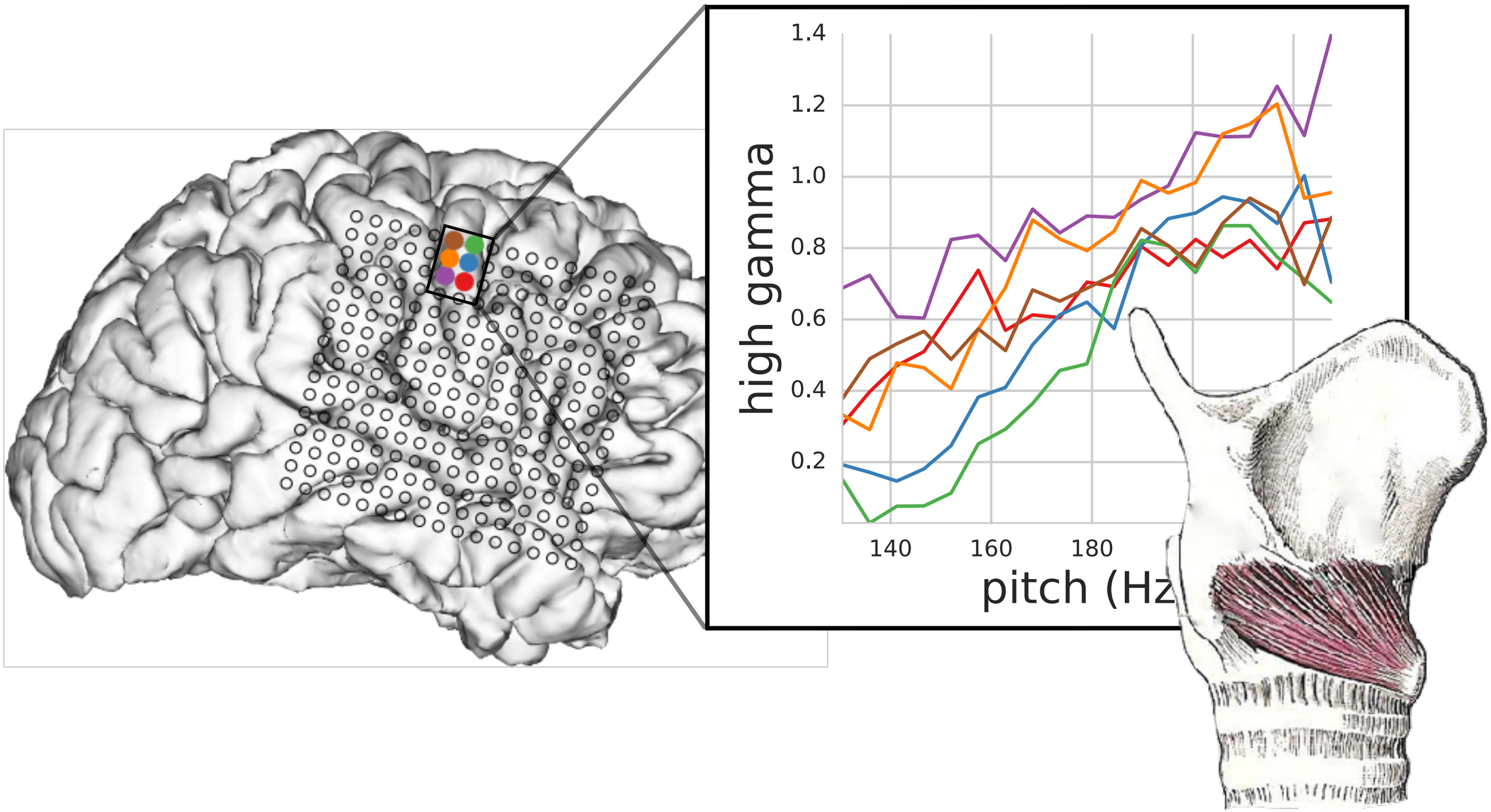
Findings:

- In dLMC, higher pitch has higher activation
- In the superior temporal gyrus, an auditory area, electrodes are split between preferring higher pitches and lower pitches

High gamma increases with pitch in dLMC

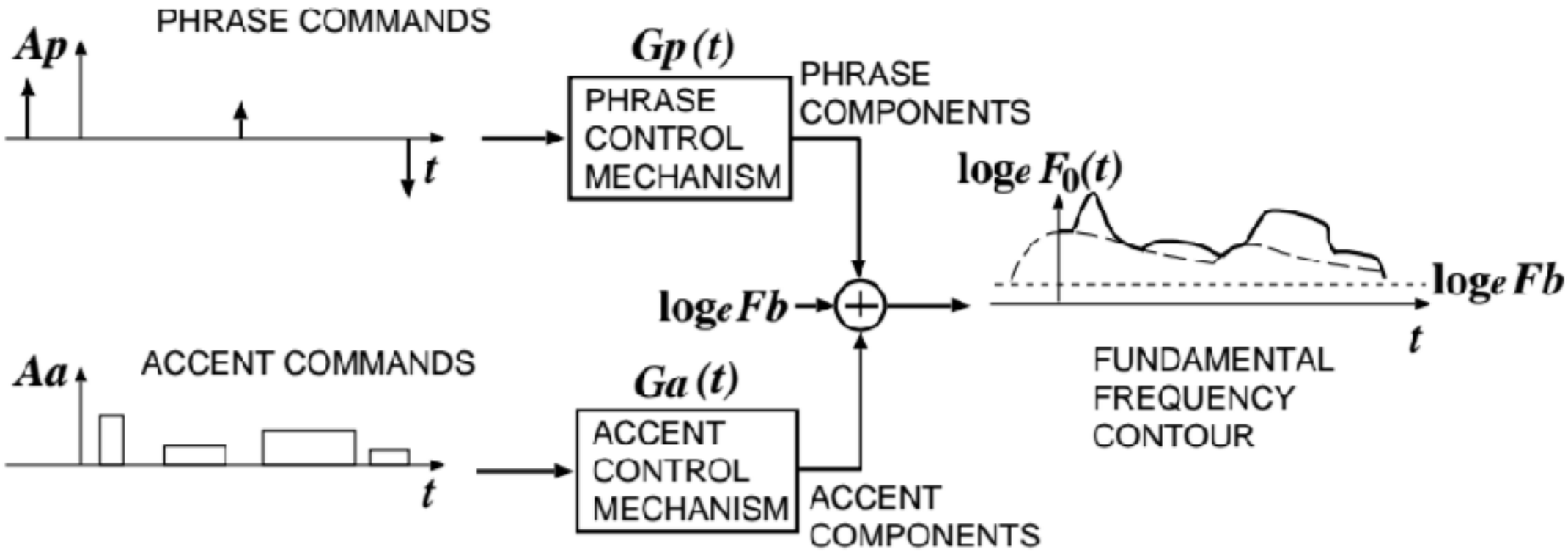


High gamma increases with pitch in dLMC



Encoding of Components of Prosody

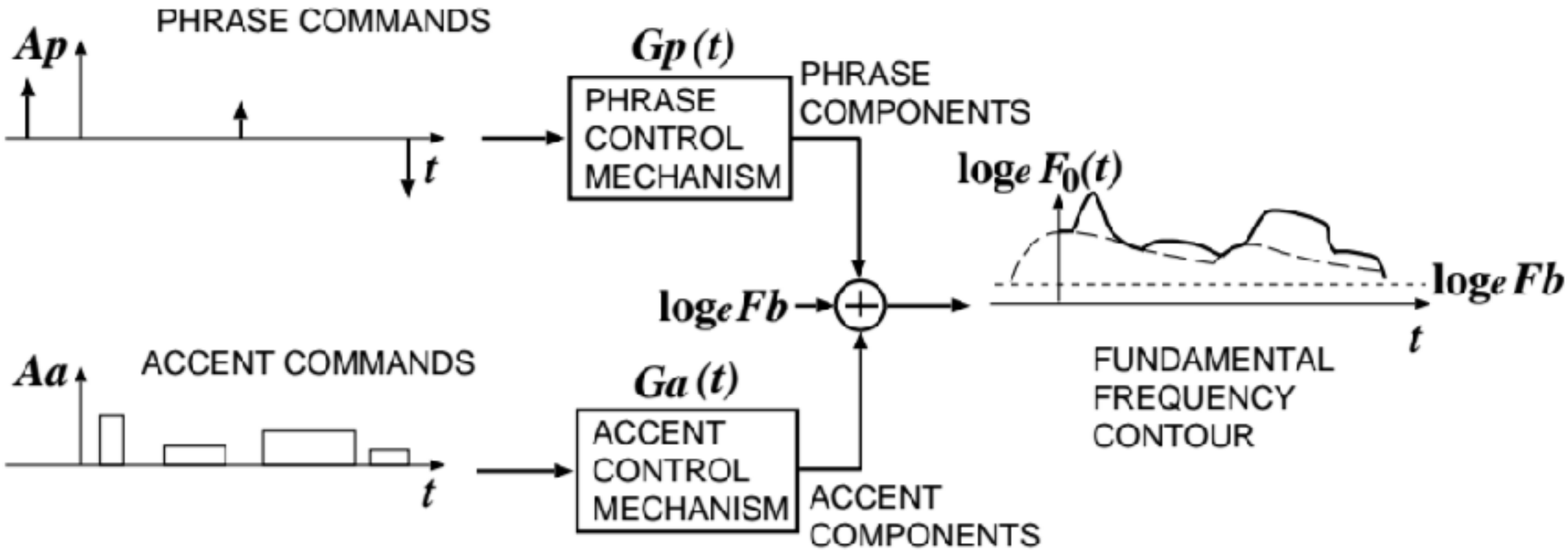
Fujisaki Model: a parsimonious explanation for pitch contours



(Fujisaki, Speech Prosody, 2004)

Encoding of Components of Prosody

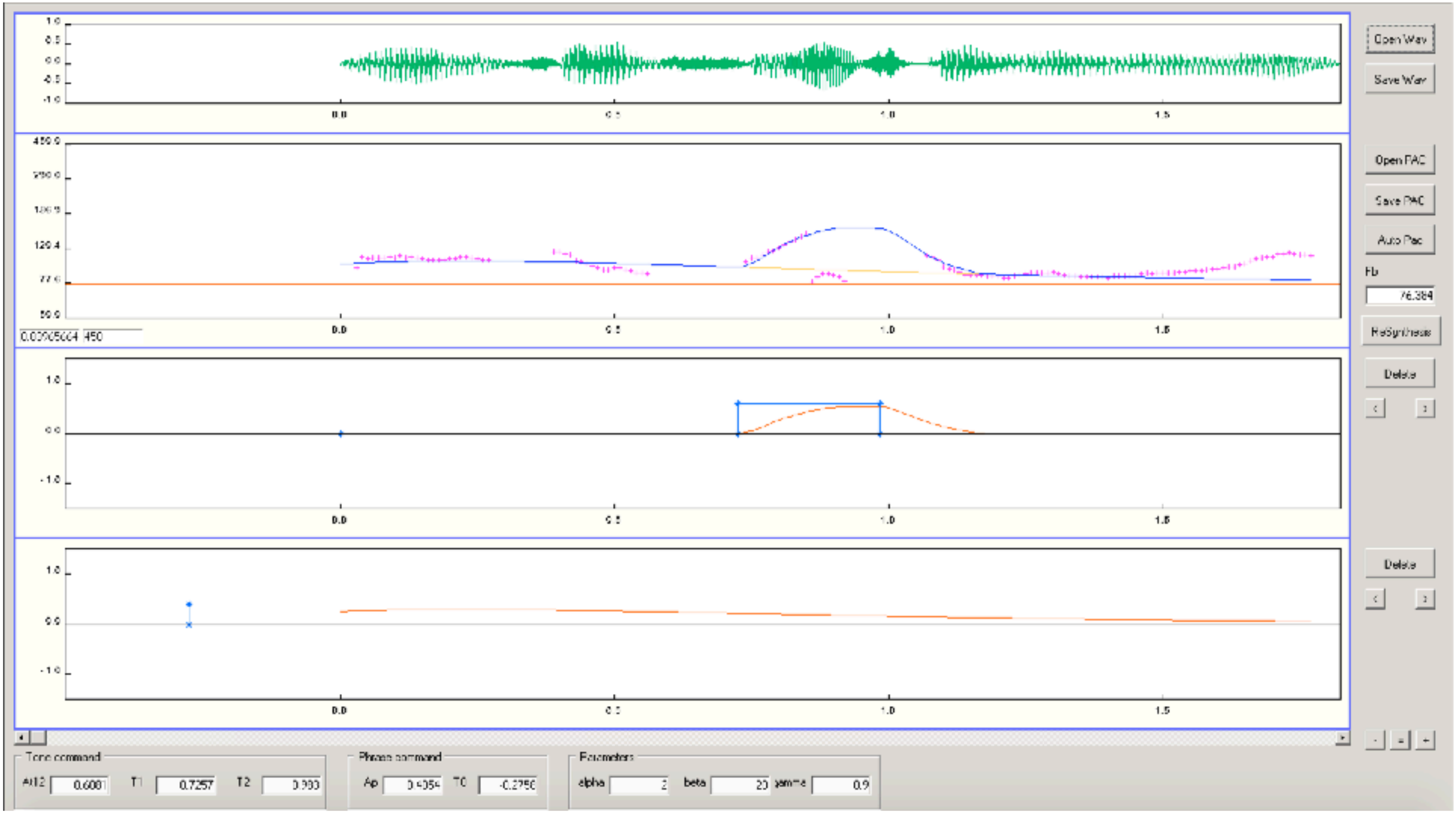
Fujisaki Model: a parsimonious explanation for pitch contours



Hypothesis: different components controlled separately

(Fujisaki, Speech Prosody, 2004)

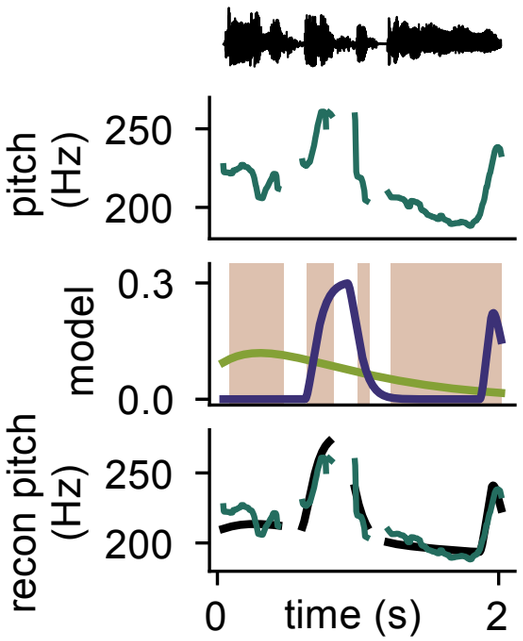
Fitting the Fujisaki model using FujiParaEditor



Written by Dr. Hansjörg Mixdorff

Encoding of Fujisaki components

phrase
accent
voicing



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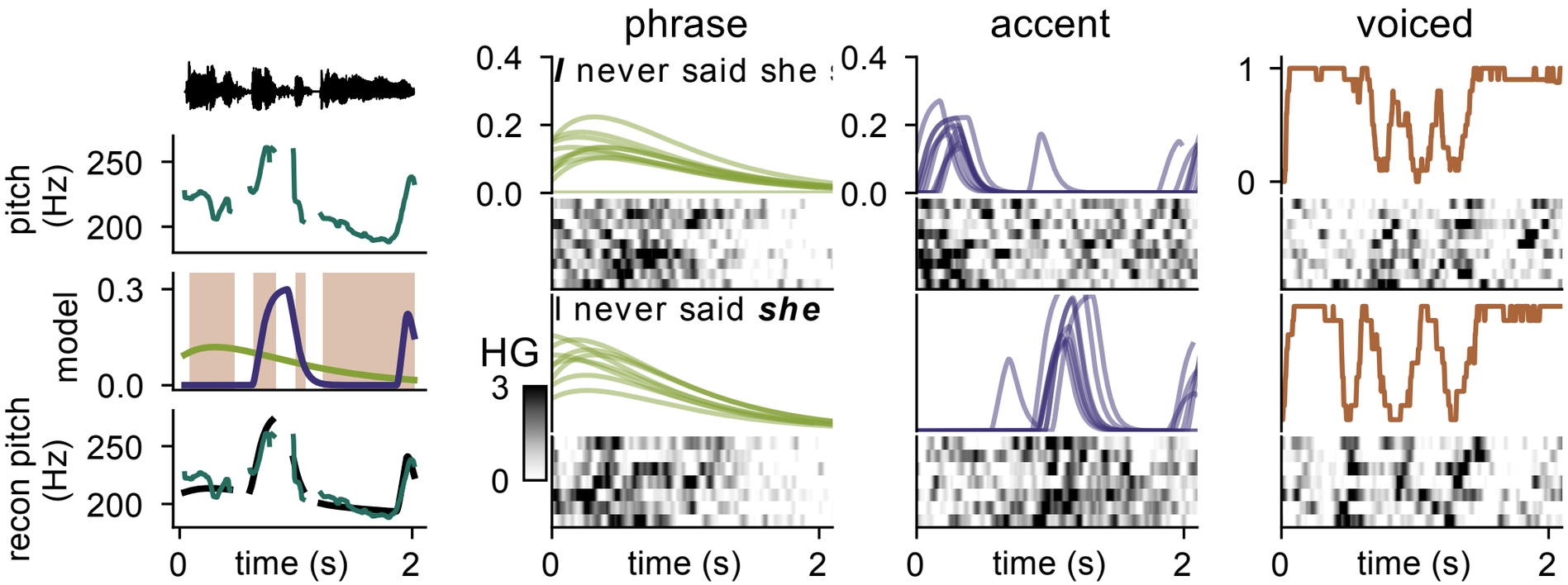

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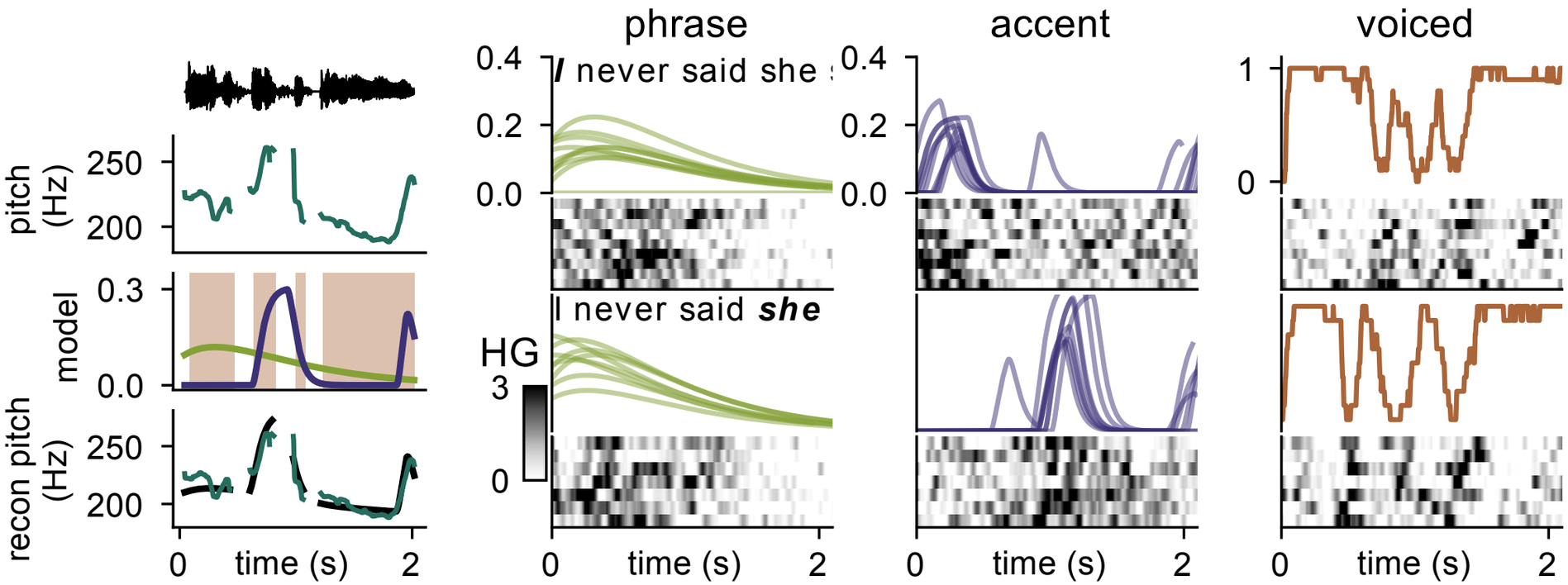

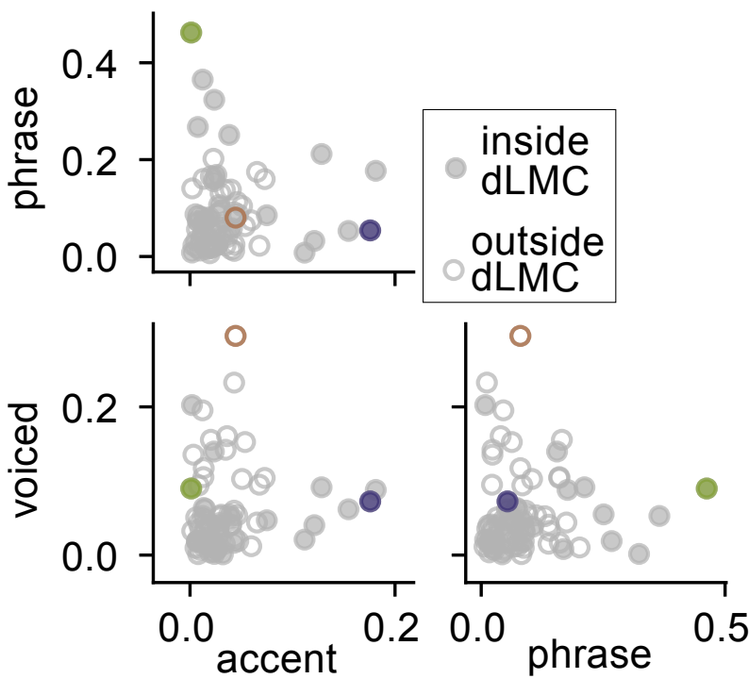

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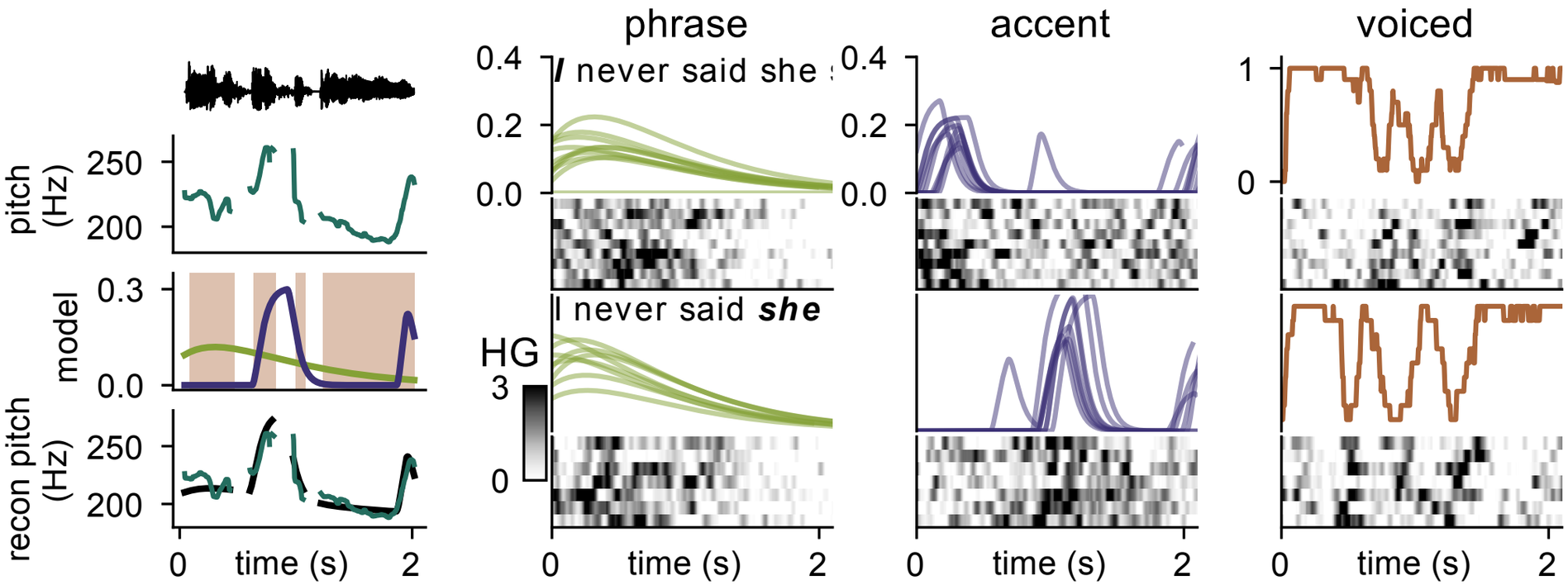
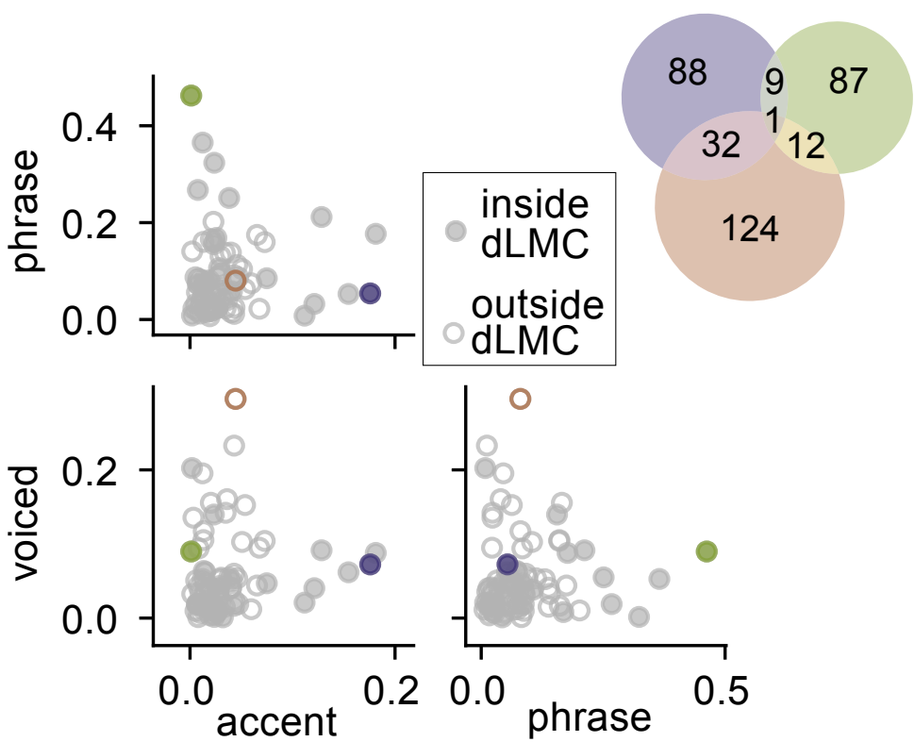
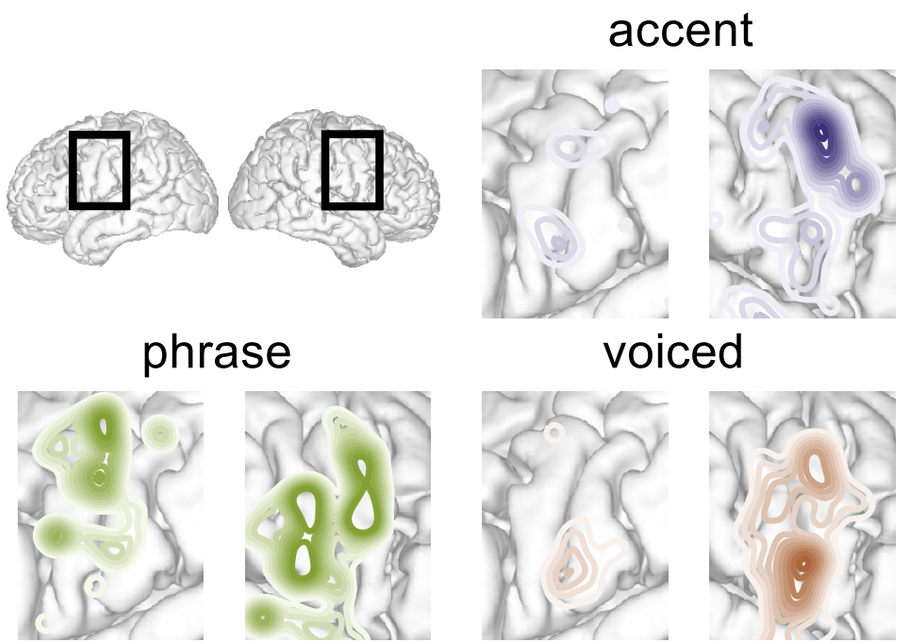
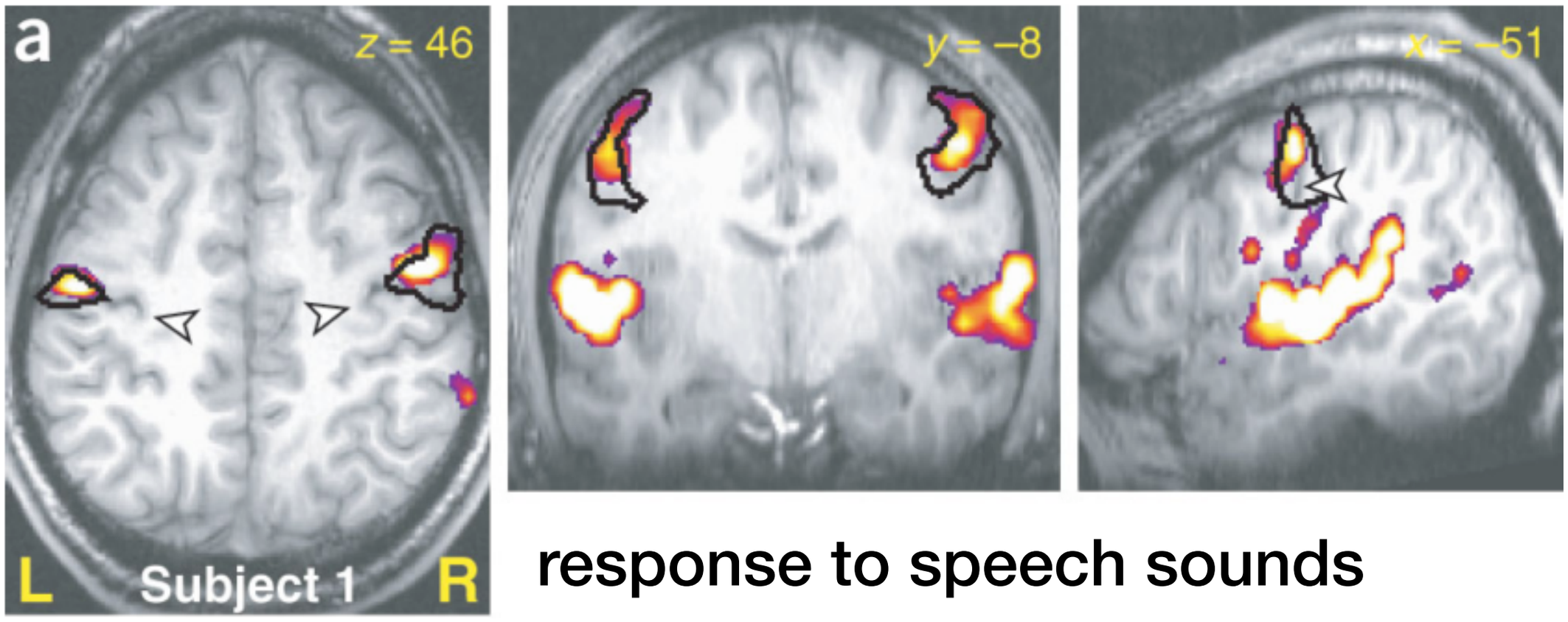






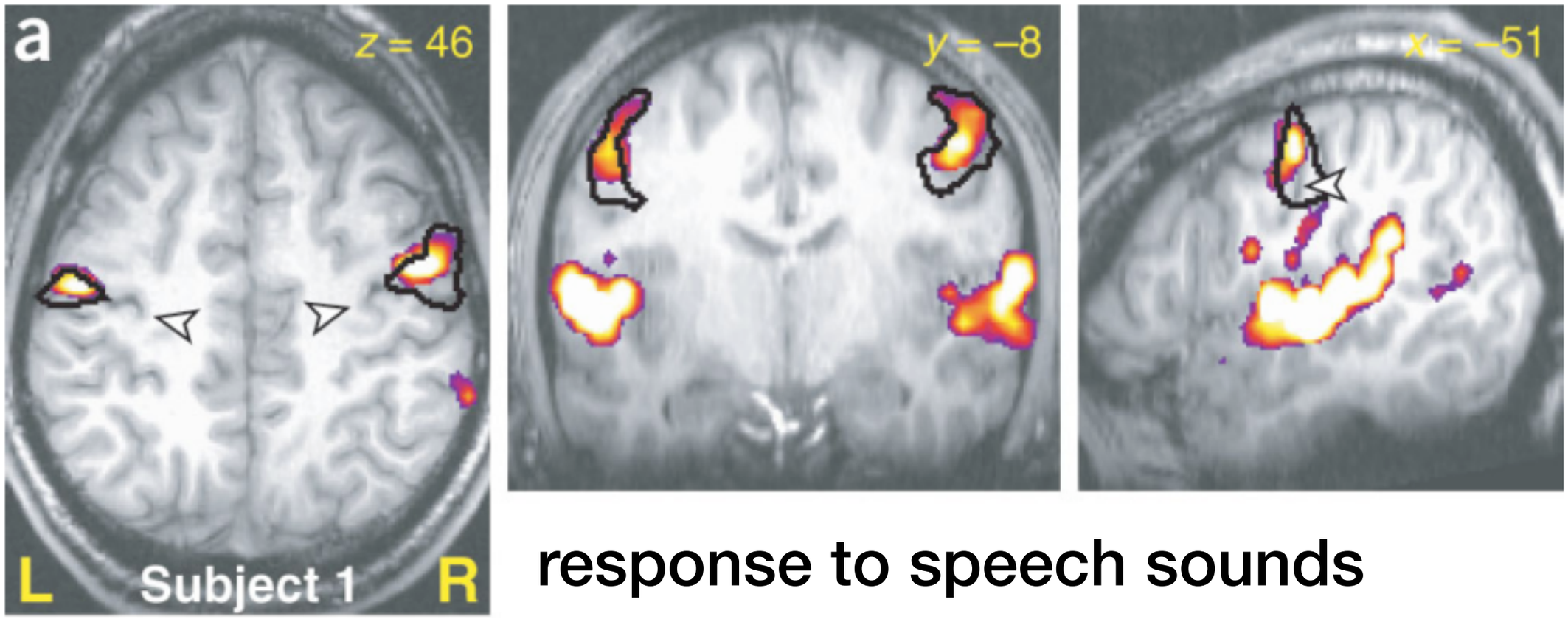
Auditory response M1



response to speech sounds

(Wilson et al. 2004)

Auditory response M1



response to speech sounds

(Wilson et al. 2004)

Does this area overlap with dLMC? Does it encode pitch?

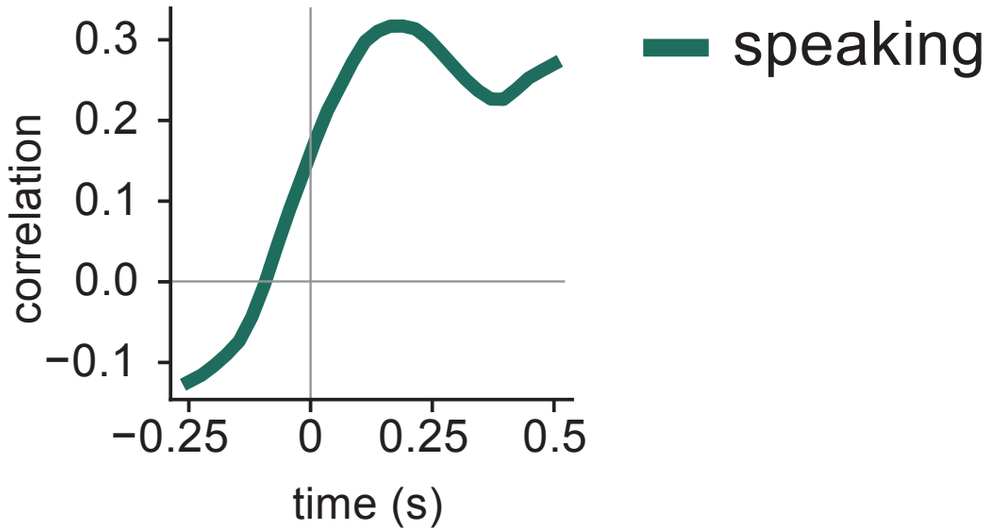
Auditory control: Playback

The recording of the task was played back to the subject

Auditory control: Playback

The recording of the task was played back to the subject

Cross-correlation
(example electrode)



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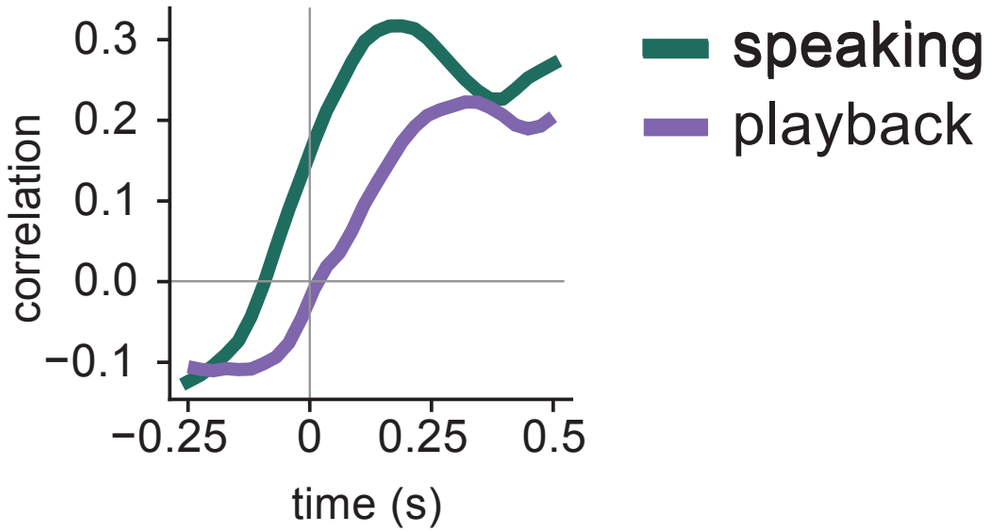

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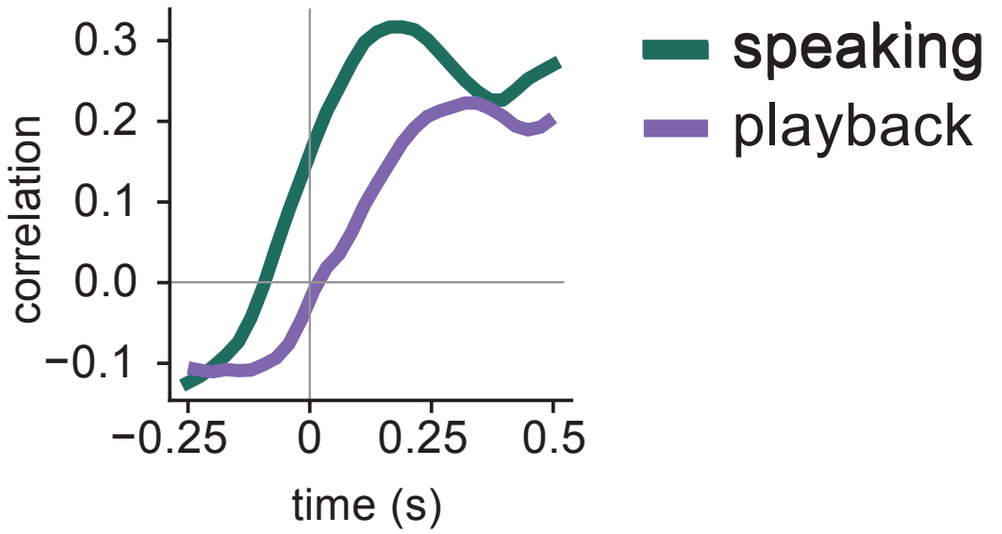
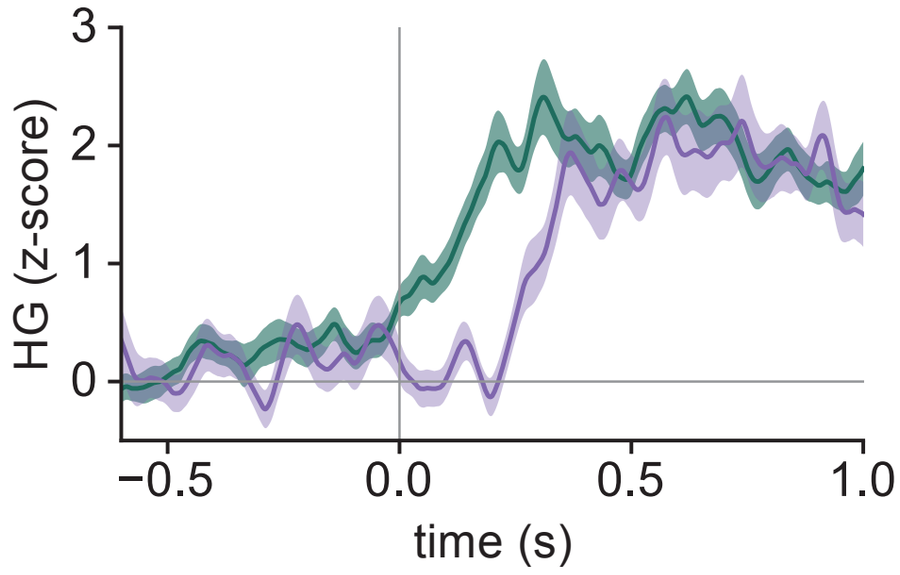


Onset delay
(example electrode)



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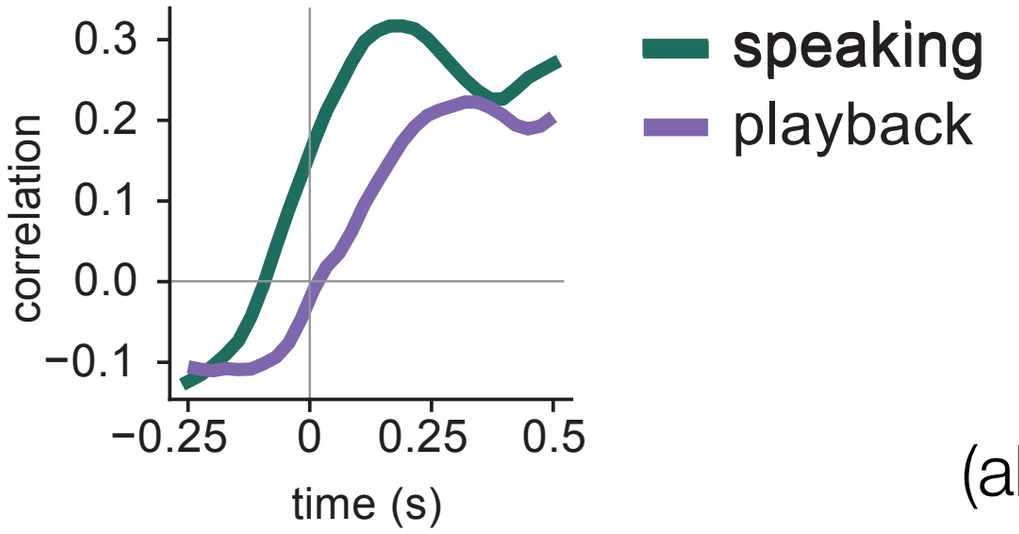
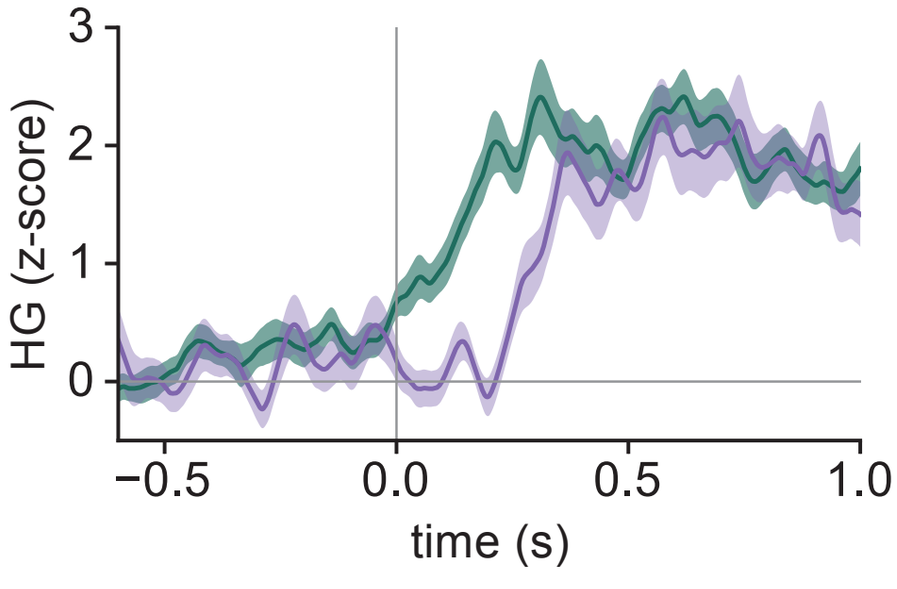
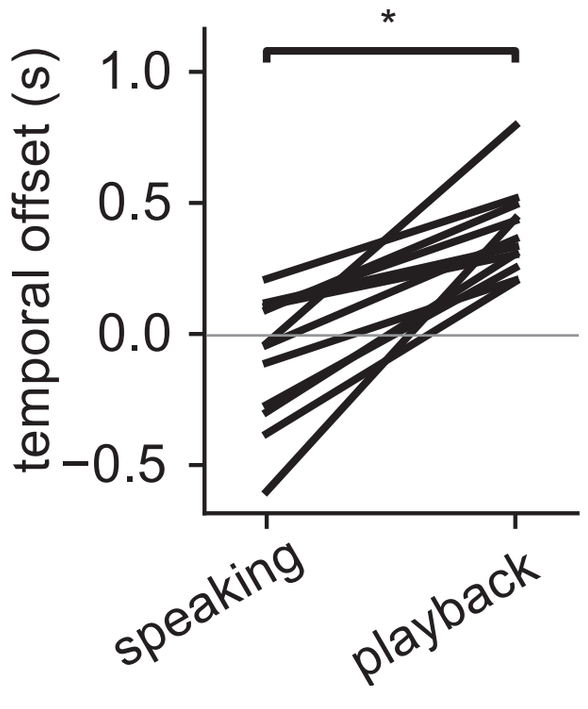


Onset delay
(example electrode)



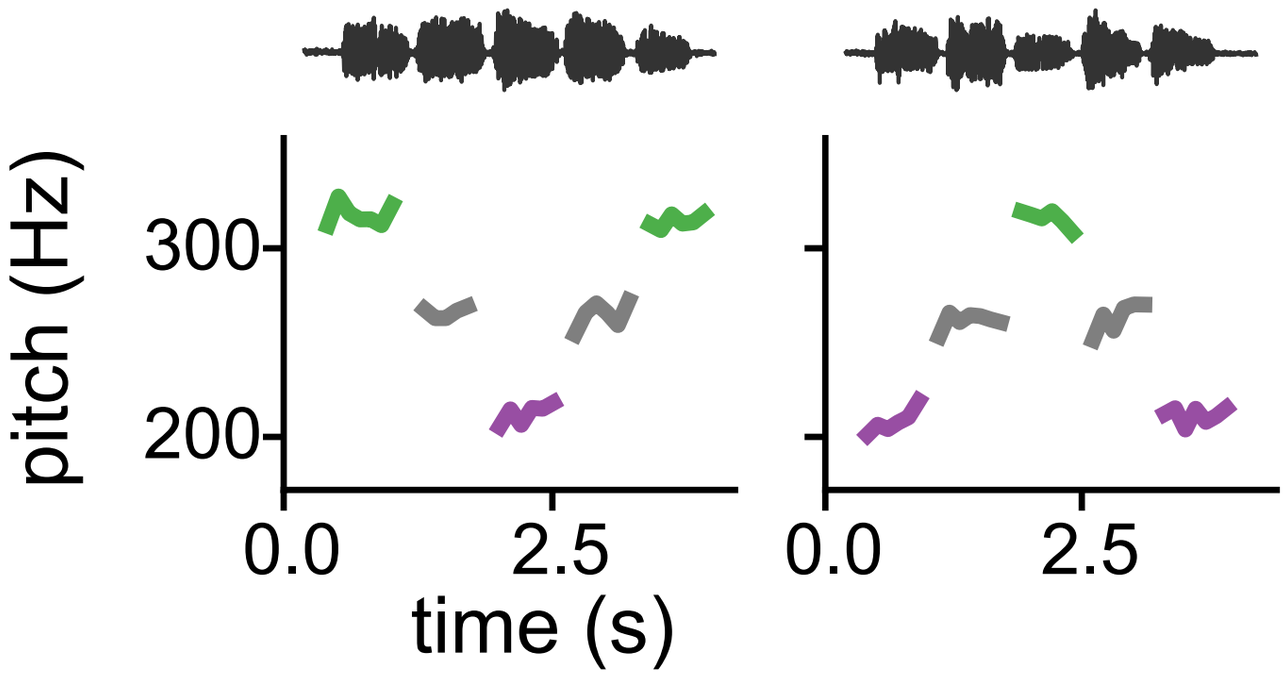
Onset delay
(all dLMC electrodes)



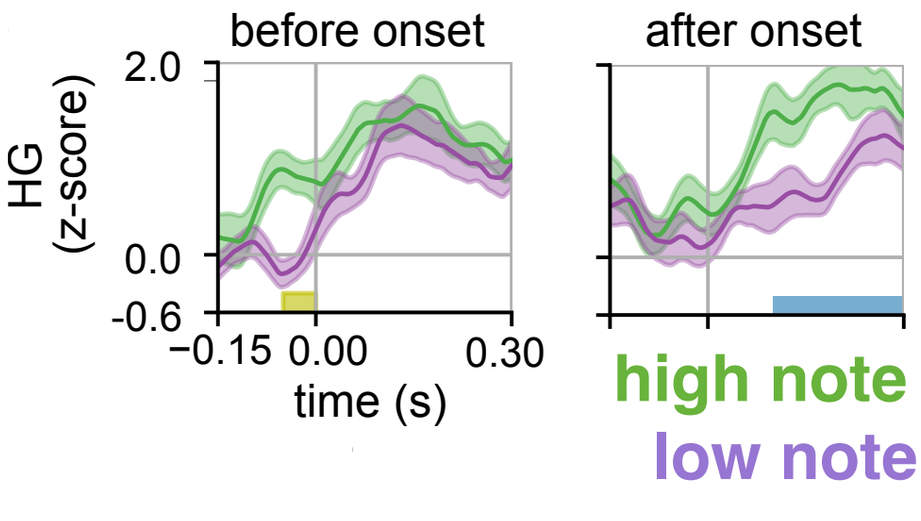
Pitch control during singing

Test whether laryngeal control is unique to speech

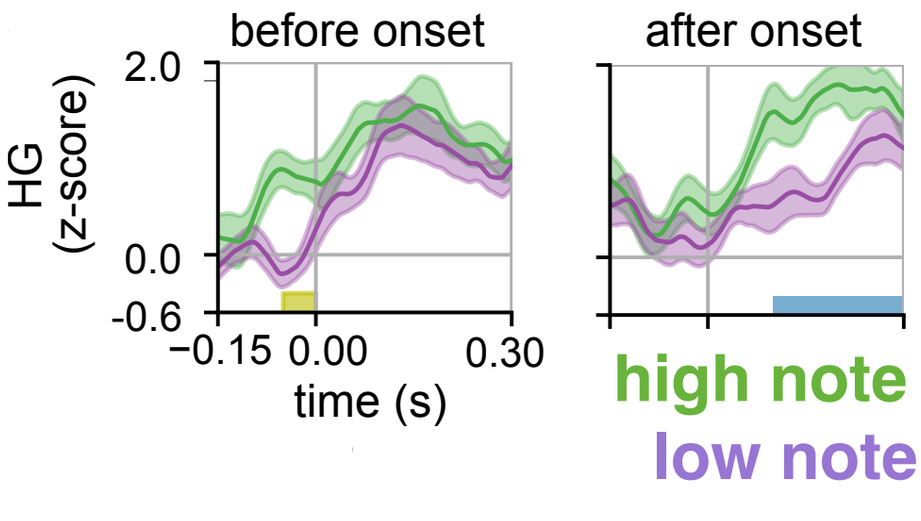
Task: Call-and-response singing task



Pitch control during singing

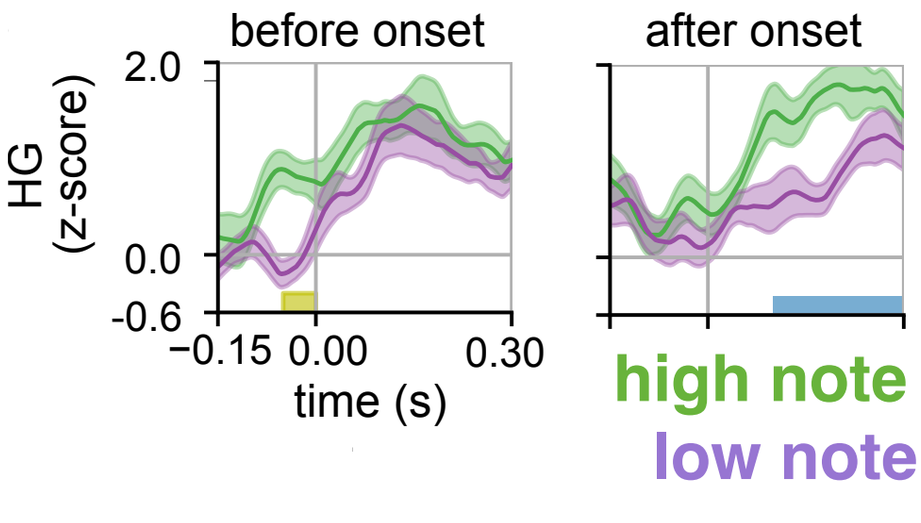


Pitch control during singing



Findings:

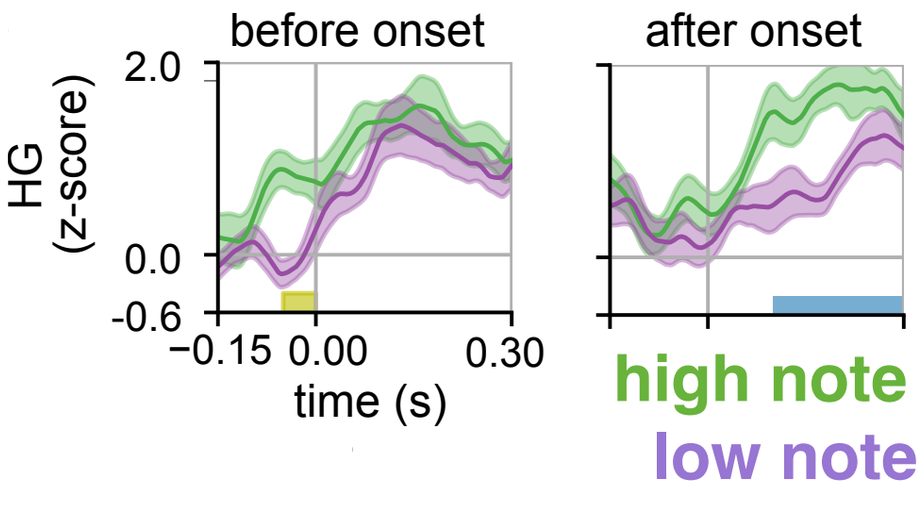
Pitch control during singing



Findings:

- Higher pitch has higher activation

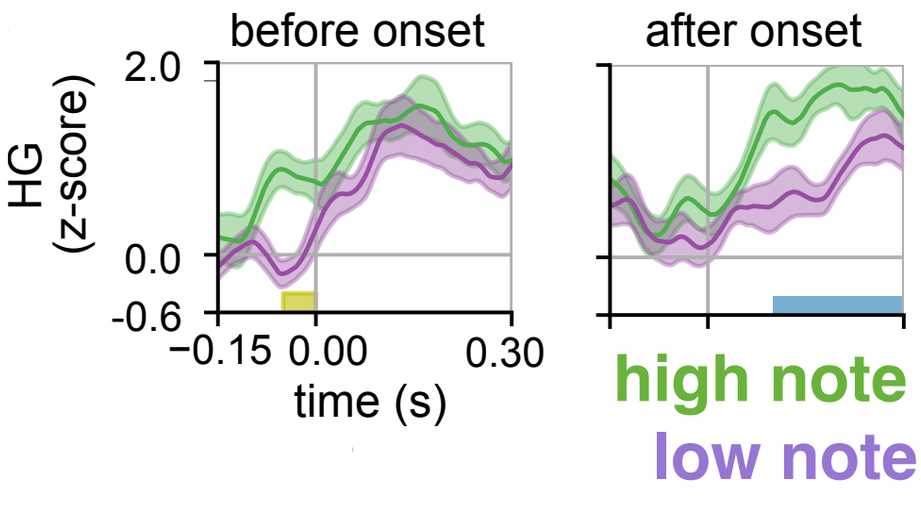
Pitch control during singing



Findings:

- Higher pitch has higher activation
- Representation starts before sound

Pitch control during singing



Findings:

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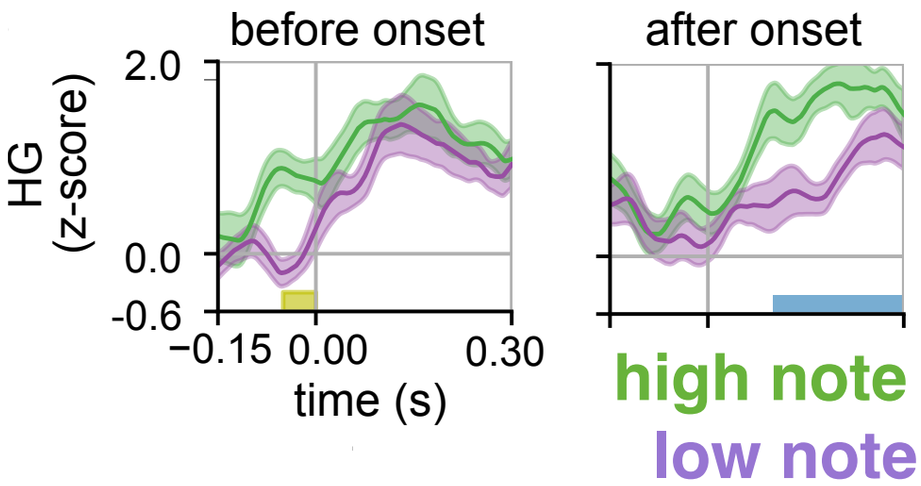
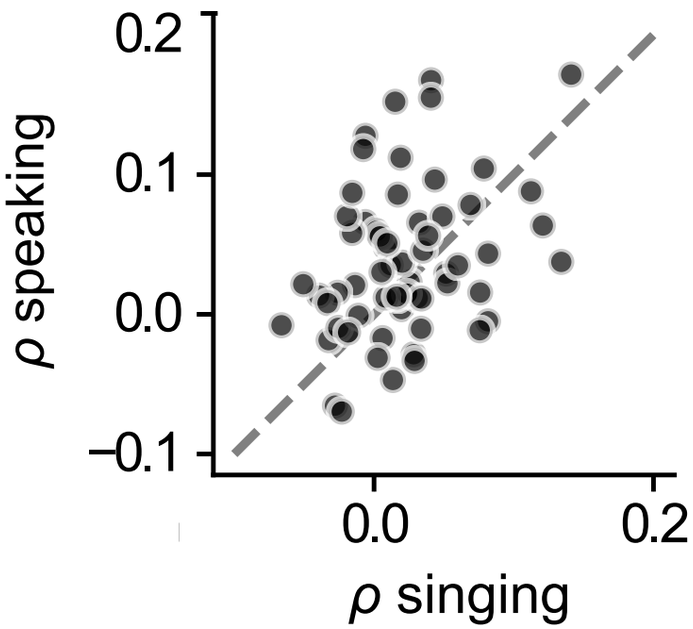
- Same electrodes as during speech

Pitch control during singing





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Summary: The dLMC encodes fine control of vocal pitch

- Correlated with pitch when speaking and singing
- Encodes fast pitch accents
- Control of pitch distinct from control of voicing

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But is it causal?

Cortical Stimulation

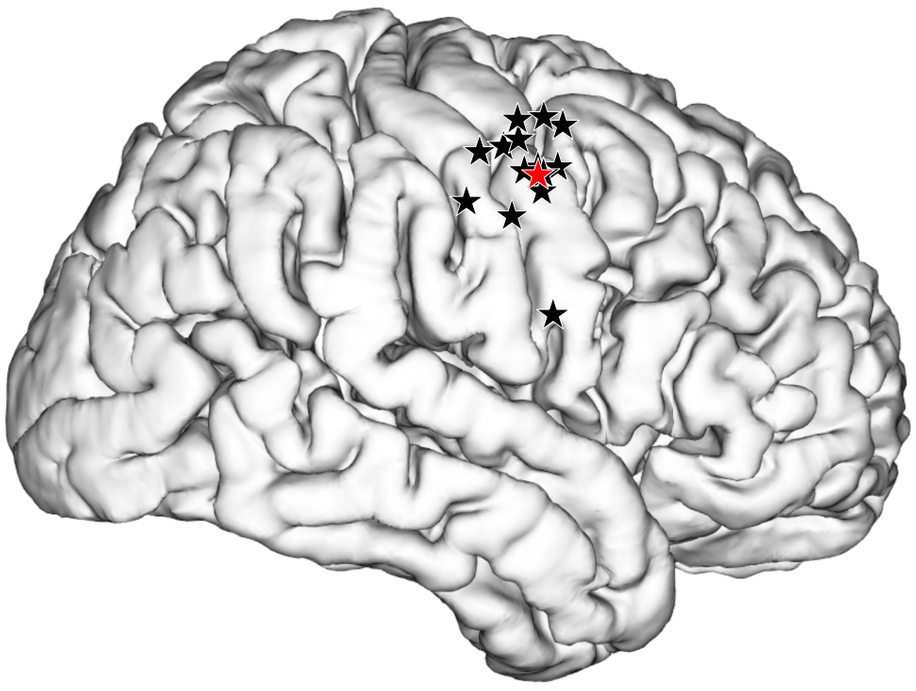
“Asleep”

Patient is asleep, with an endotracheal tube in the throat. The tube blocks any vocalizations, and has electrodes on the focal folds that measure contractions.

Cortical stimulation of dLMC evokes larynx response

Patients are anesthetized with electrodes placed on vocal chords

Brain locations that made larynx respond



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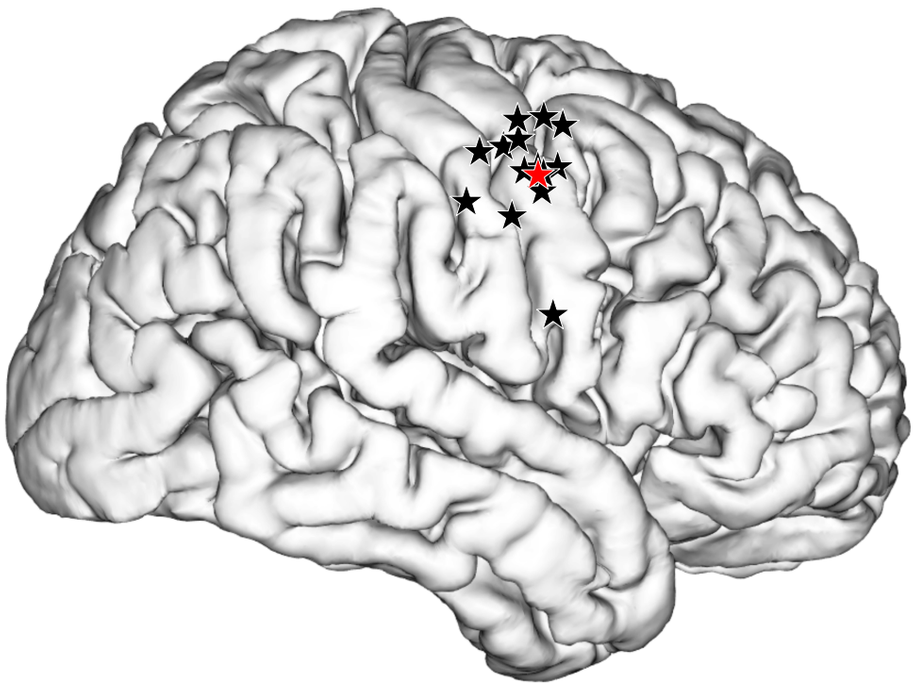
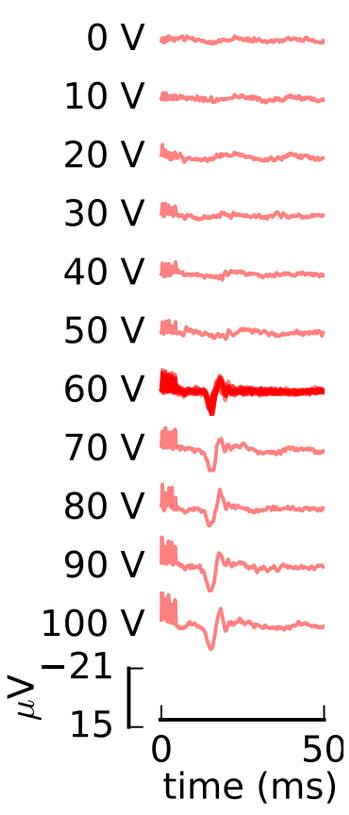


larynx response



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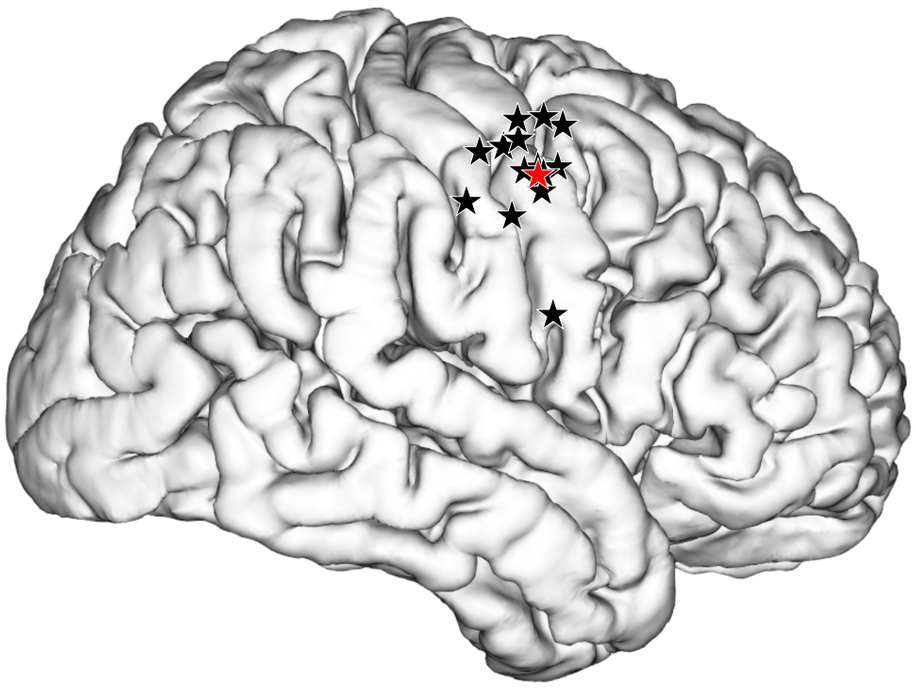
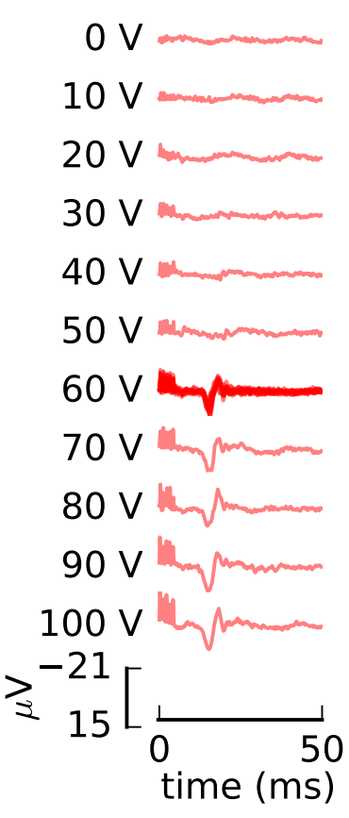
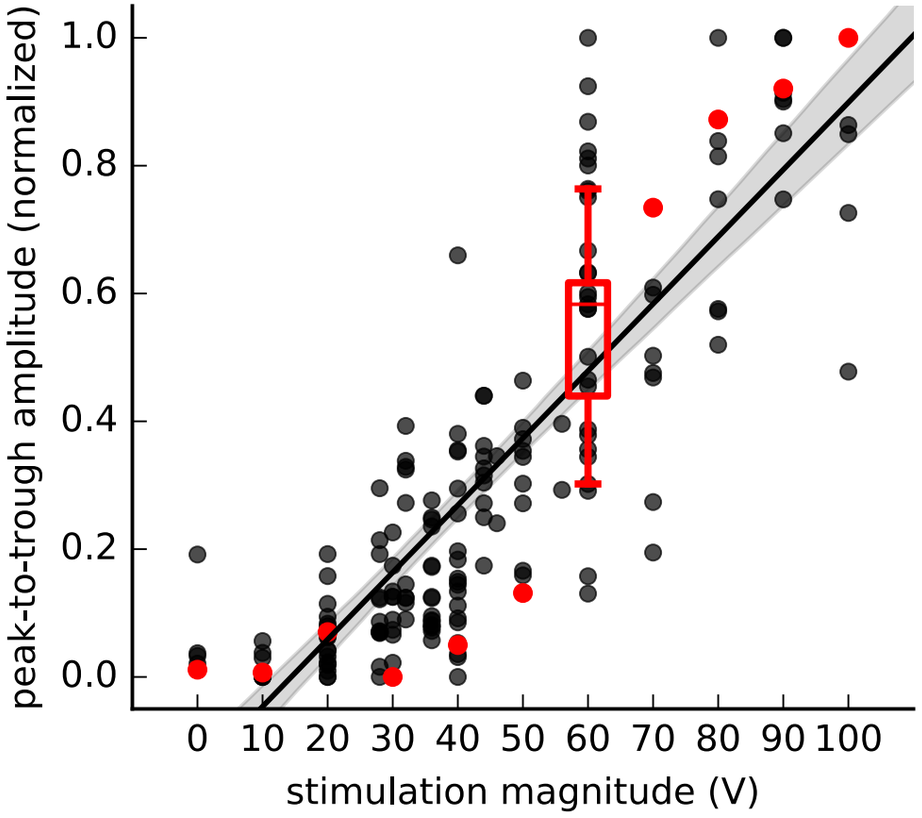


larynx response



Stronger stimulation cause stronger response



Cortical Stimulation

“Asleep”

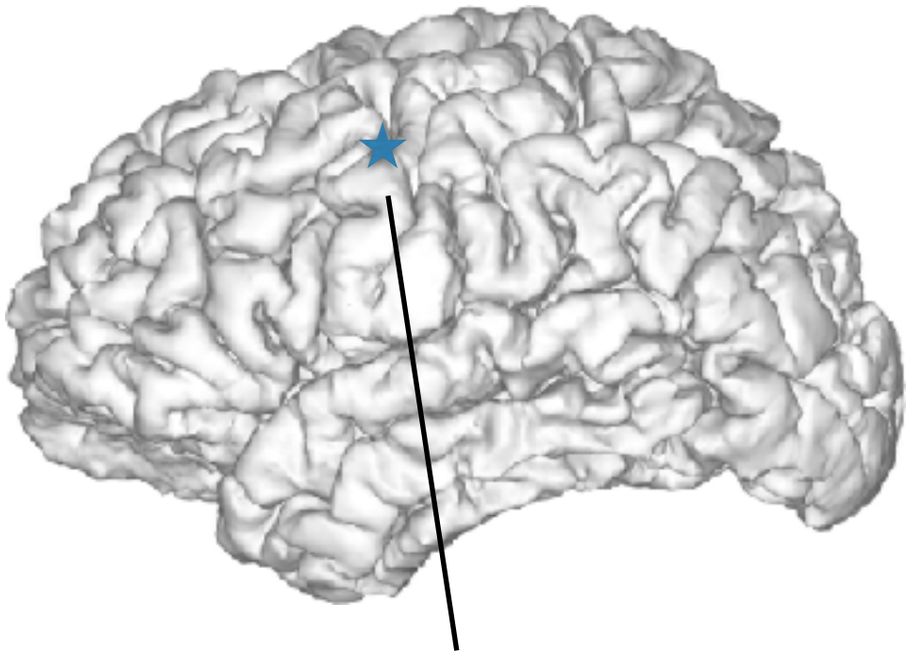
Patient is asleep, with an endotracheal tube in the throat. The tube blocks any vocalizations, and has electrodes on the focal folds that measure contractions.

Stimulation evokes laryngeal contraction

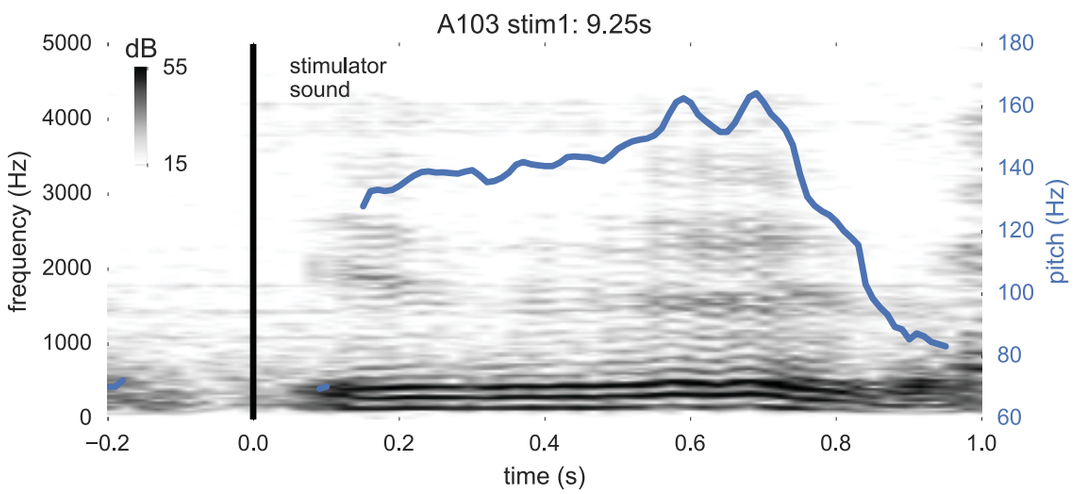
“Awake”

Patients are awake, doing simple tasks like counting and describing the experience of stimulation.

“Awake” dLMC stimulation **evokes vocalization** with varied acoustic structure



chest voice



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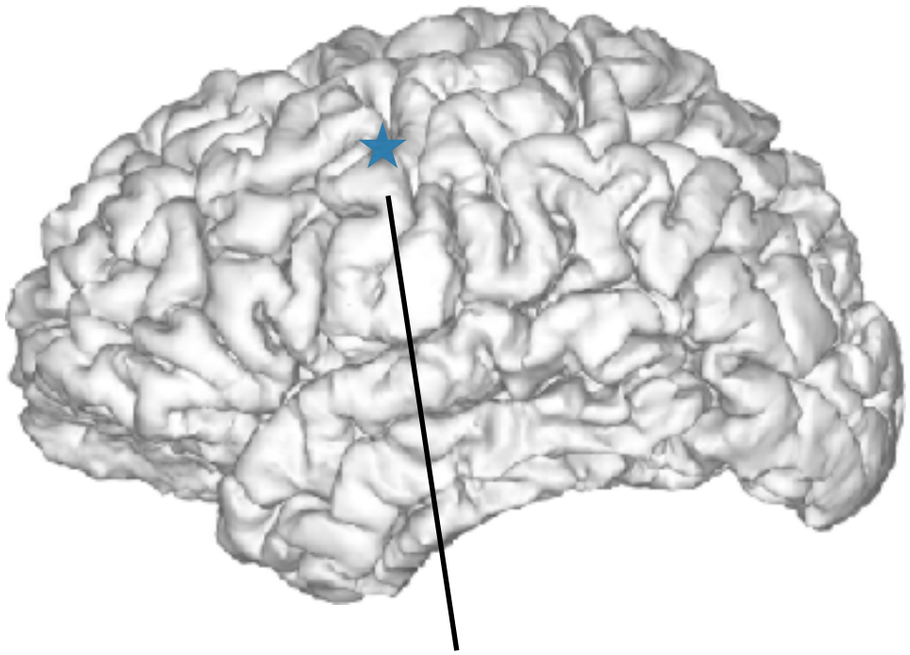

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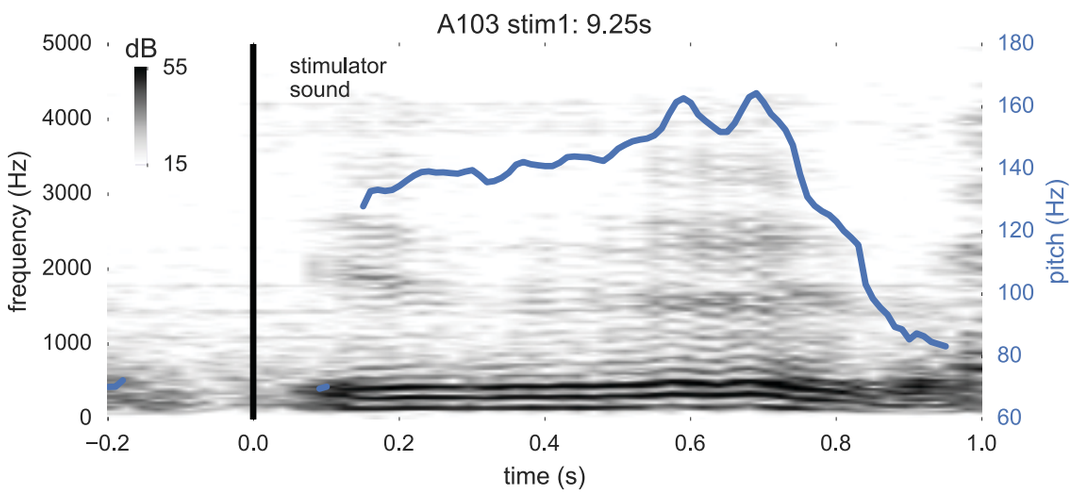

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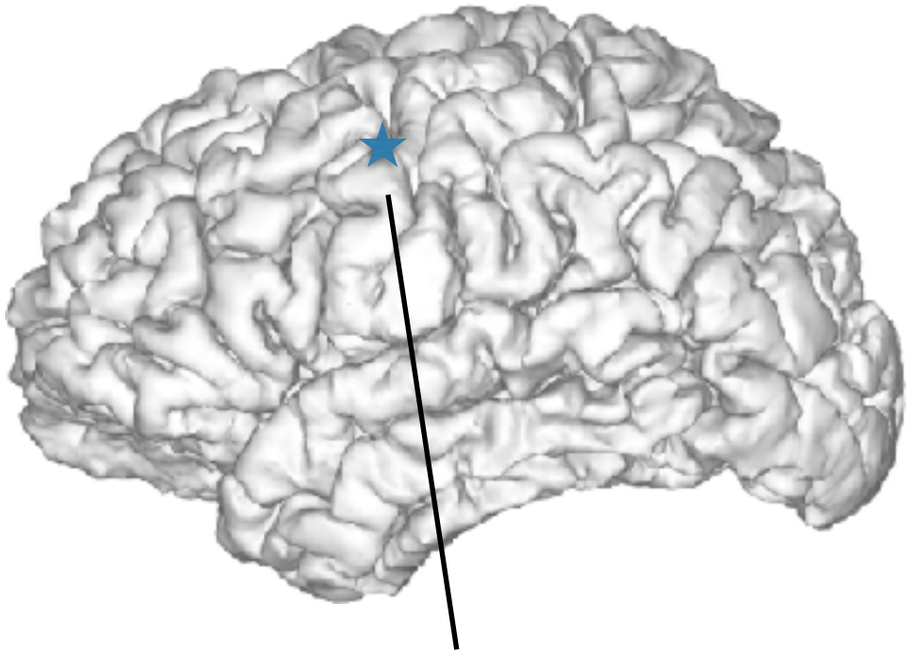
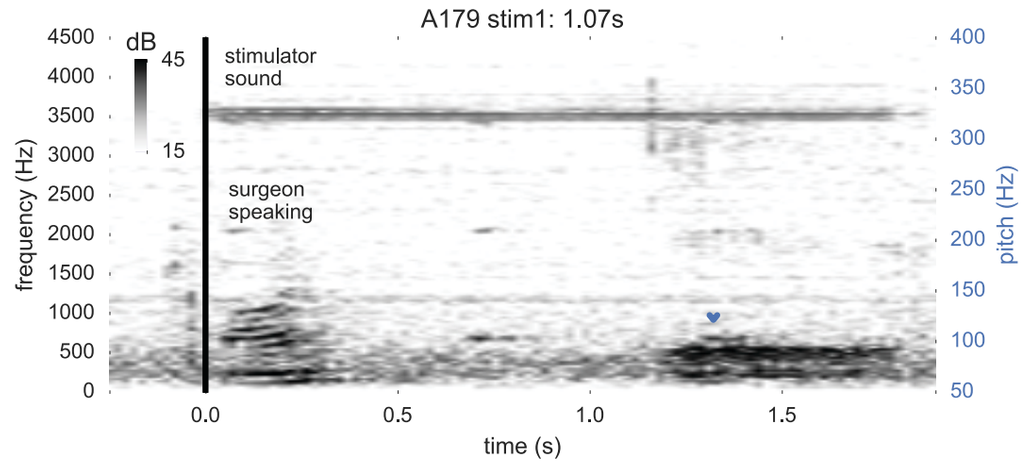


vocal fry



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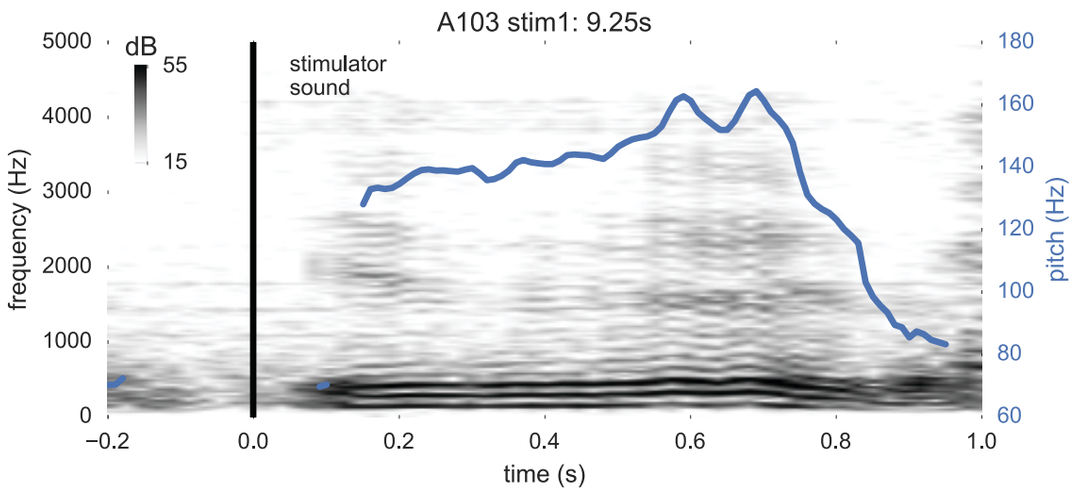

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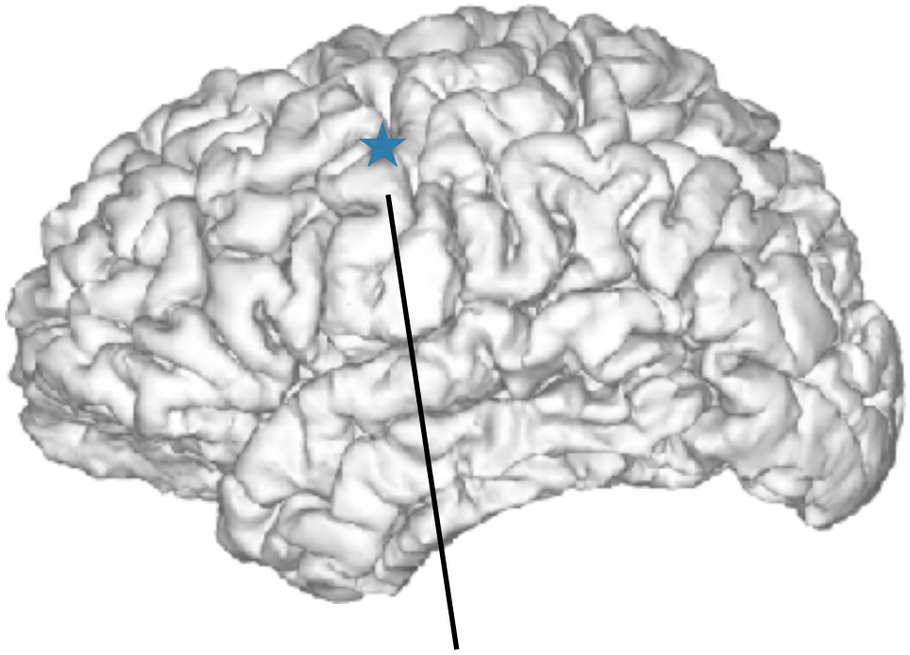

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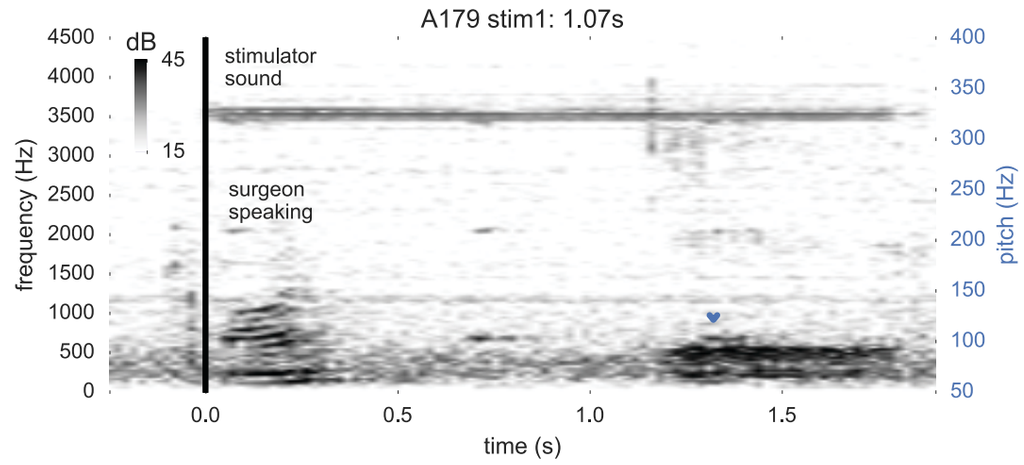

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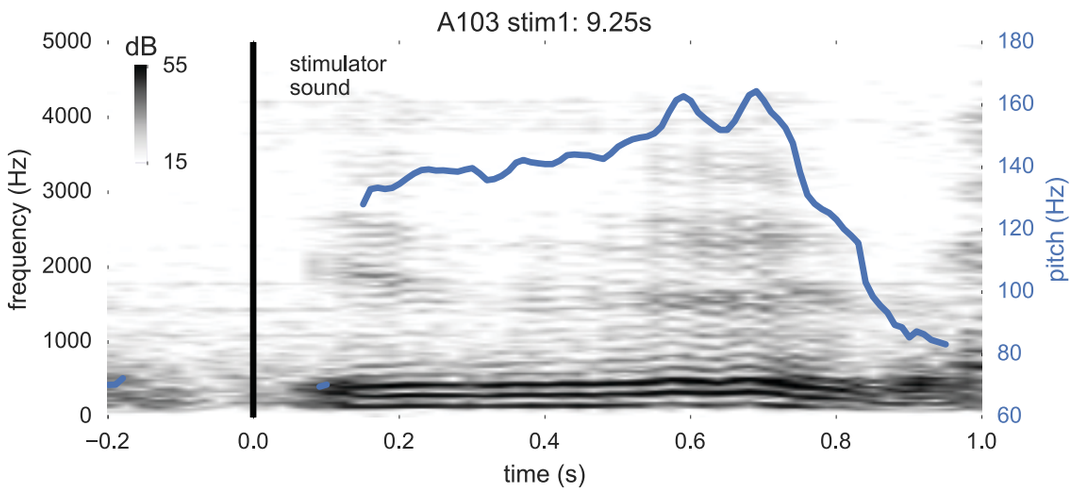

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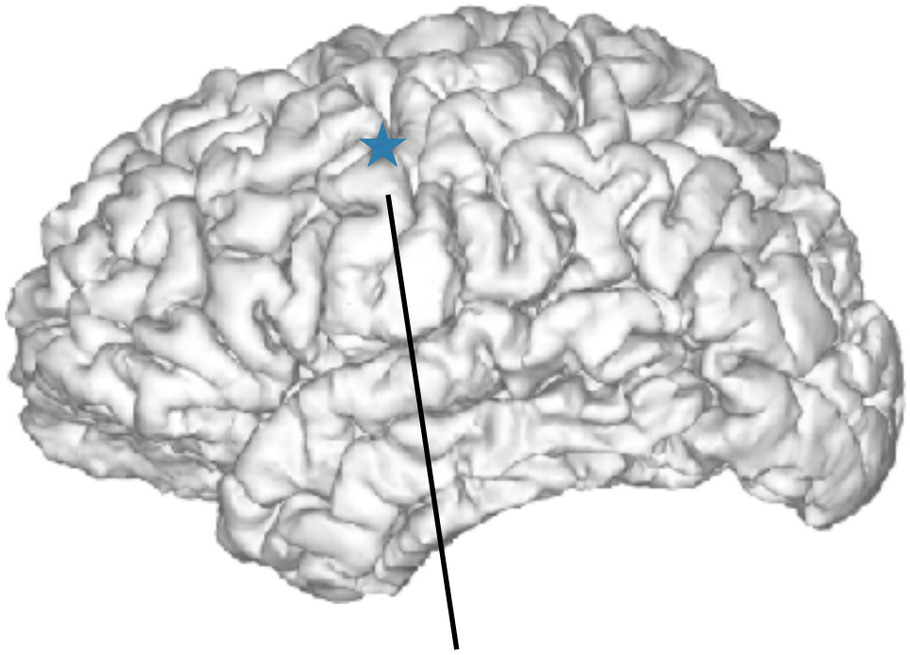
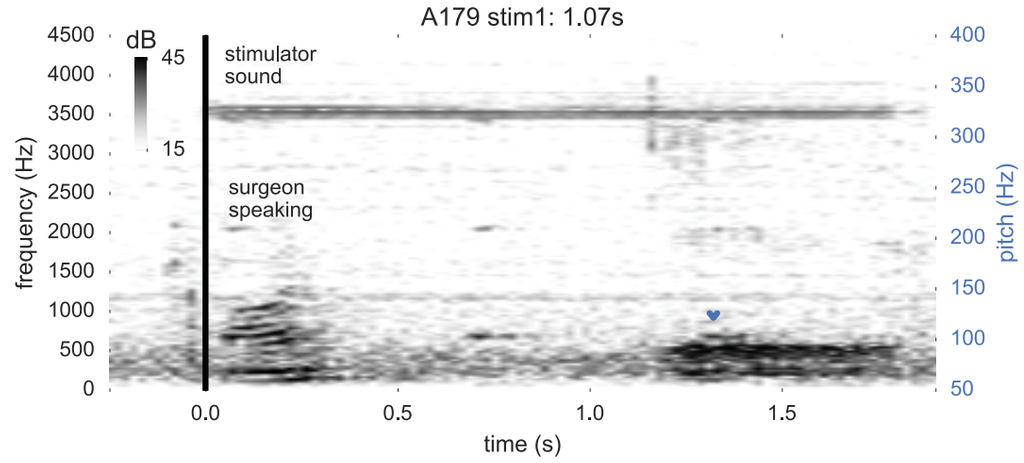


vocal fry



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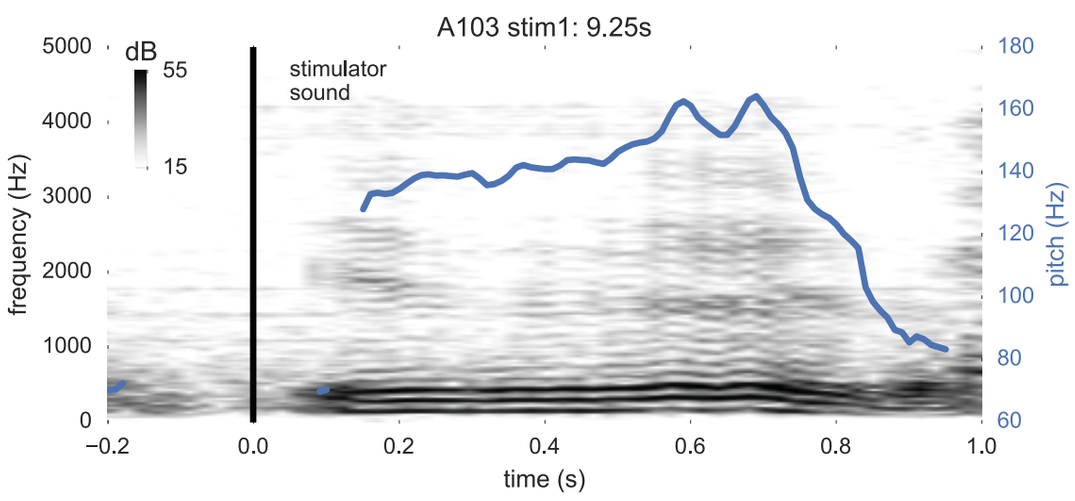
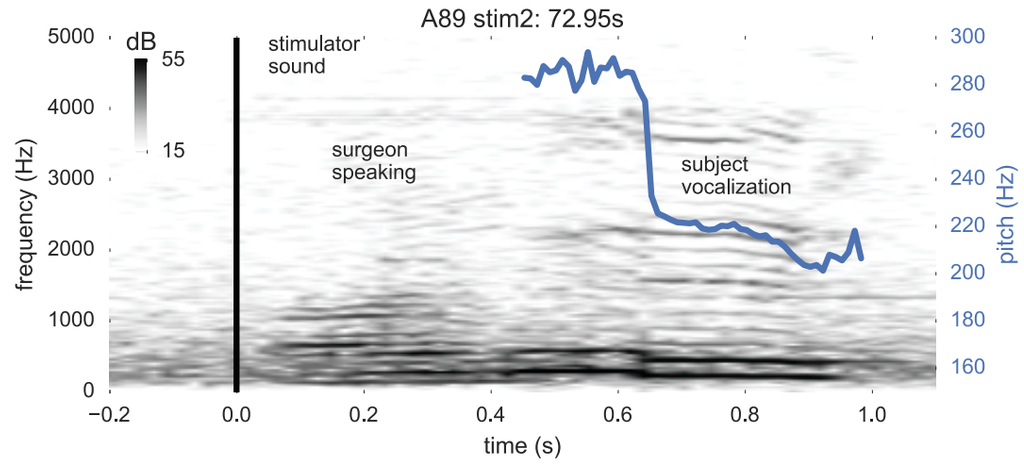


falsetto



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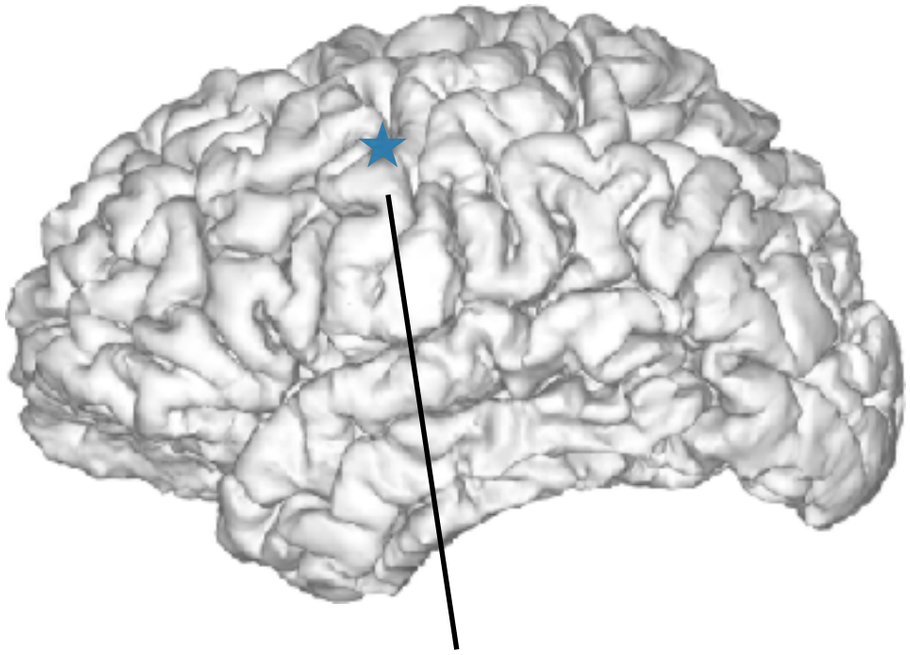

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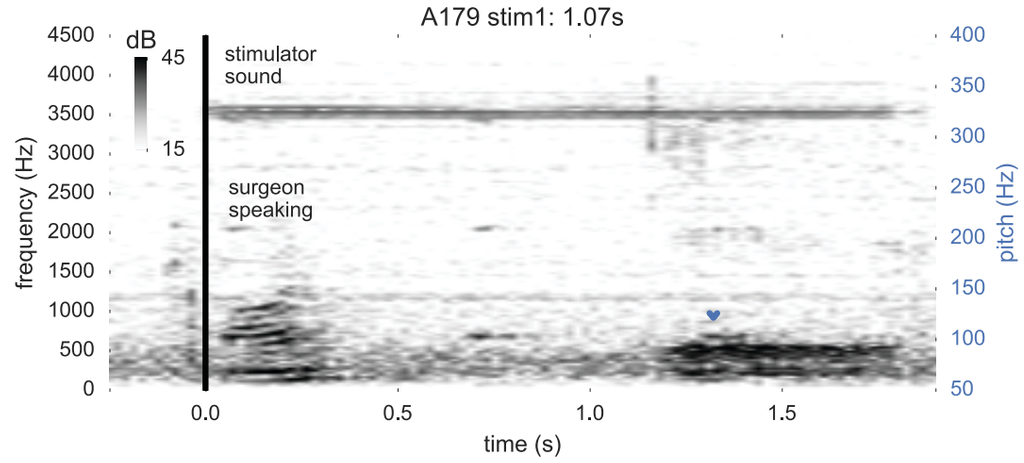
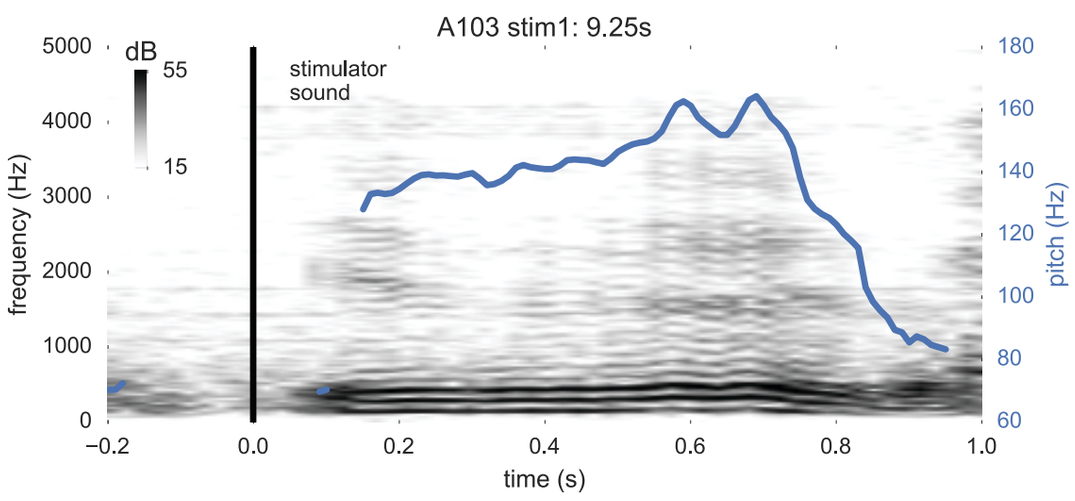
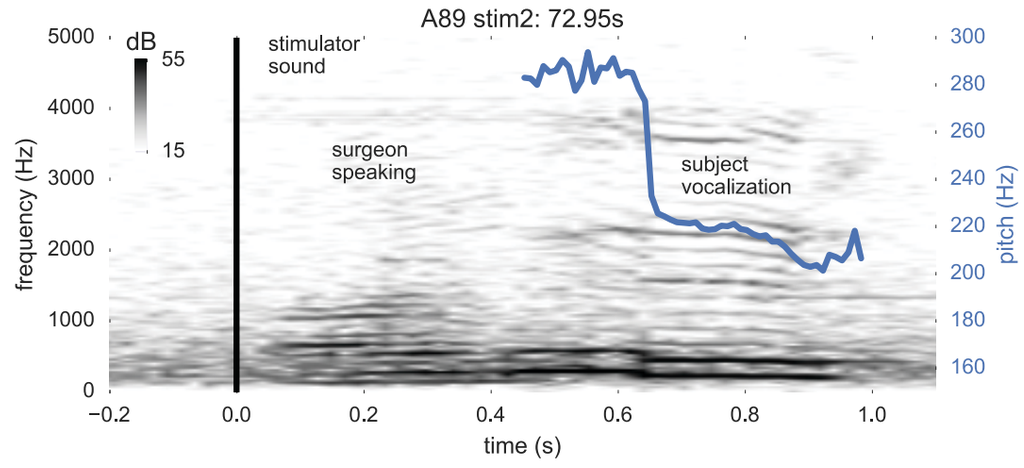


chest voice



falsetto



Results

The dLMC is a sensorimotor speech area that encodes pitch

Auditory

- Responds to acoustic stimuli and represents vocal pitch

Motor

- Correlated with pitch when speaking and singing
- Monotonically increases with pitch
- Cortical stimulation evokes vocalizations and a graded laryngeal motor response

Role of sensorimotor representation

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Two possibilities:

Role of sensorimotor representation

Two possibilities:

1. Motor theory of speech perception

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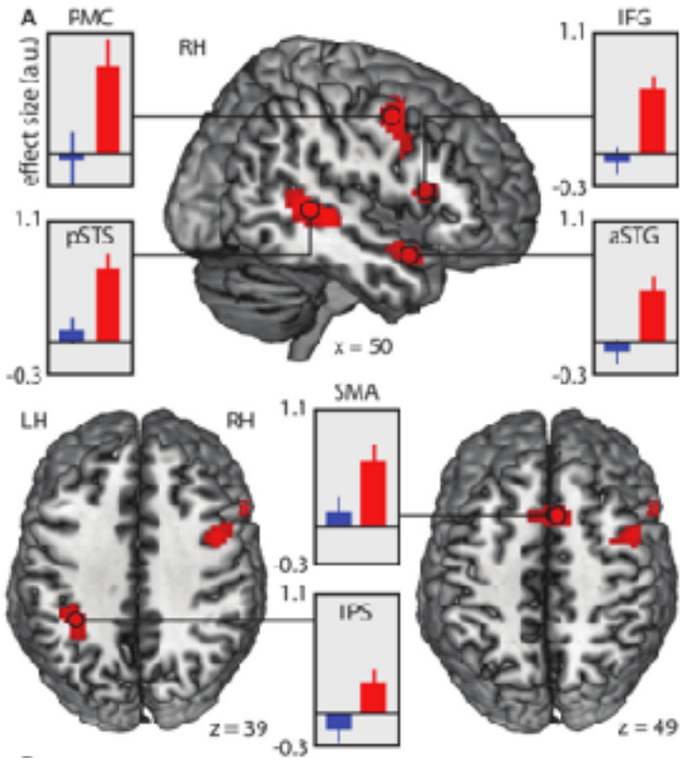
    - Specifically for voice/pitch control

Evidence for motor theory in dLMC



(Sammler et al. 2015)

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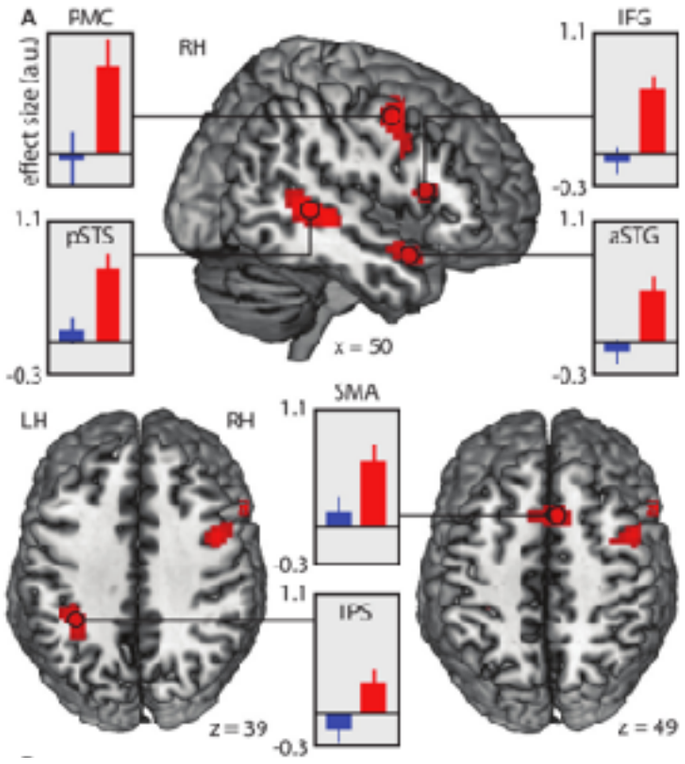

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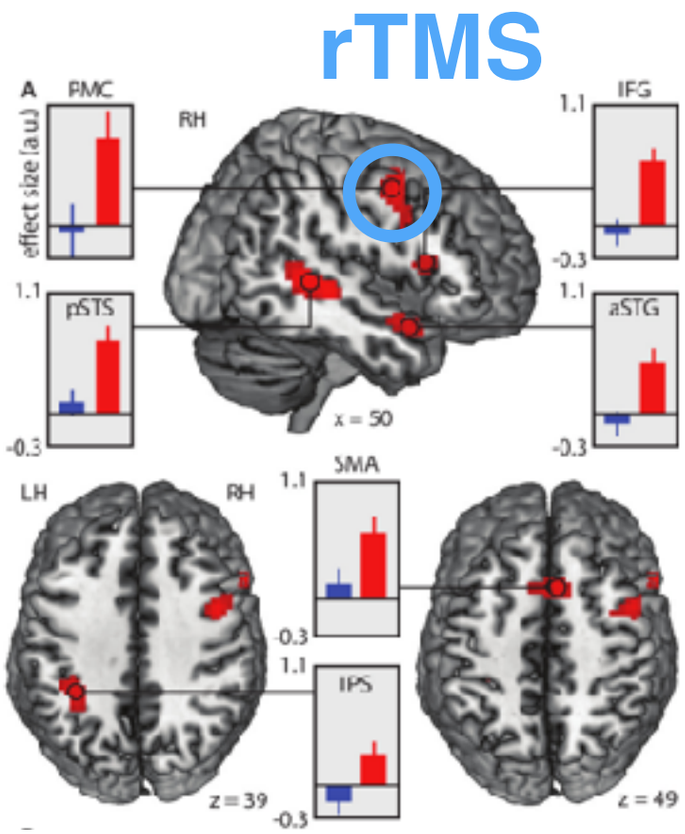

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- The right PMC is more active when focusing on pitch
- rTMS over right PMC worsens pitch discrimination but not phoneme discrimination

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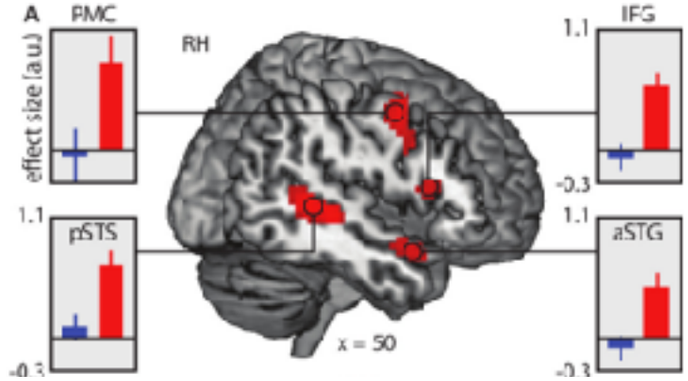
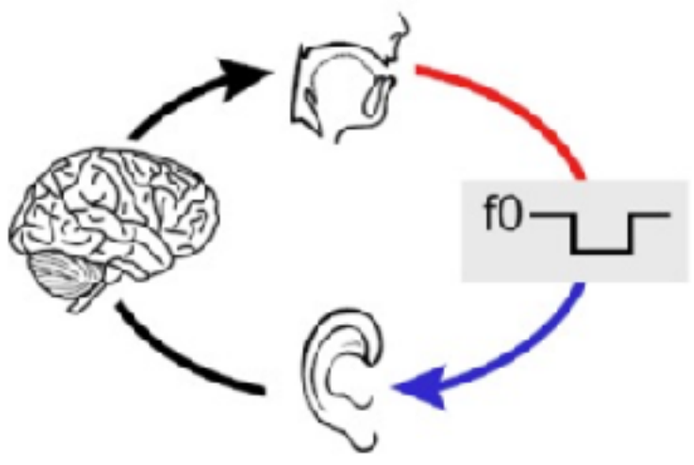
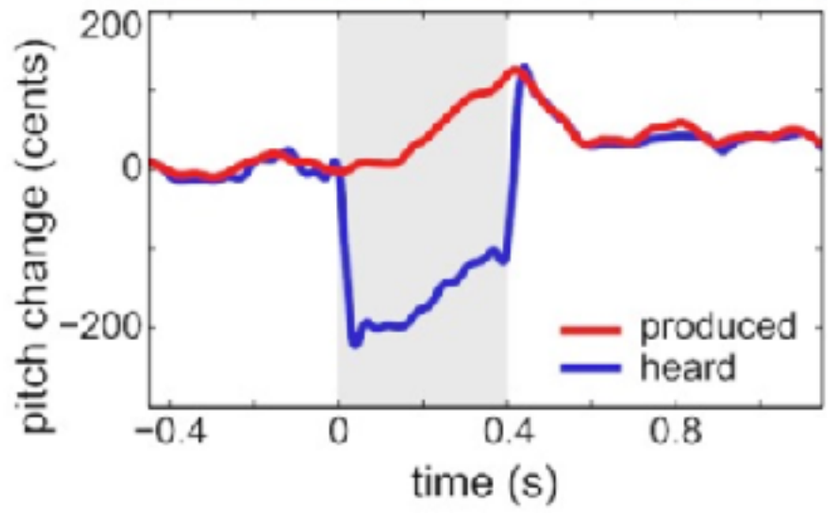


2. Feedback control
   - Why passive listening response? Seems wasteful.

Sensorimotor role: evidence for feedback control in vLMC, not dLMC





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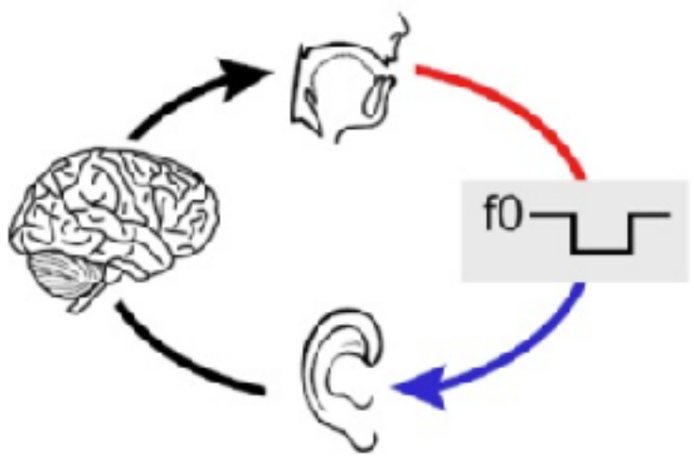

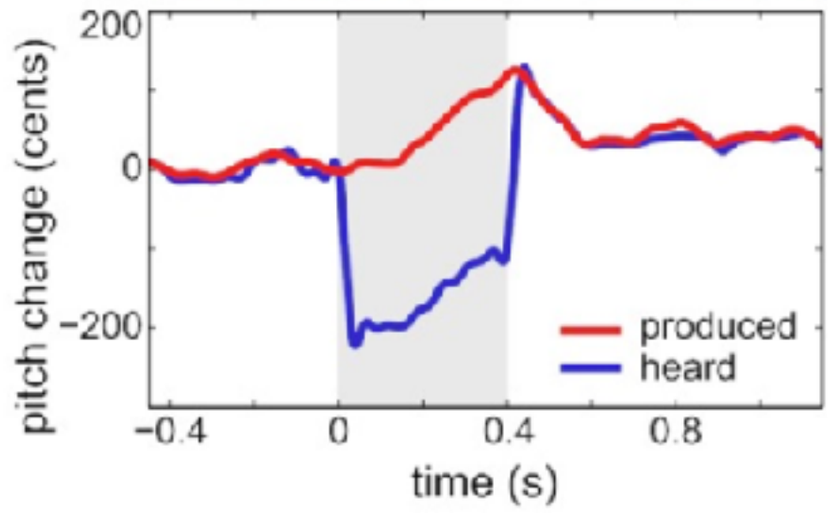

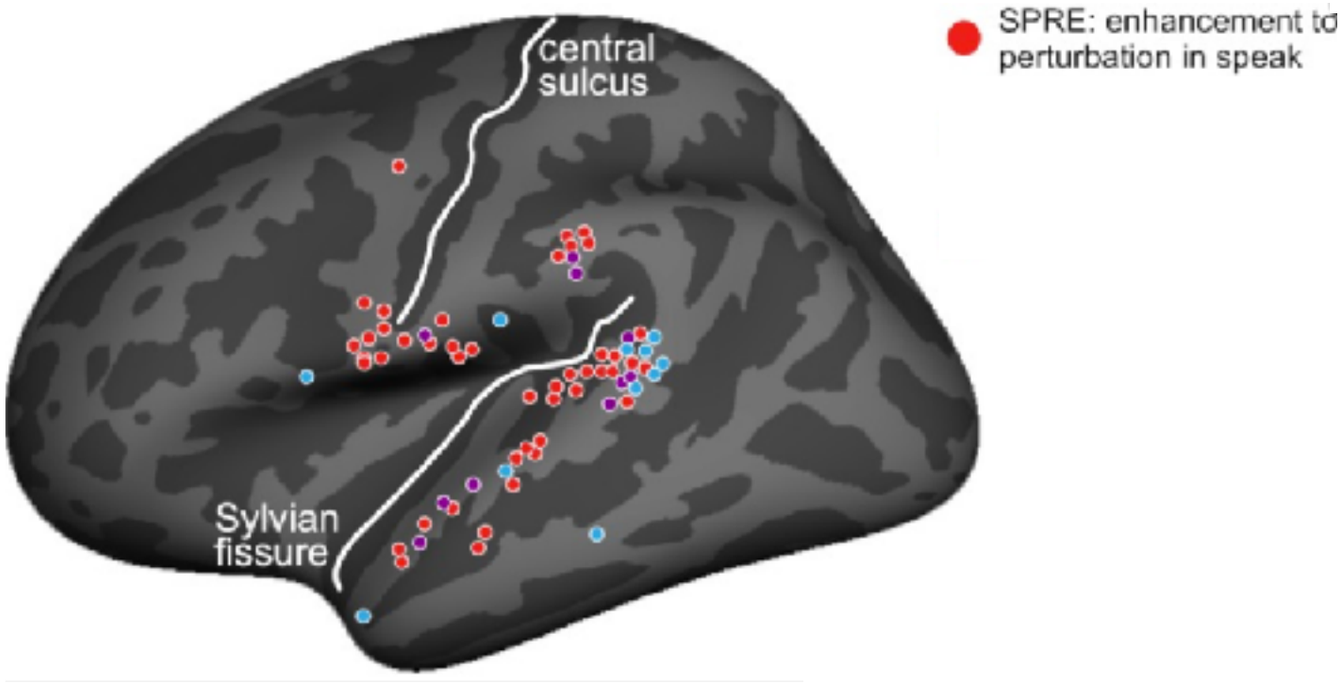

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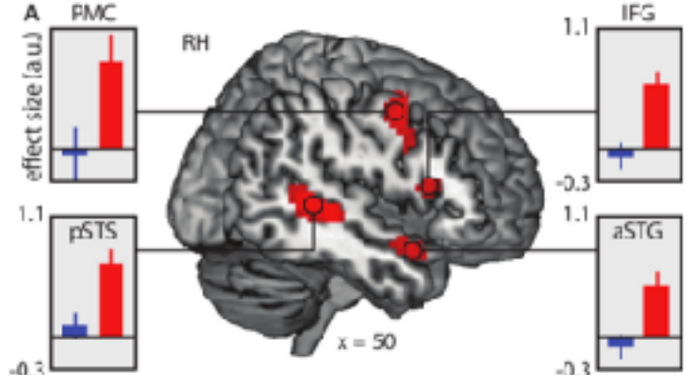

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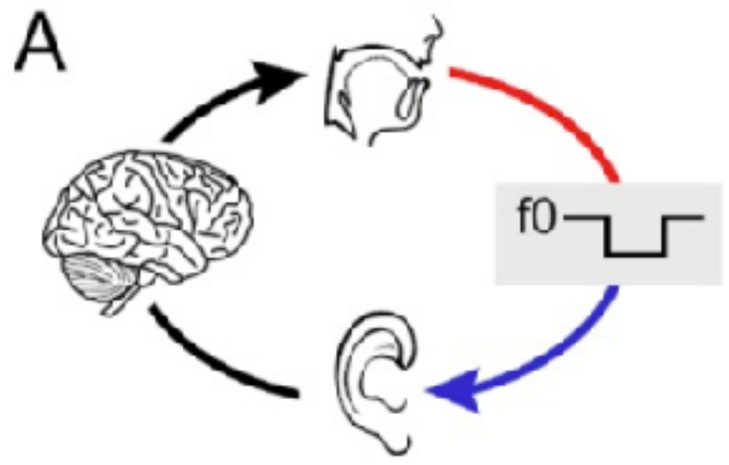

Either way, merging of motor and auditory pitch representation could be key to development of speech

Estimating produced vocal pitch from brain activity

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Some people are locked in and unable to move at all

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With a speech prosthetic we could be able to record their intended speech and provide an alternate way for them to to **communicate**

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So how well could we **infer prosody**?

Estimating produced vocal pitch from brain activity: Kalman Filter

---

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t + \mathbf{w}_t \qquad \mathbf{w}_\bullet \sim \mathcal{N}(0, \mathbf{Q})$$

$$\mathbf{y}_t = \mathbf{C}\mathbf{x}_t + \mathbf{v}_t \qquad \mathbf{v}_\bullet \sim \mathcal{N}(0, \mathbf{R})$$

x: pitch
y: neural activity
t: time
w,**v**: noise

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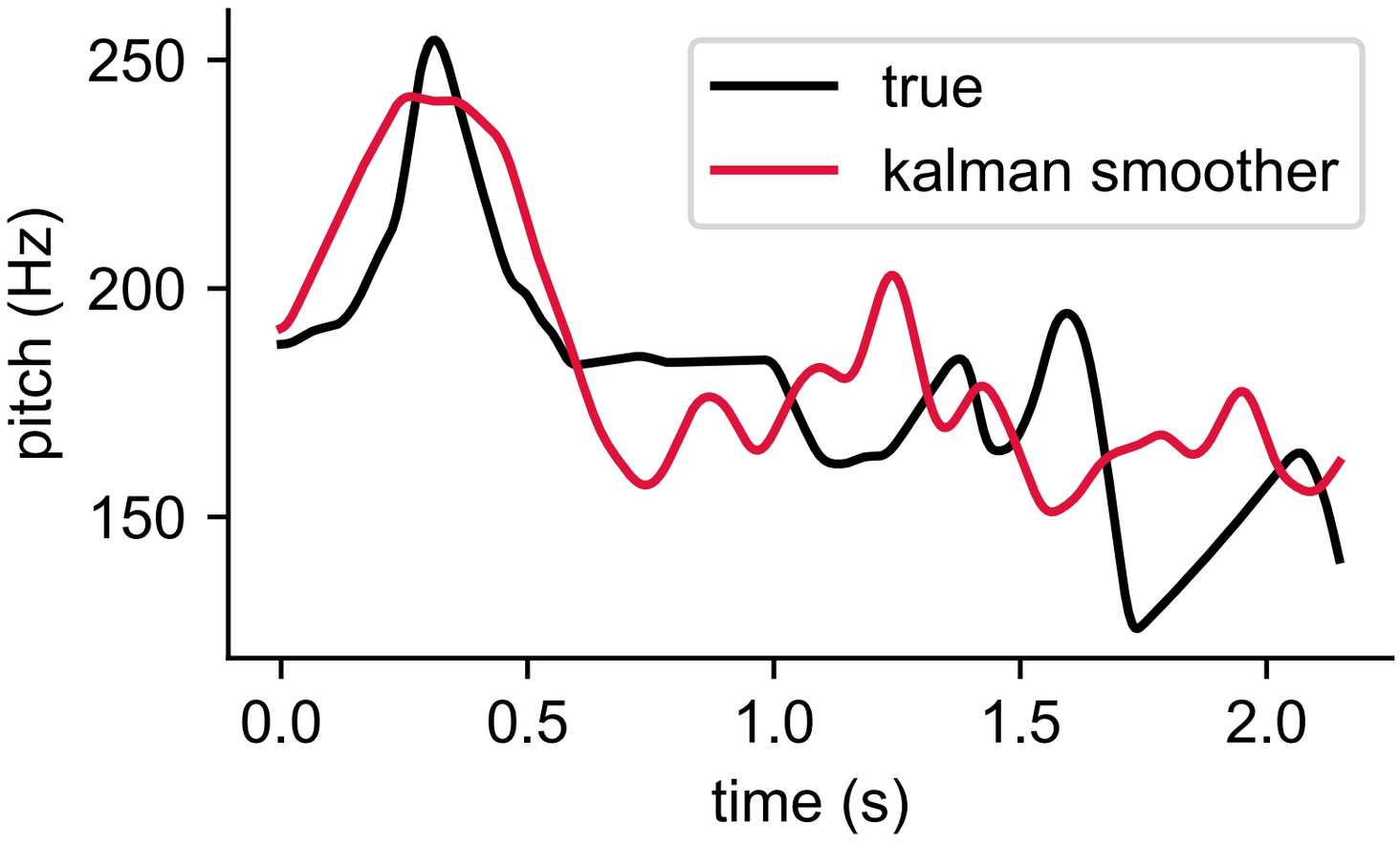
Estimating produced vocal pitch from brain activity: Kalman Filter

---

example sentence



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models neural encoding of pitch

correlation across
held out sentences = 0.7

Estimating **word of emphasis** directly

Linear Discriminant Analysis

$$y|w = i \sim \mathcal{N}(\mu_i, \Sigma)$$

Estimating **word of emphasis** directly

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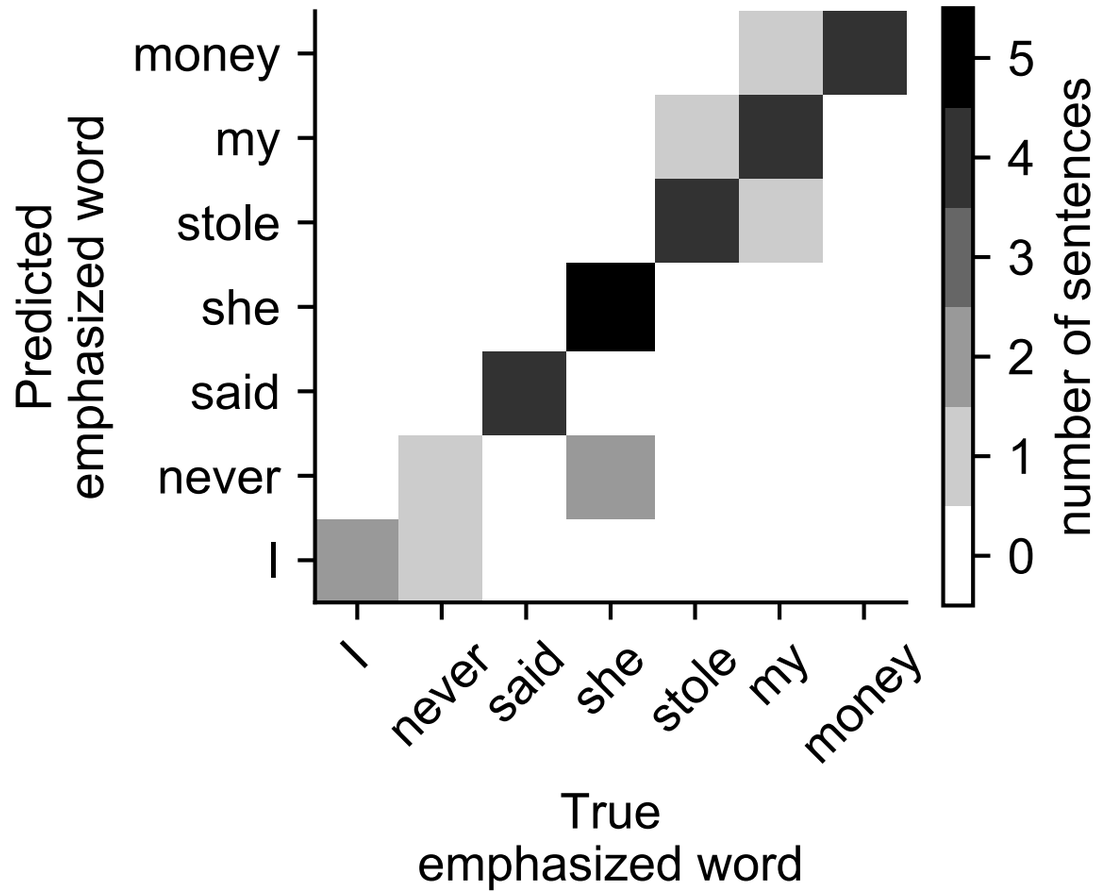
Classification Accuracy (80%)



The Chang Lab

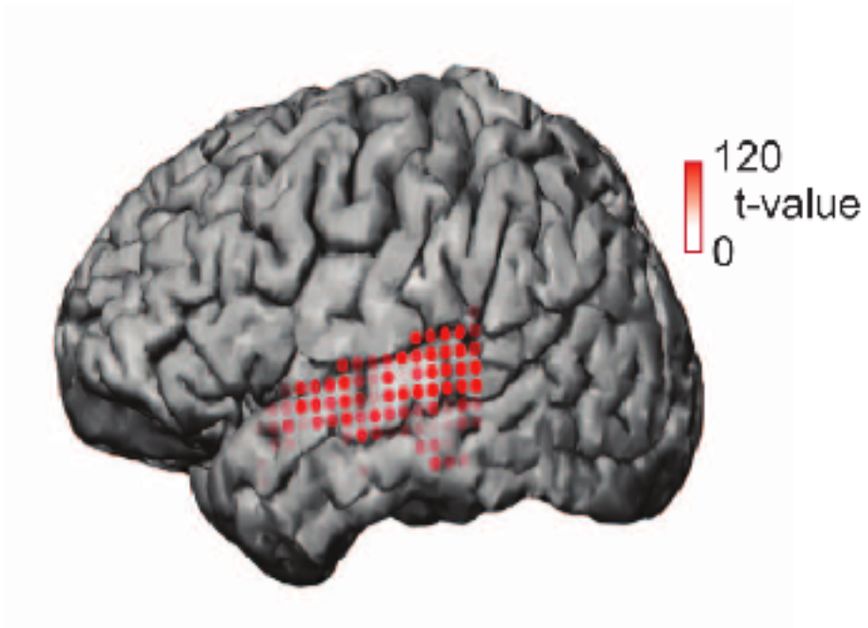
Jonathan Breshears

Matt Leonard

Questions?

Previous work: ECoG activity related to **speech sounds**

Task: Passive listening to continuous speech corpus (which is phonetically transcribed)



(Mesgarani et al., *Science*, 2014)

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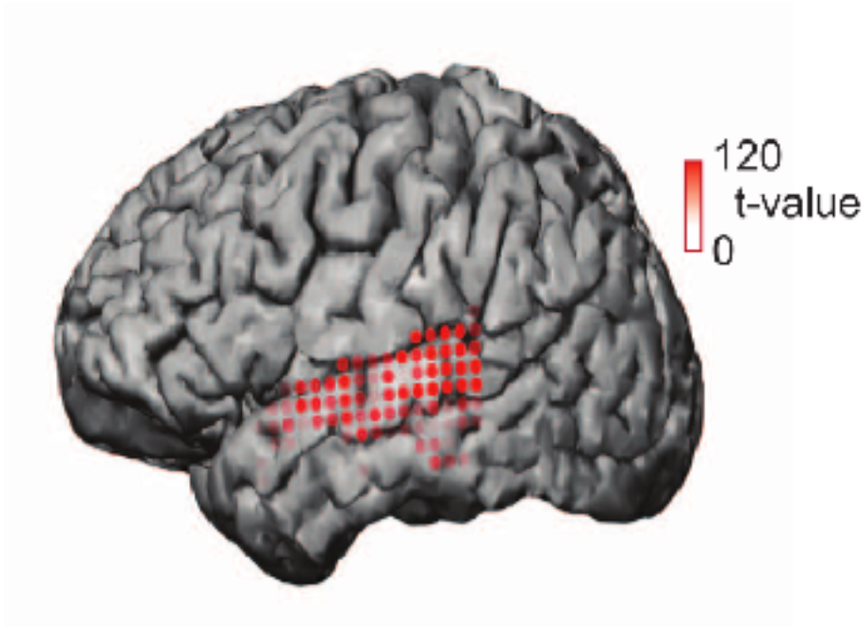

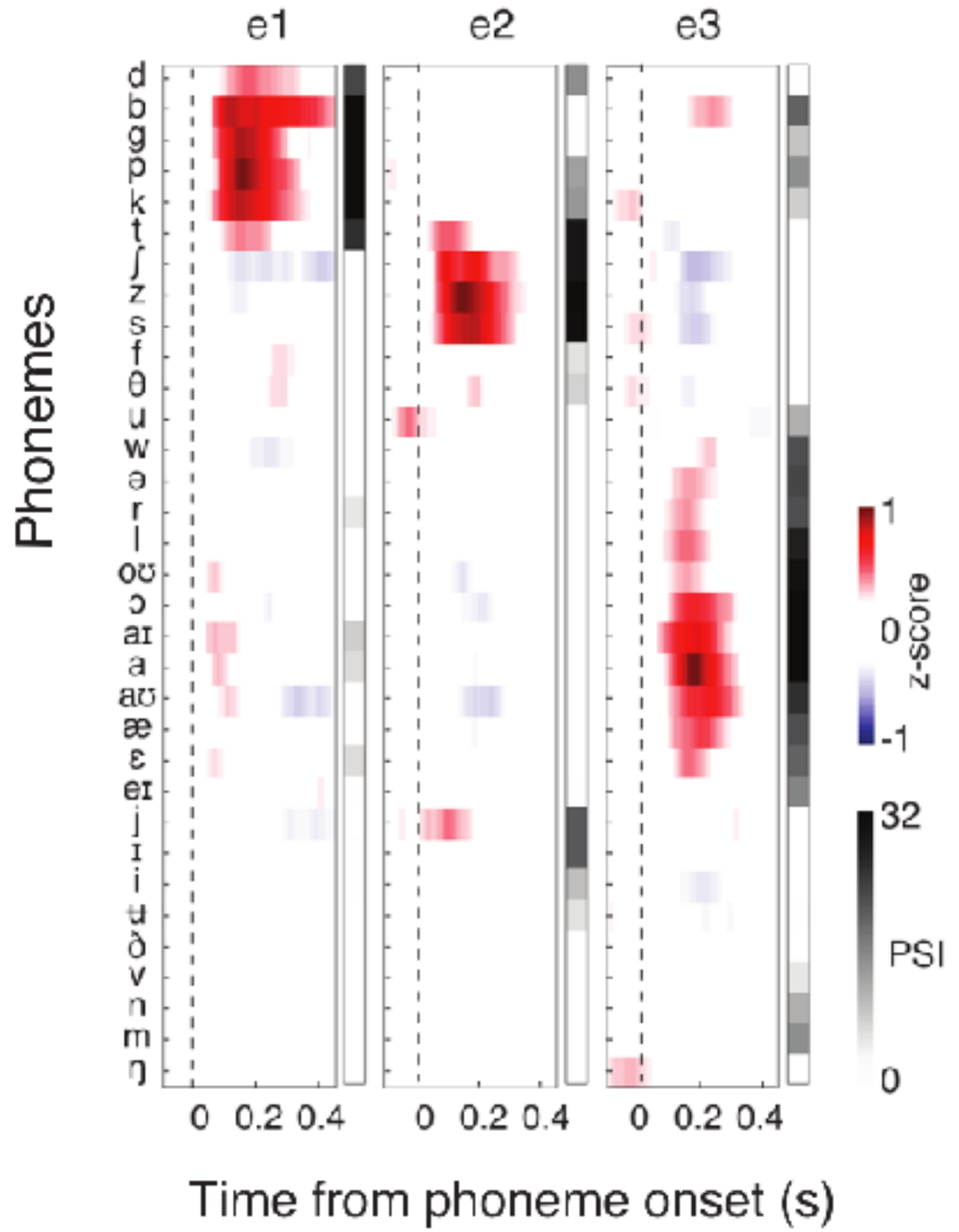

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Cortical Representation of pitch **perception**

(Claire Tang et al.,
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2. How does the representation of intonation relate to the neural encoding of pitch values?
   - Absolute vs. relative pitch?

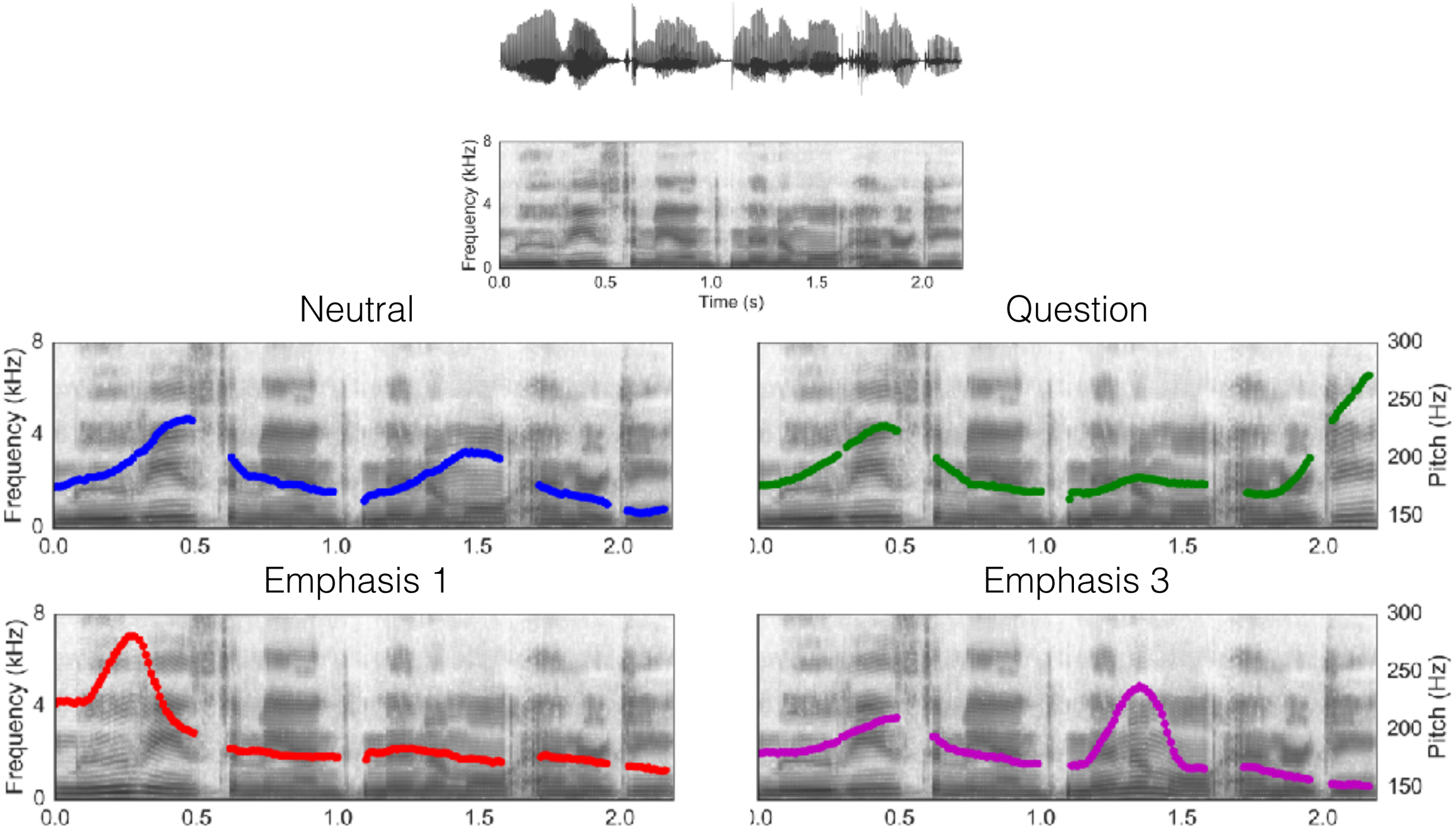
(Claire Tang et al., *Science* 2017)

Stimuli

- designed to vary intonation, phonetic content, and speaker independently.

4 intonation contours x 4 sentences x 3 speakers

Four intonation conditions have distinct pitch contours and linguistic meaning



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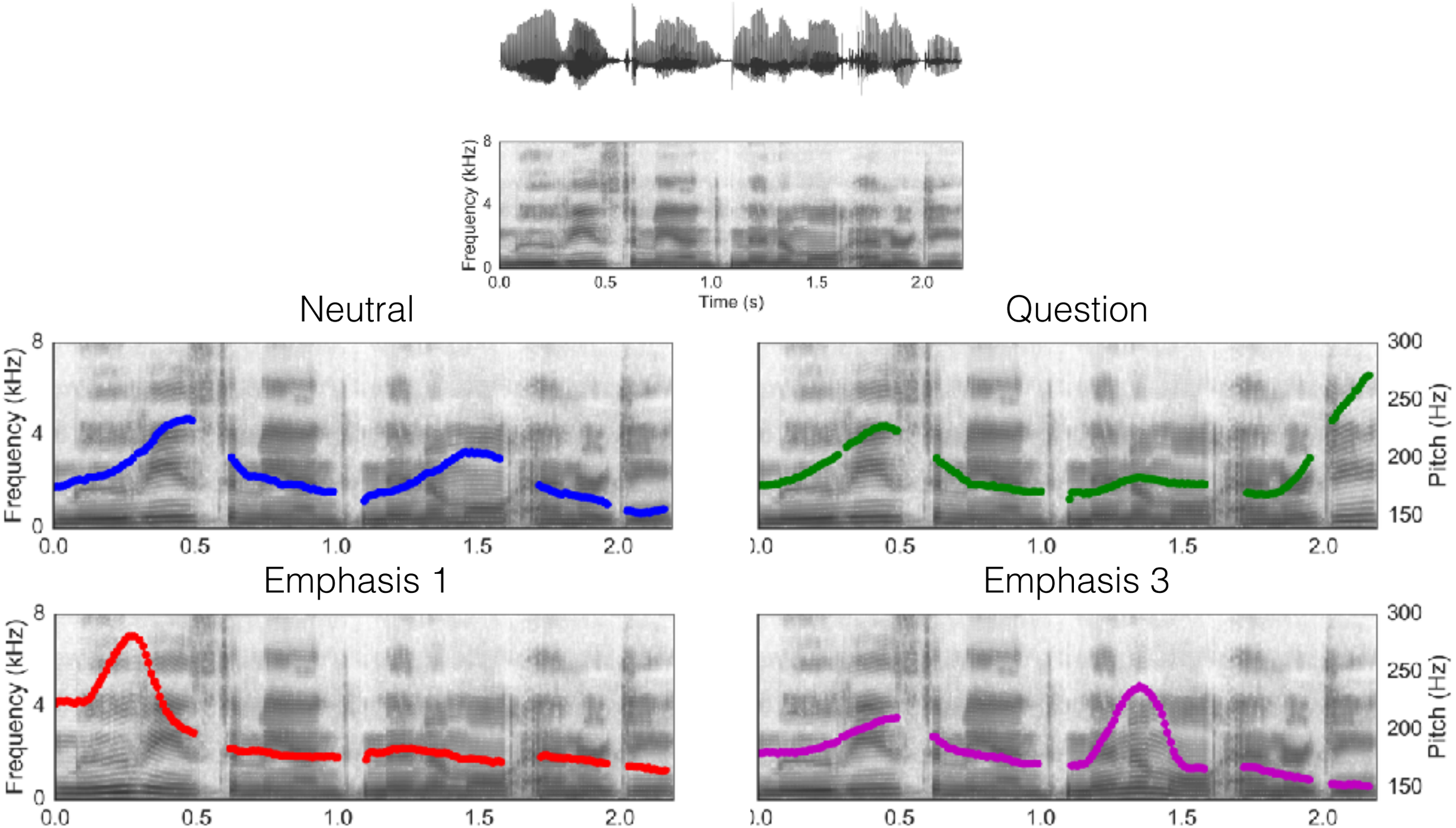

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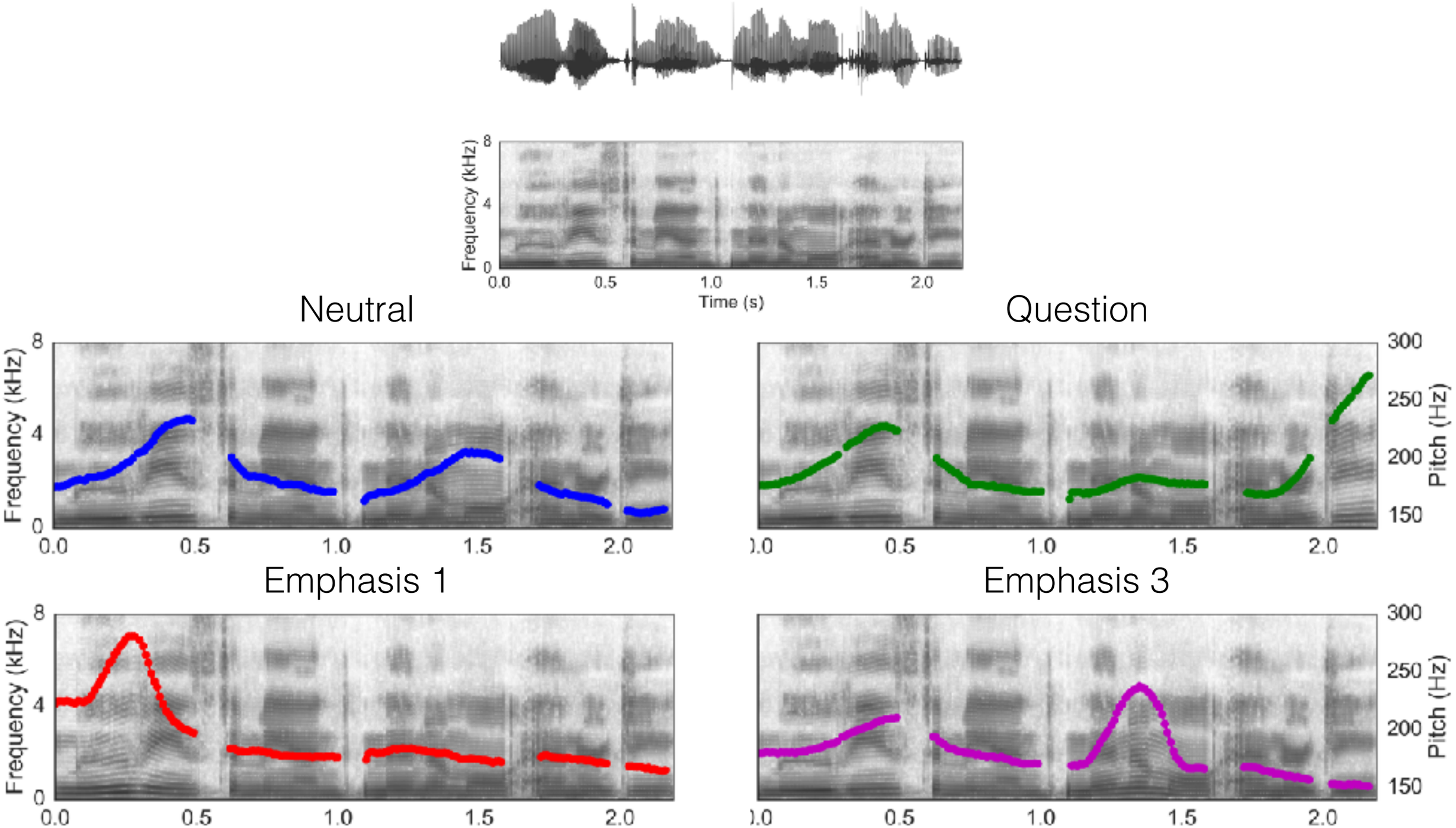

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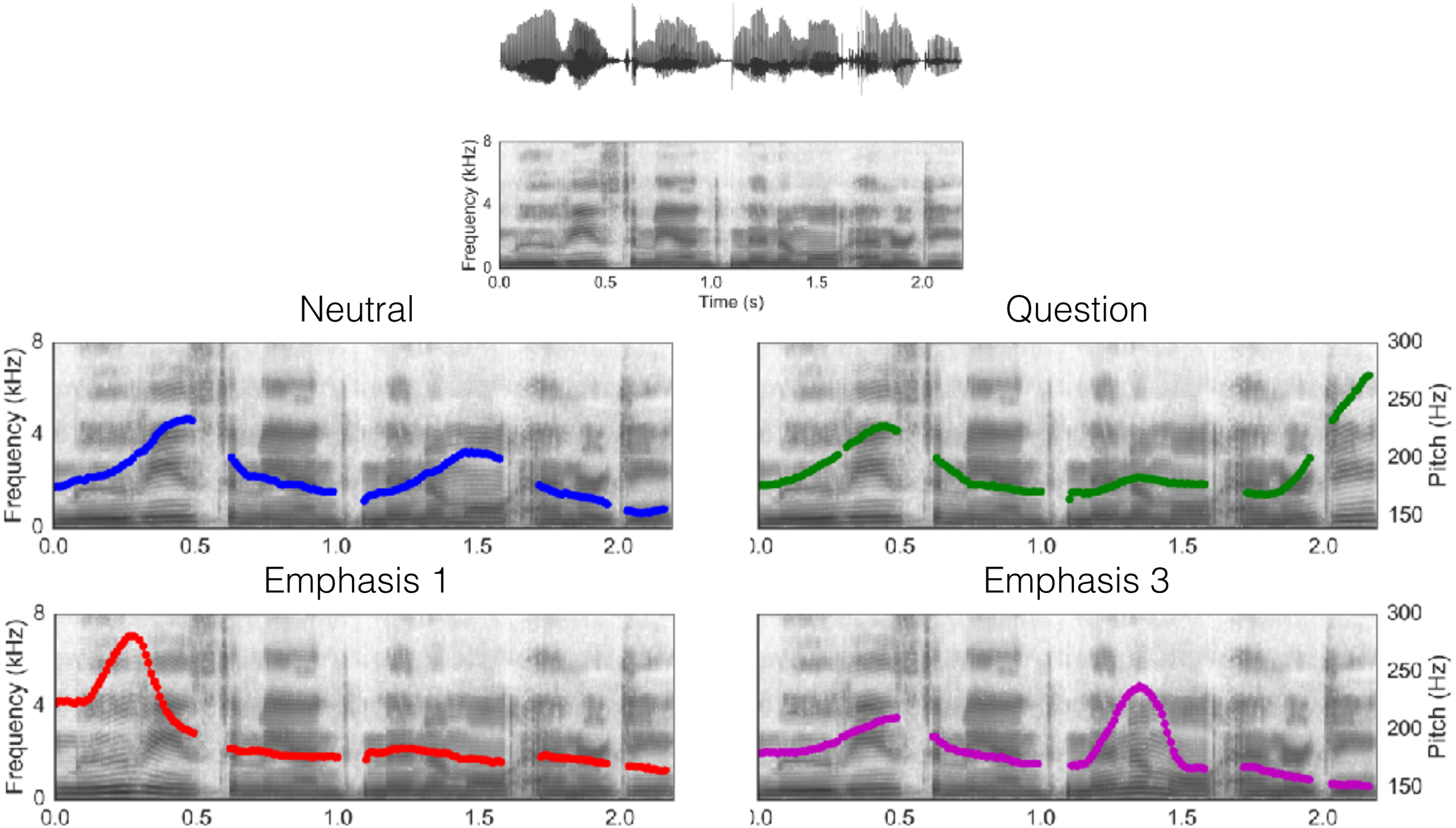

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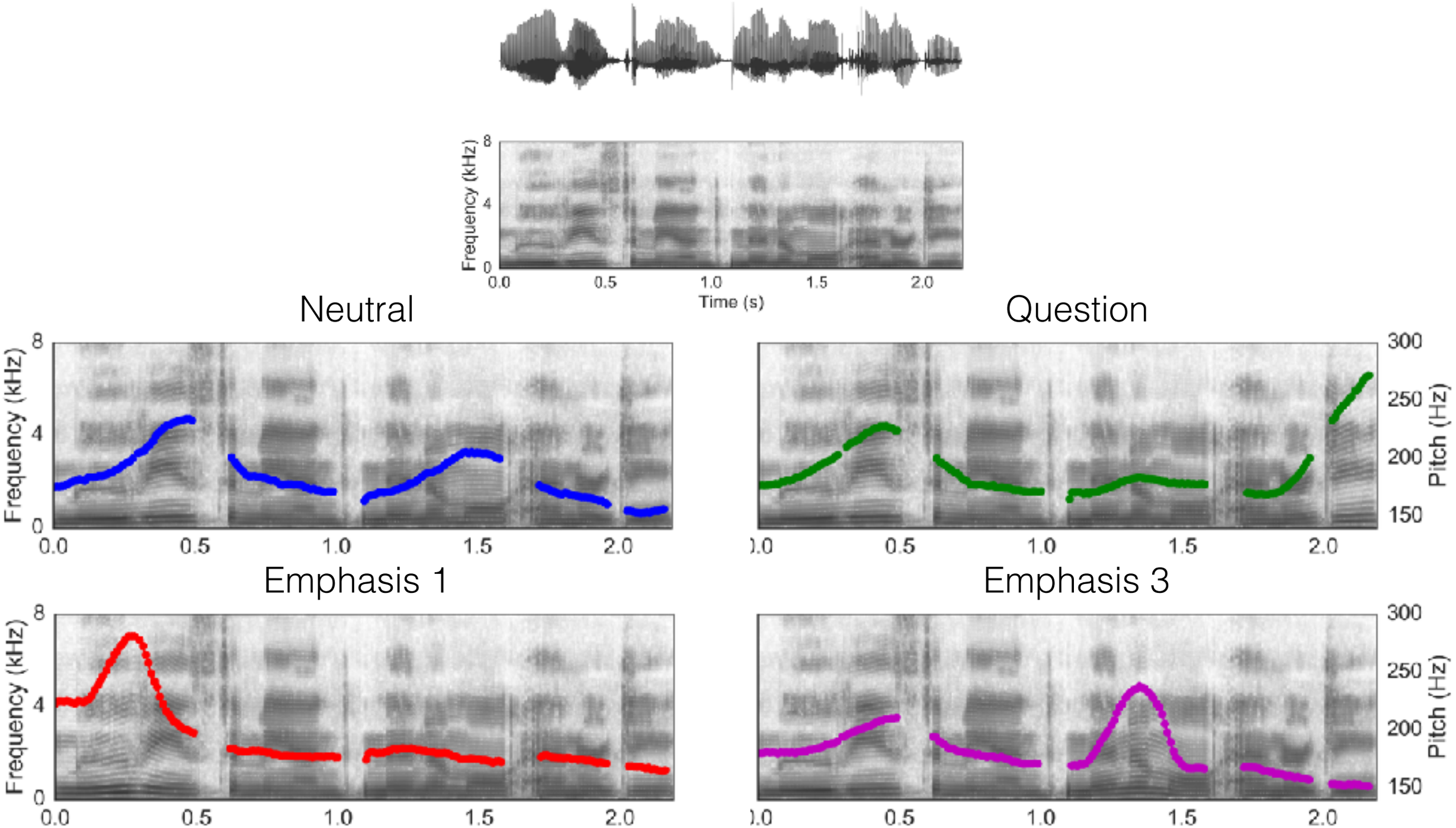
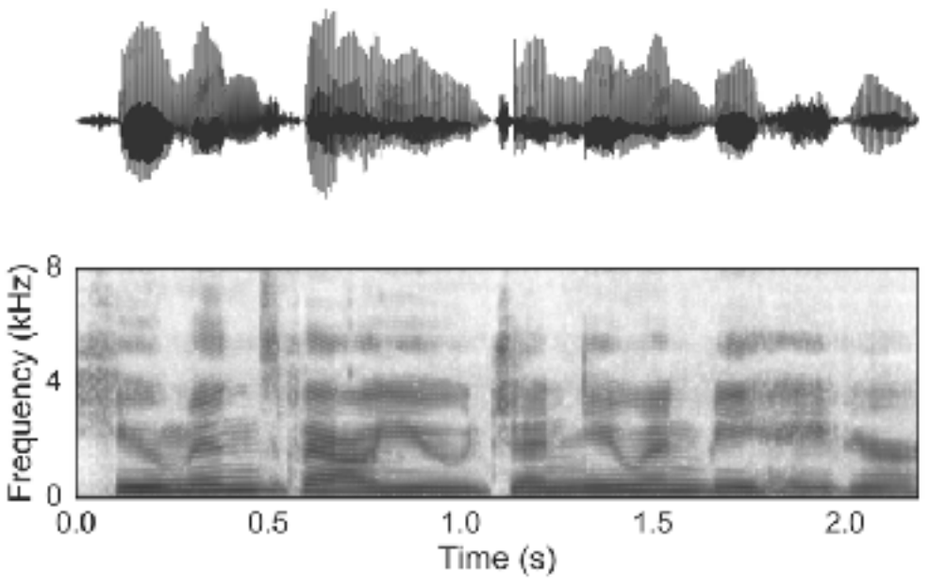
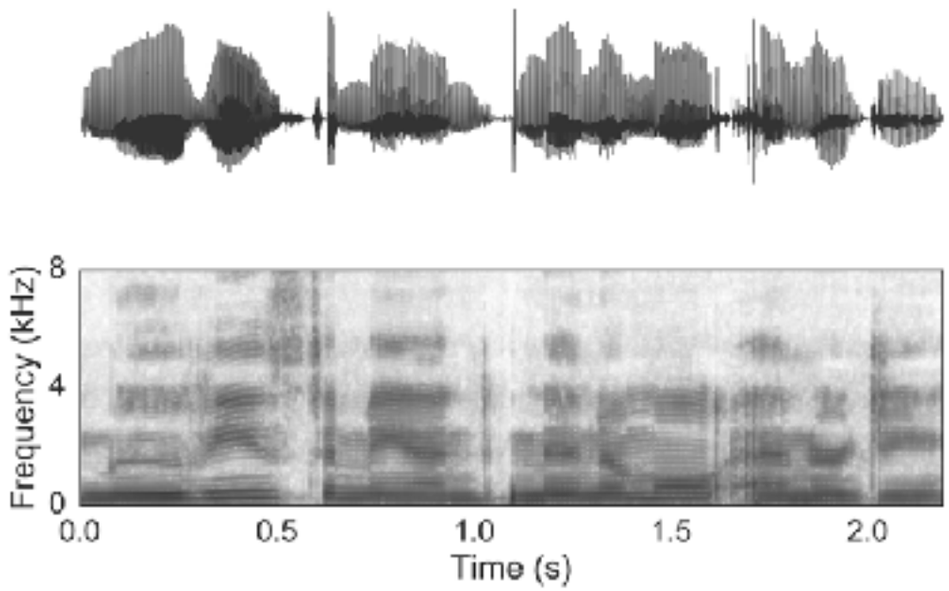


Four phonetically distinct sentences duration-matched by syllable and RMS intensity normalized

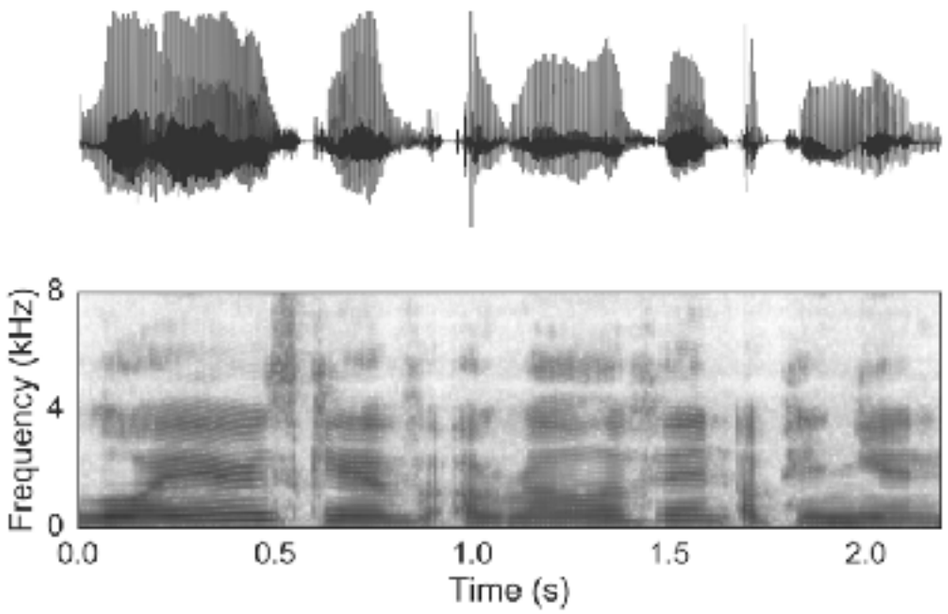
Humans value genuine behavior



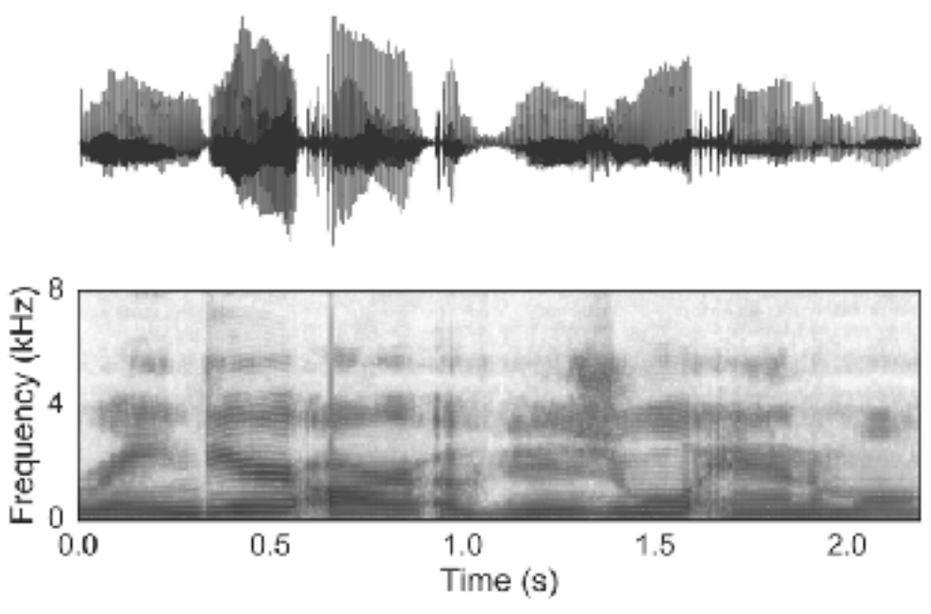
Movies demand minimal energy



Lawyers give a relevant opinion



Reindeer are a visual animal



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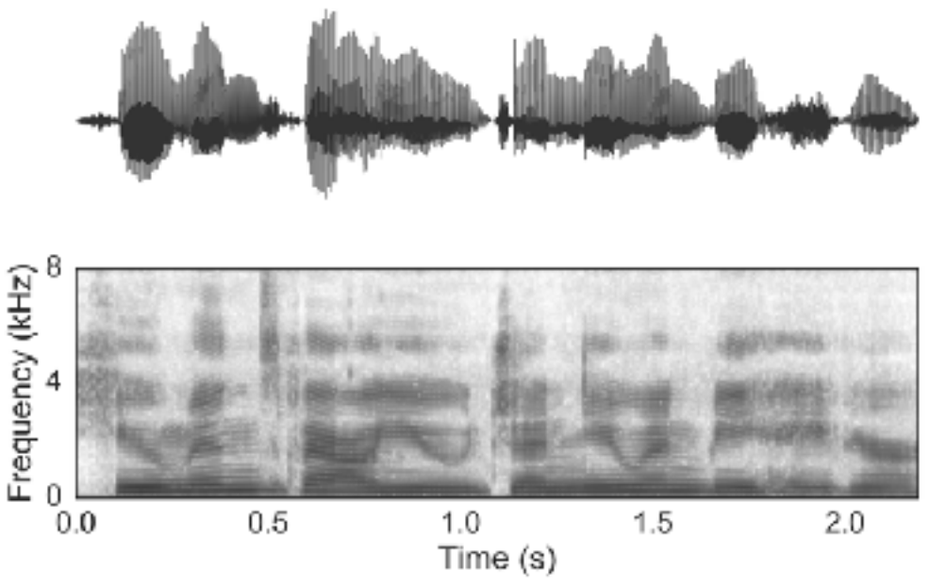

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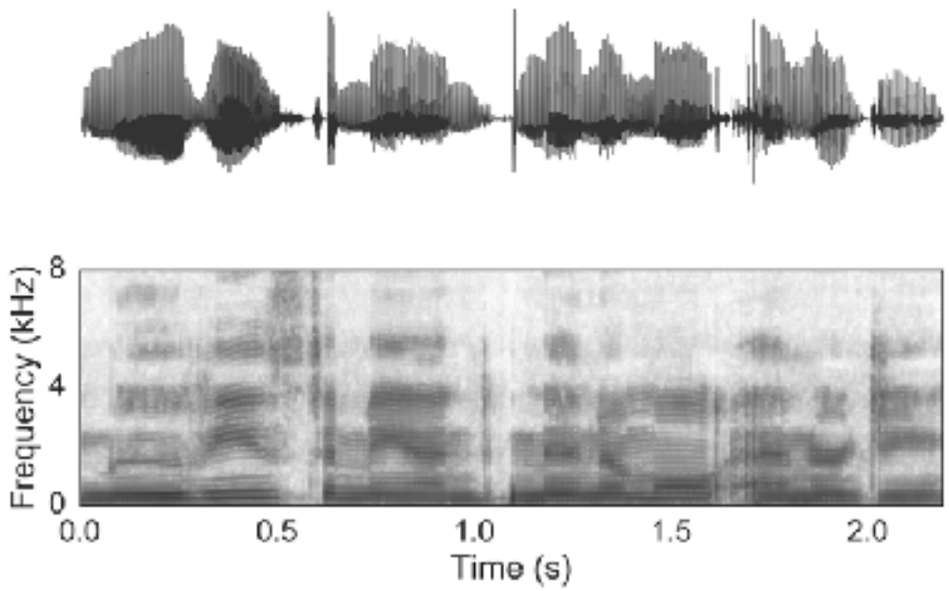

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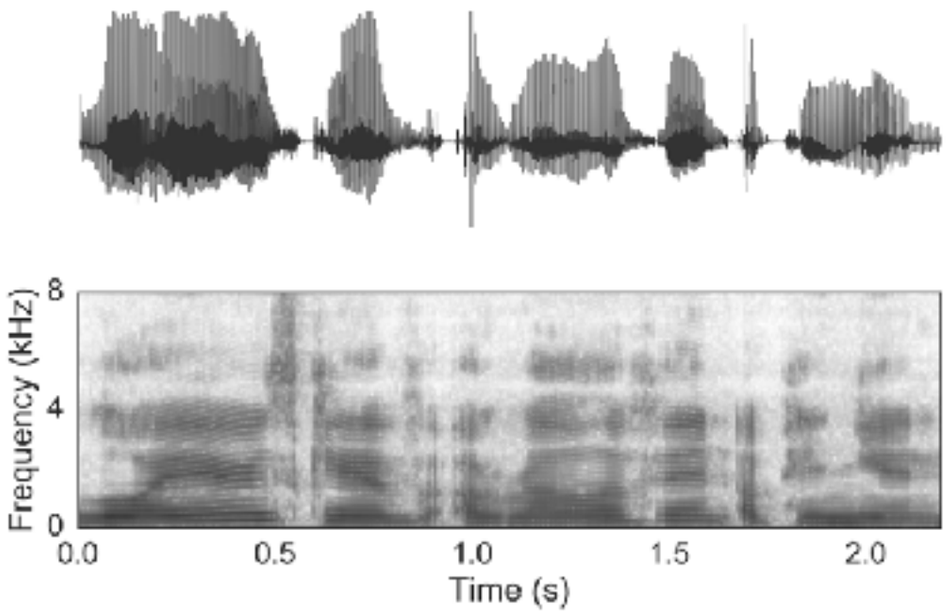

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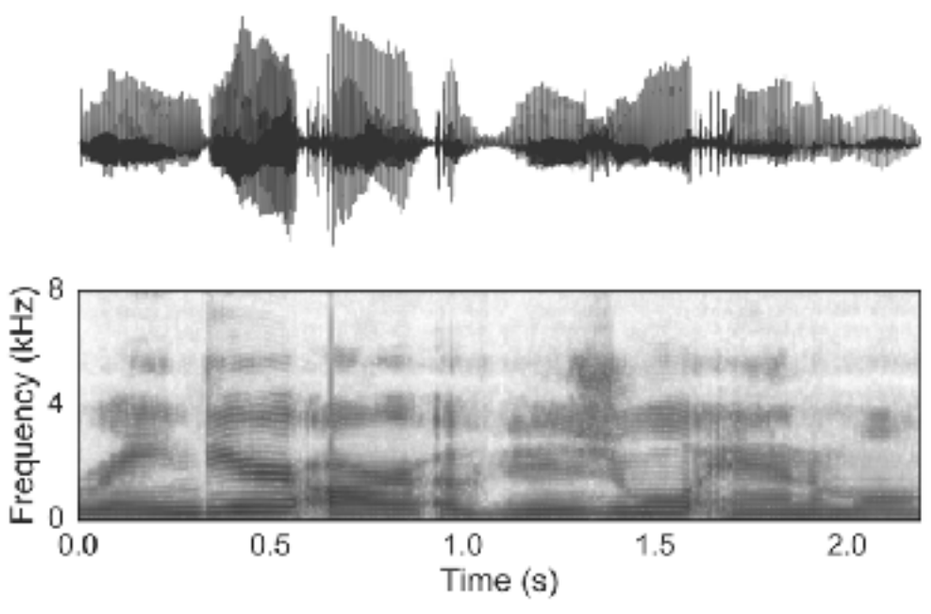

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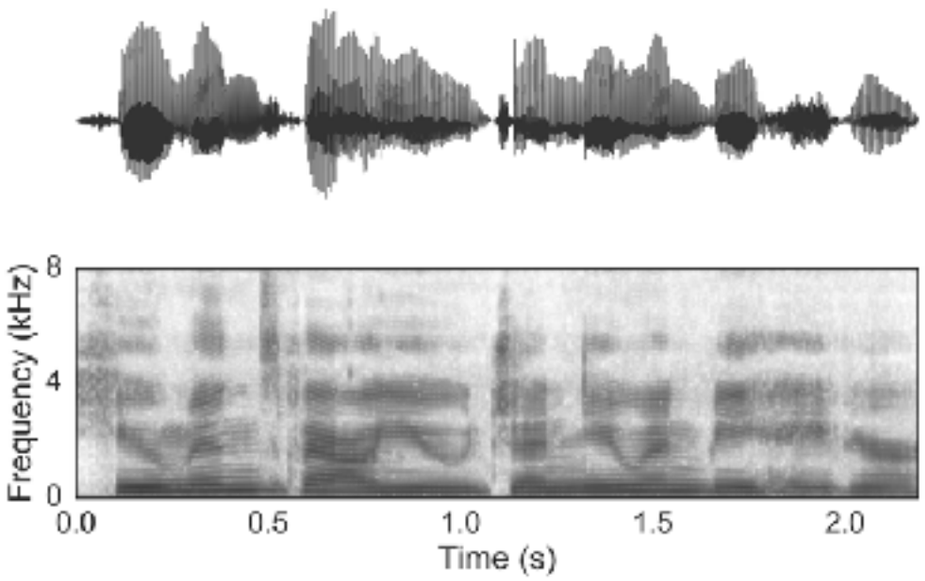

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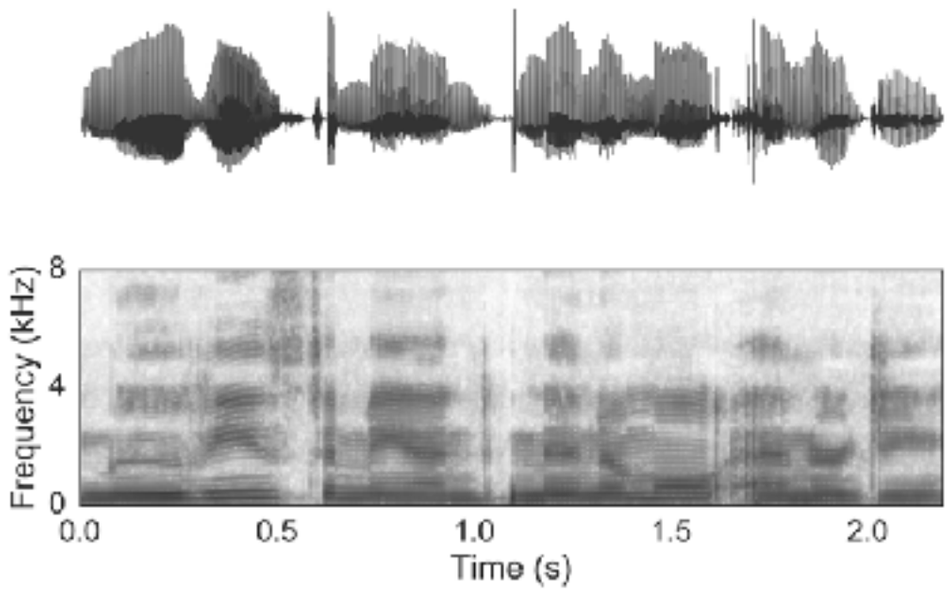

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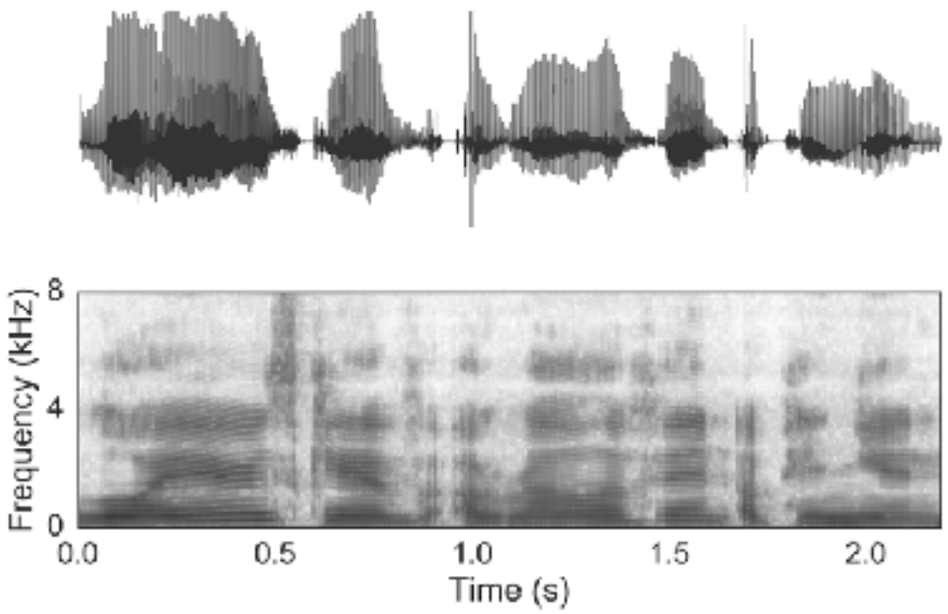

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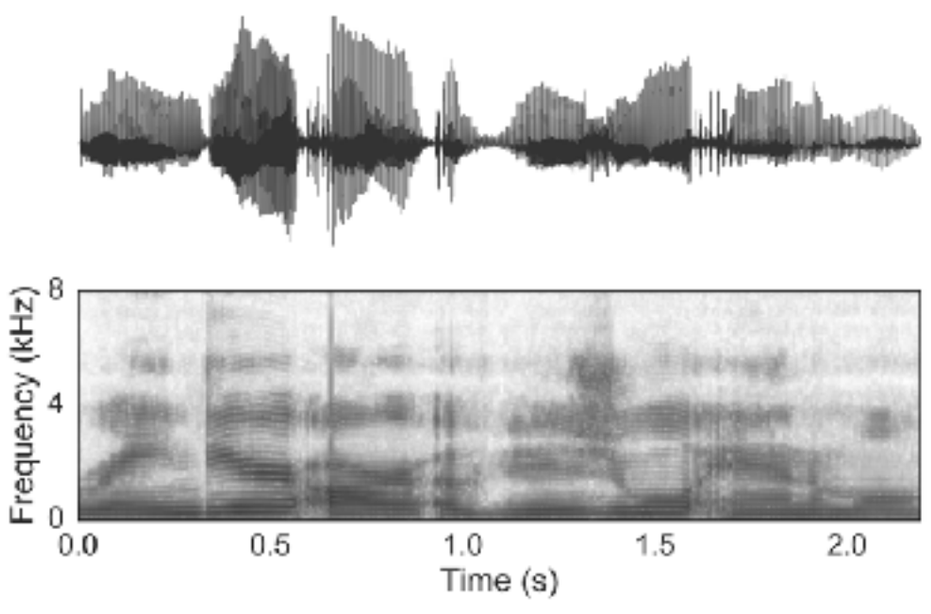

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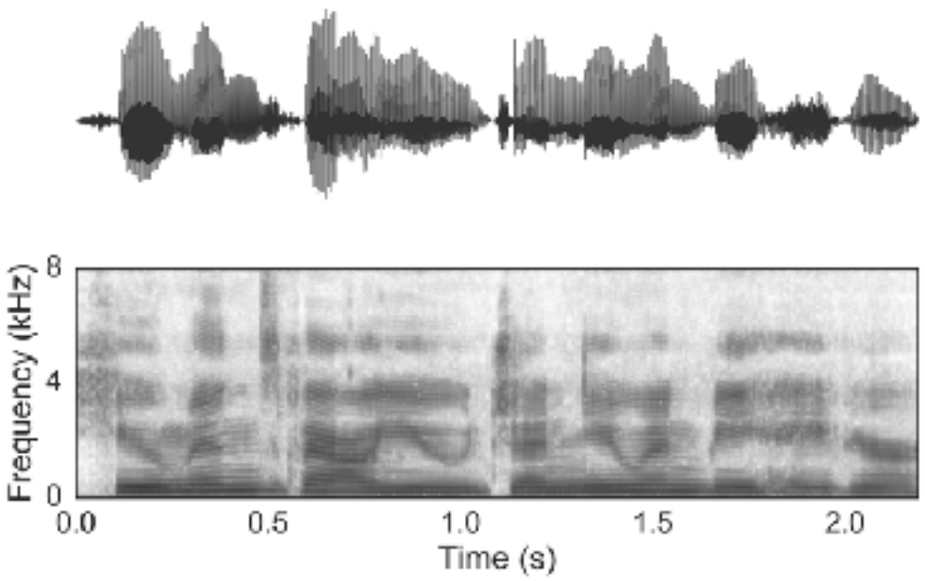

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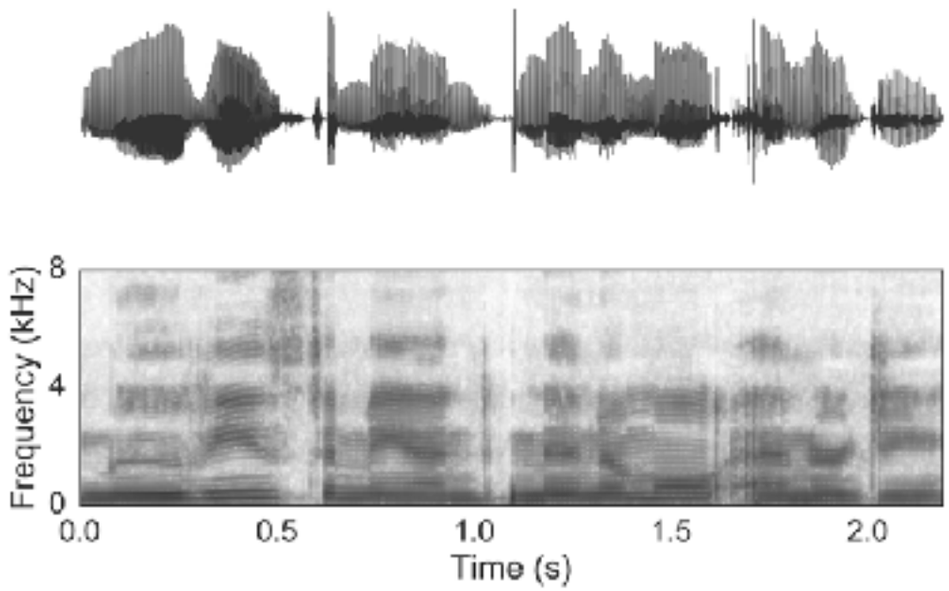

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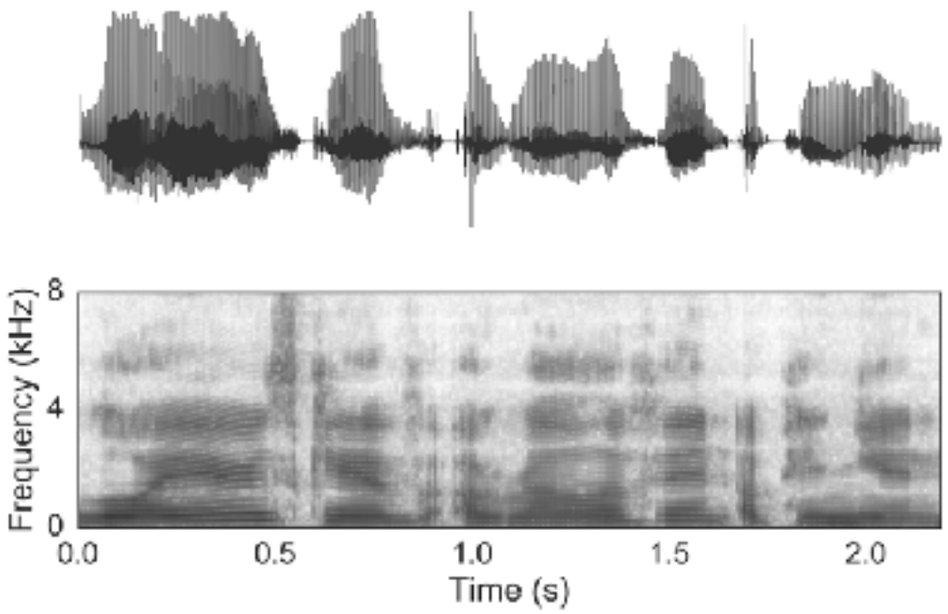

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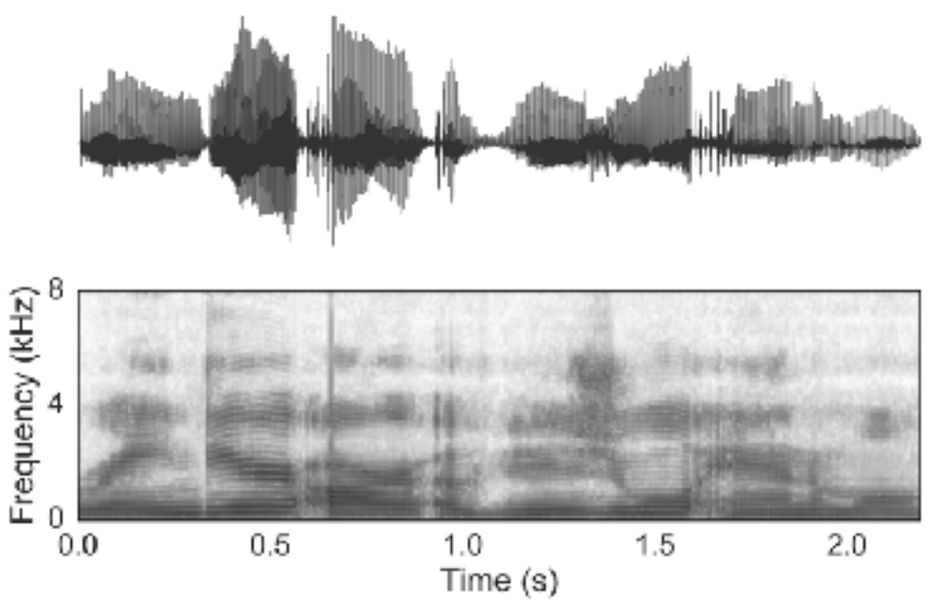

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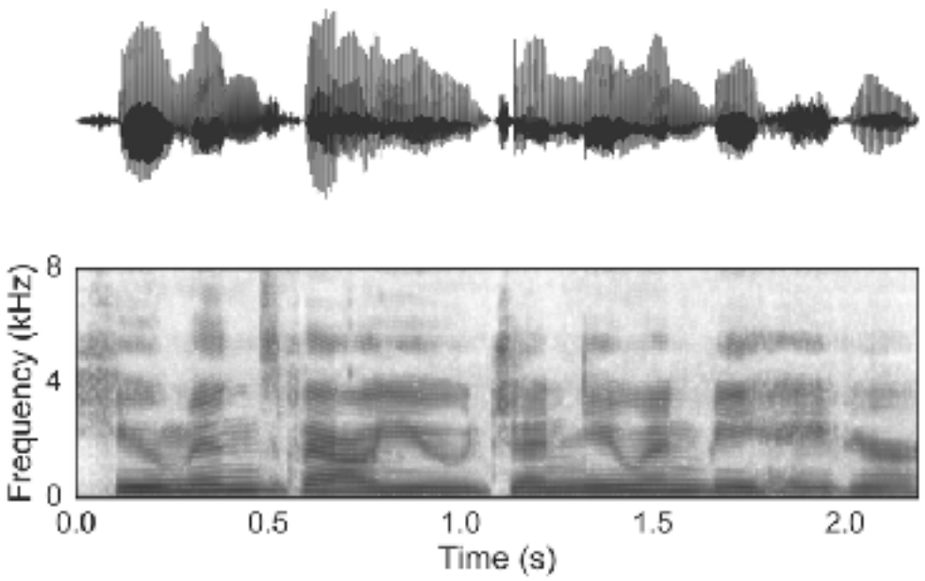

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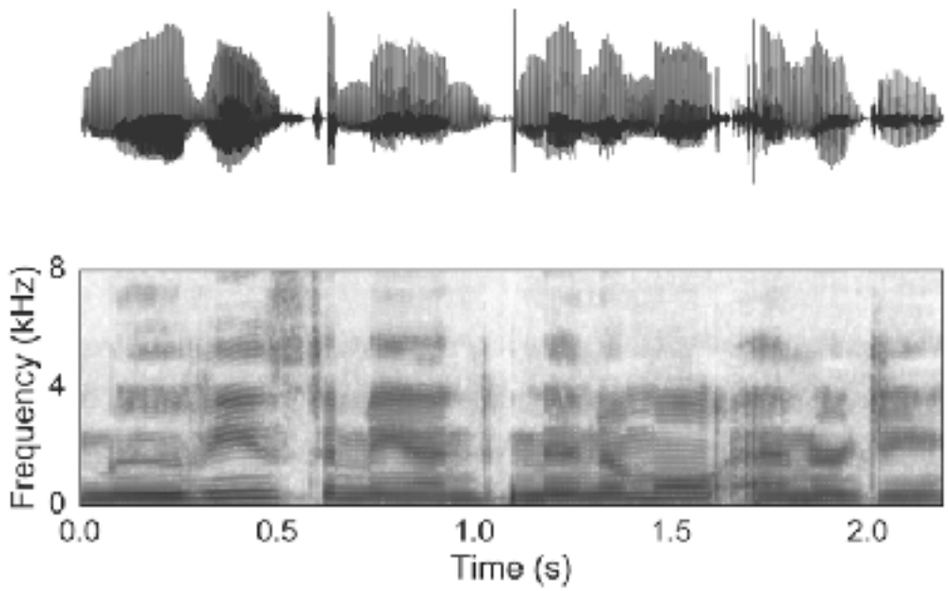

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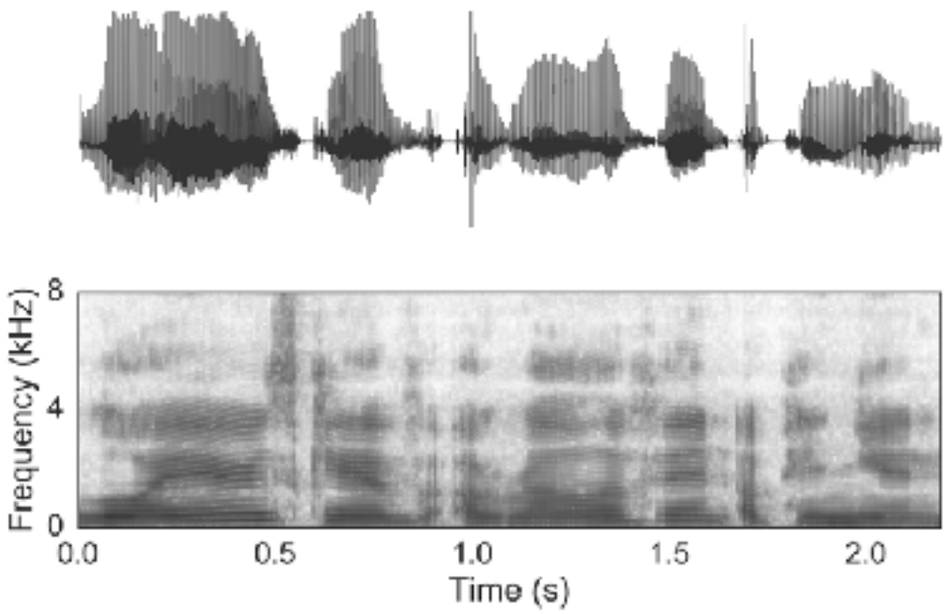

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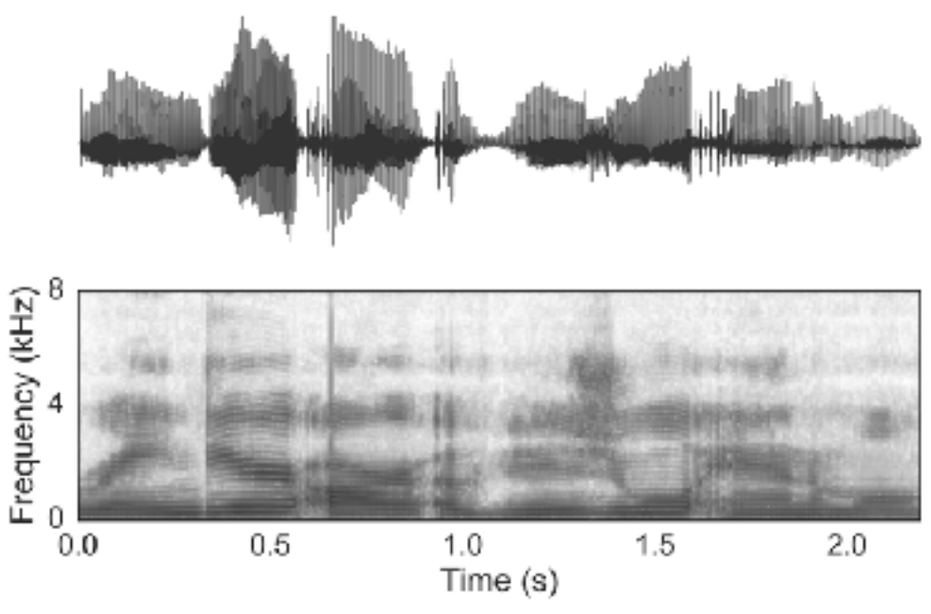
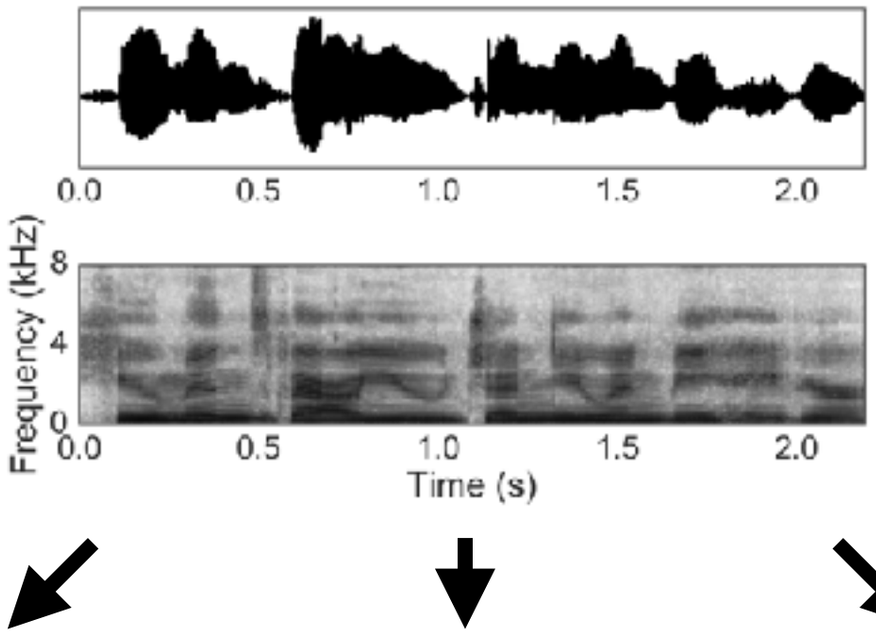


Different speakers synthesized with two pitch levels and two formant levels

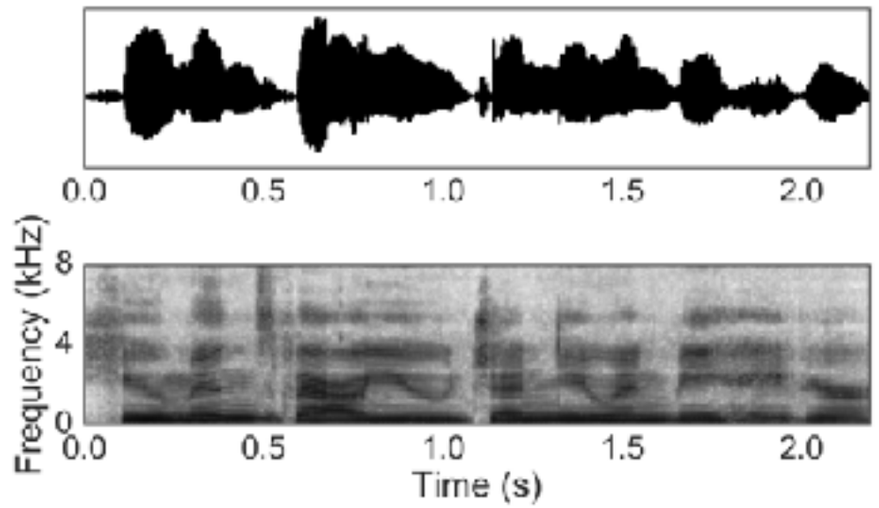


Low pitch +
Low formants

High pitch +
Low formants

High pitch +
High formants

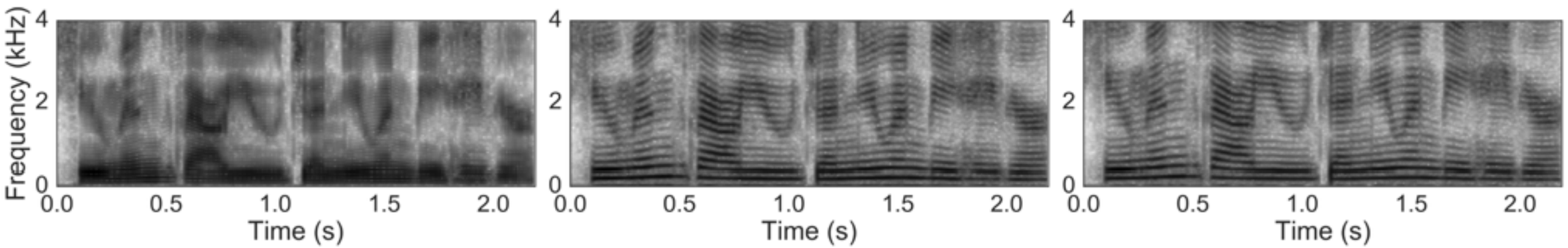
Different speakers synthesized with two pitch levels and two formant levels



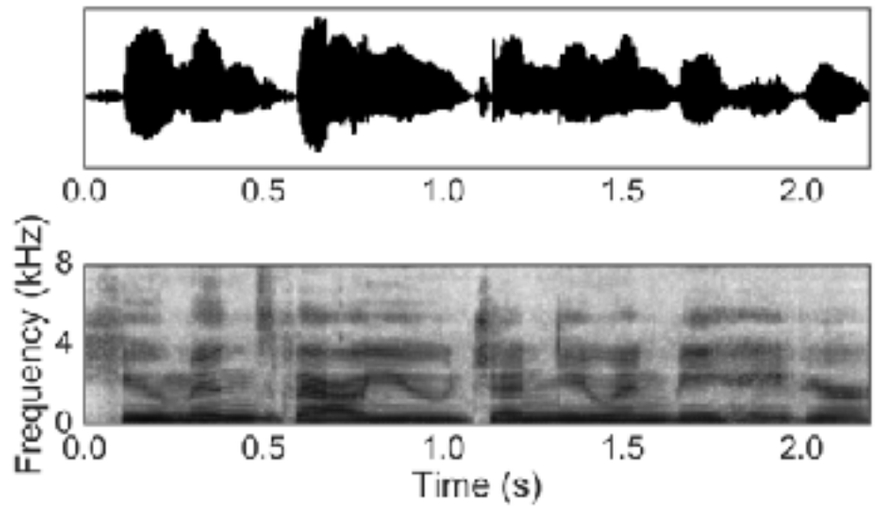
Low pitch +
Low formants

High pitch +
Low formants

High pitch +
High formants



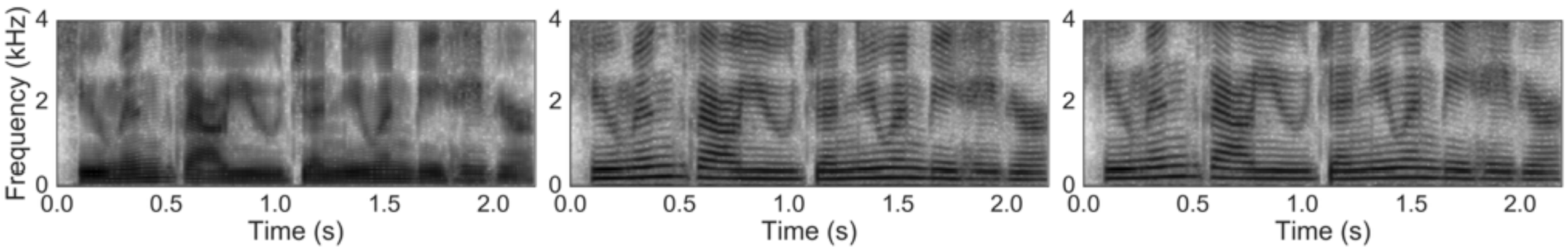
Different speakers synthesized with two pitch levels and two formant levels



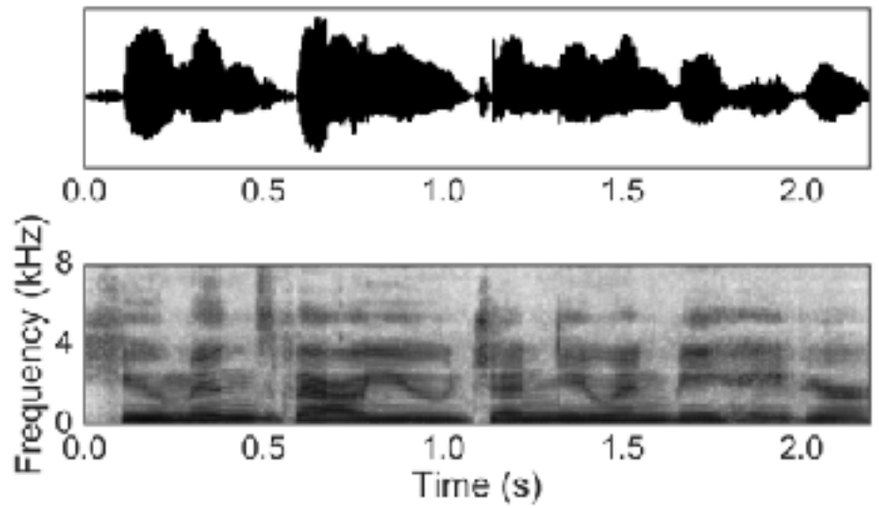
Low pitch +
Low formants

High pitch +
Low formants

High pitch +
High formants



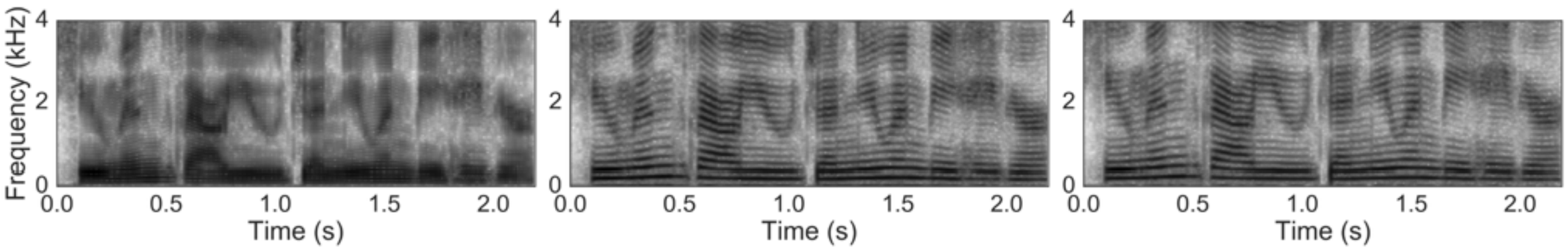
Different speakers synthesized with two pitch levels and two formant levels



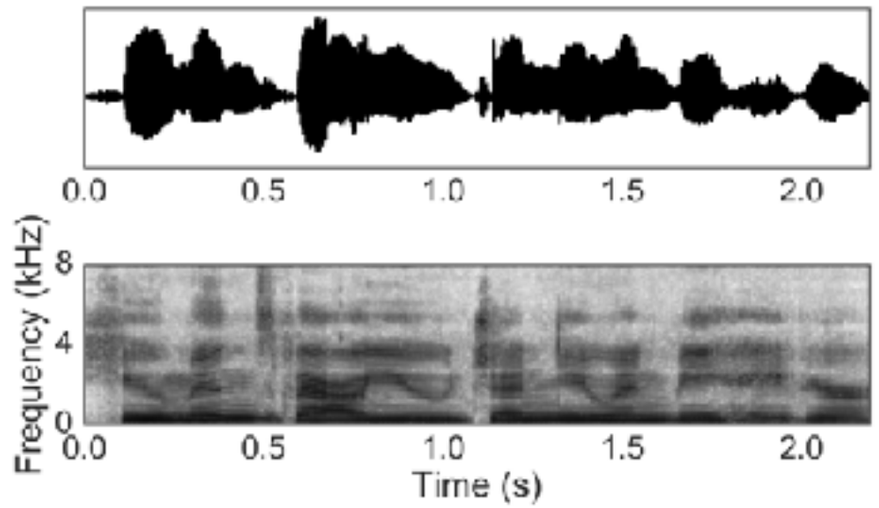
Low pitch +
Low formants

High pitch +
Low formants

High pitch +
High formants



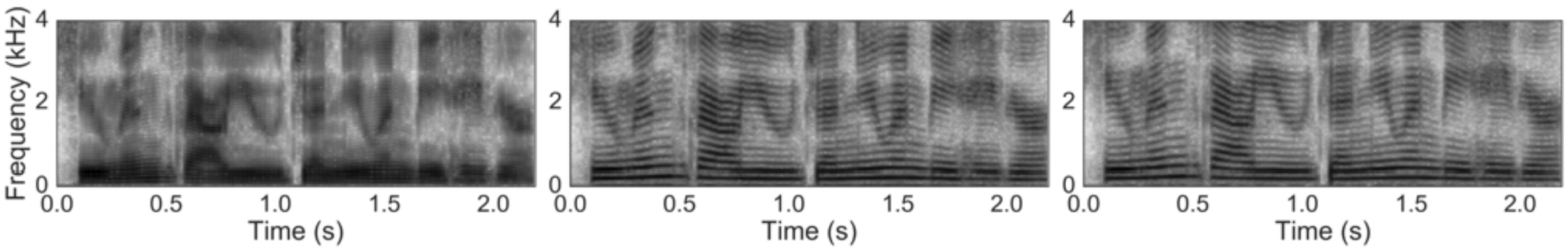
Different speakers synthesized with two pitch levels and two formant levels



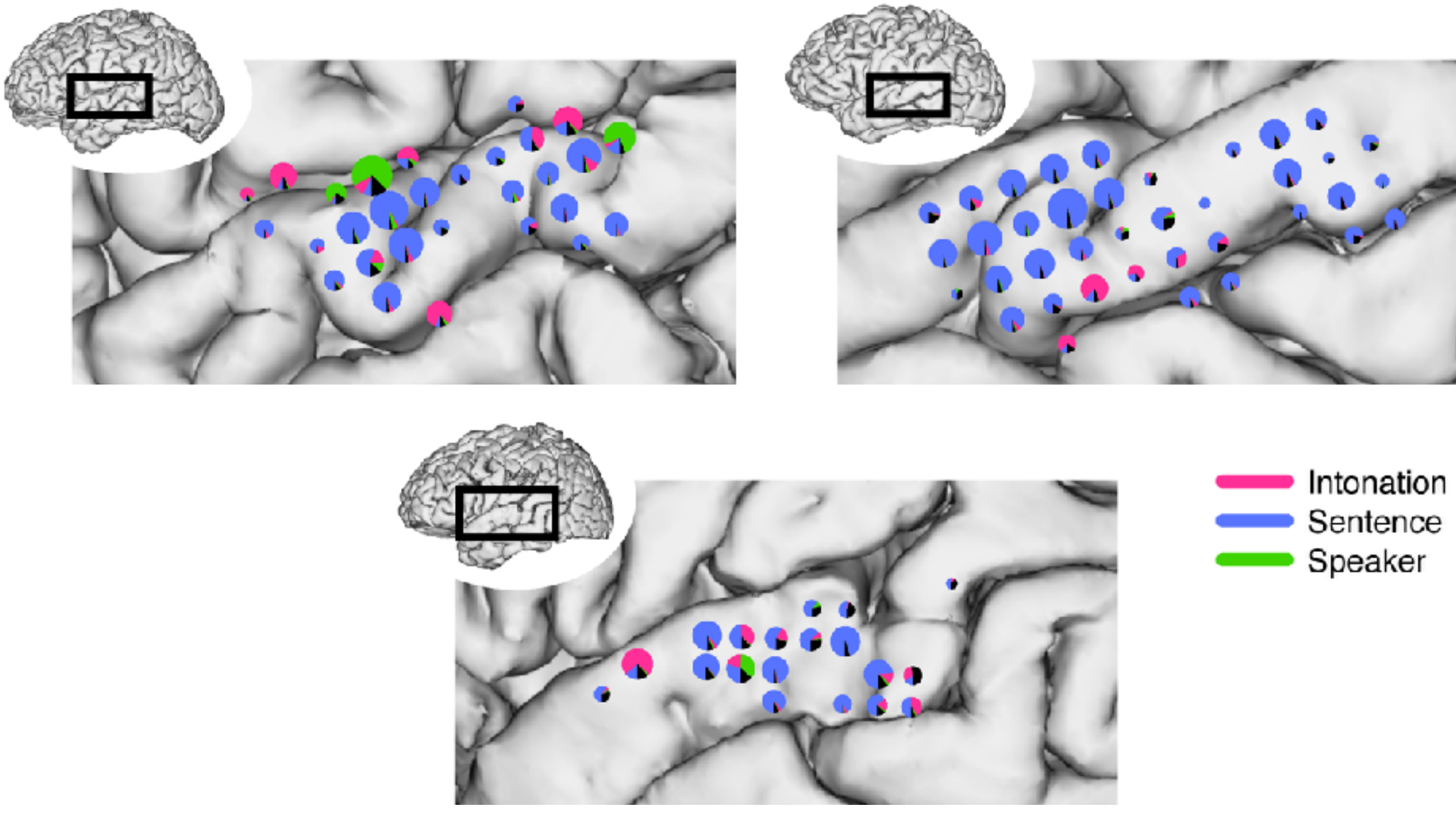
Low pitch +
Low formants

High pitch +
Low formants

High pitch +
High formants



Intonation and phonetic content are encoded in separate neural populations



Electrodes primarily encode **one**: intonation, phonetic features, or speaker

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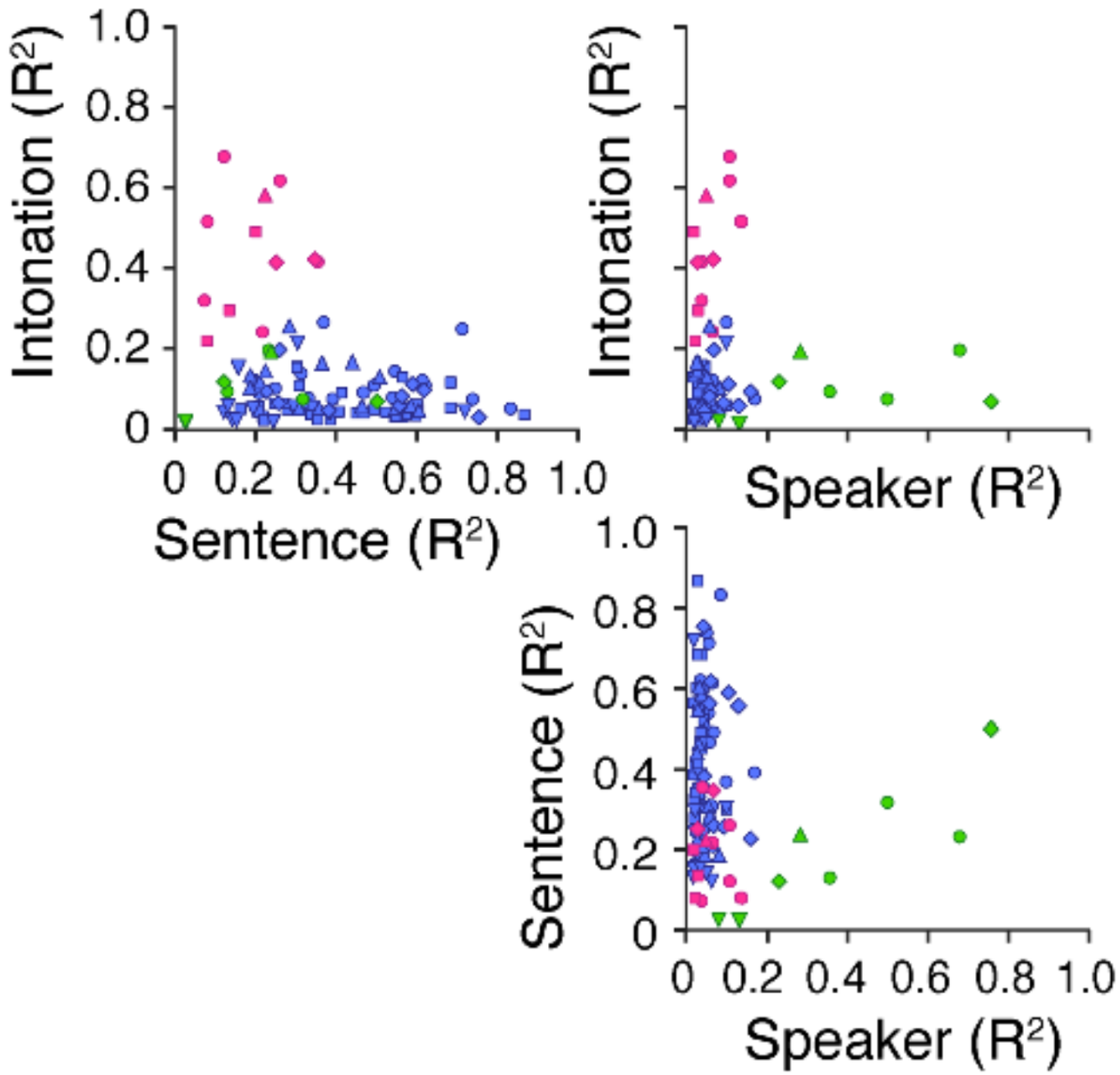


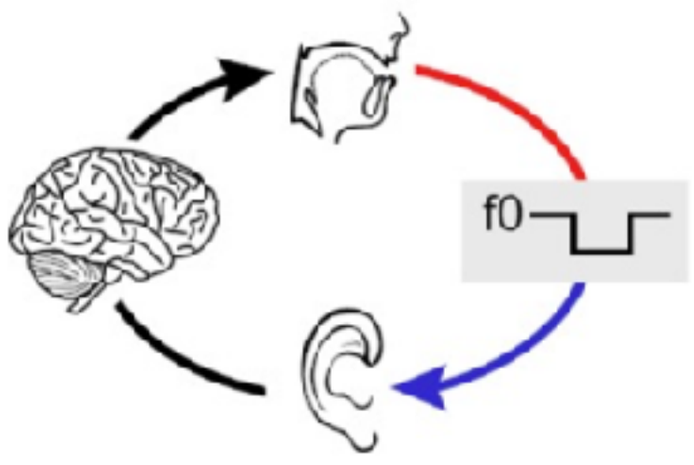
Results

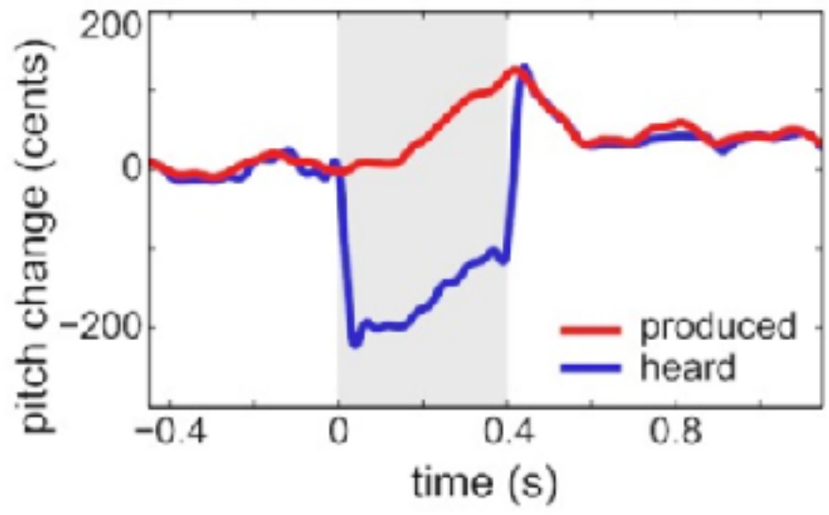
- Local neural populations in STG encode intonation.
- The representation of intonation is phonetic feature and speaker invariant.
- Intonation and phonetic content are encoded in separate neural populations.

Confounding variables

Factor	Solution
Loudness	Partial correlation
Supra-laryngeal articulators (Tongue, Jaw, Velum, etc.)	Dynamic time warping
Declination (pitch lowering)	Shuffle test

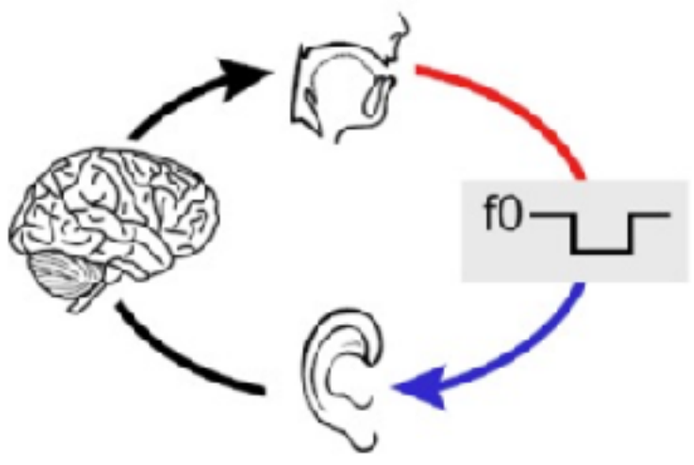
Sensorimotor role: evidence for feedback control in vLMC, not dLMC

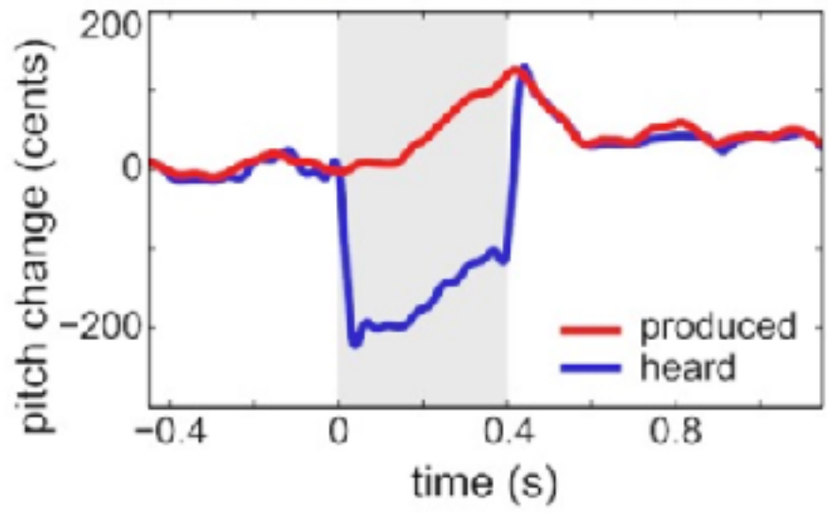


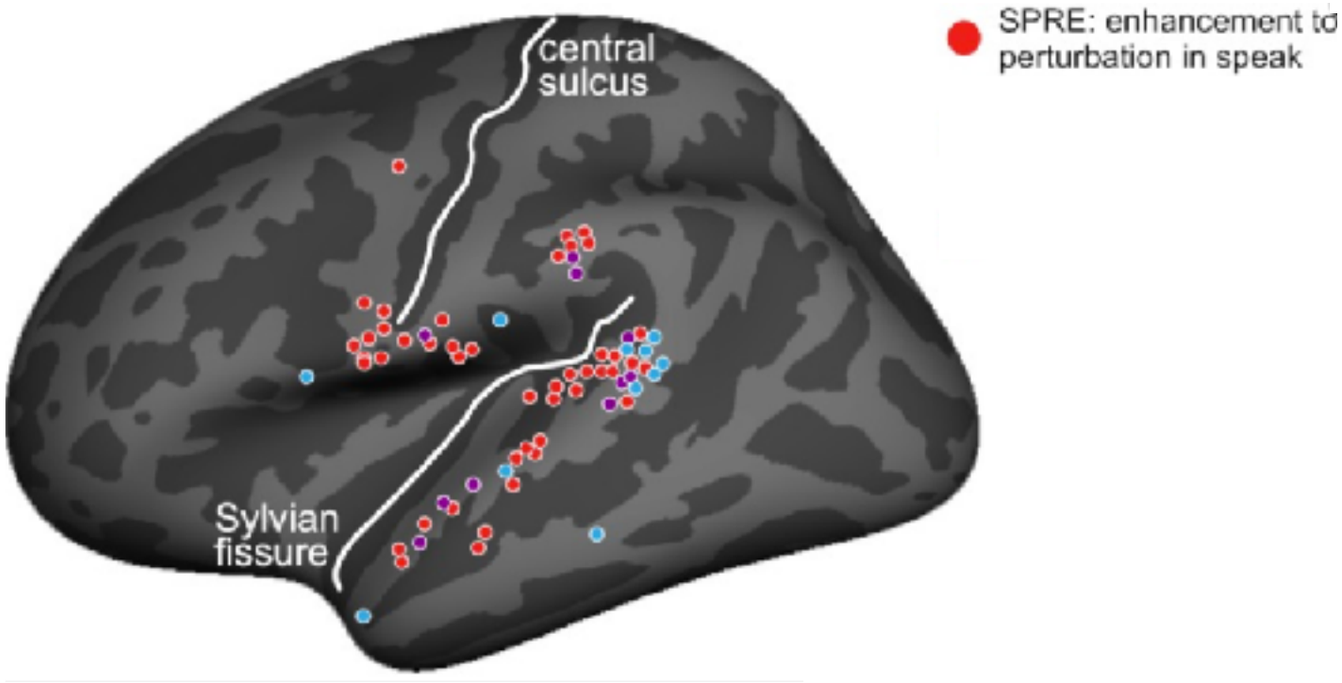


(Chang, Niziolek et al. 2013)

Sensorimotor role: evidence for feedback control in vLMC, not dLMC



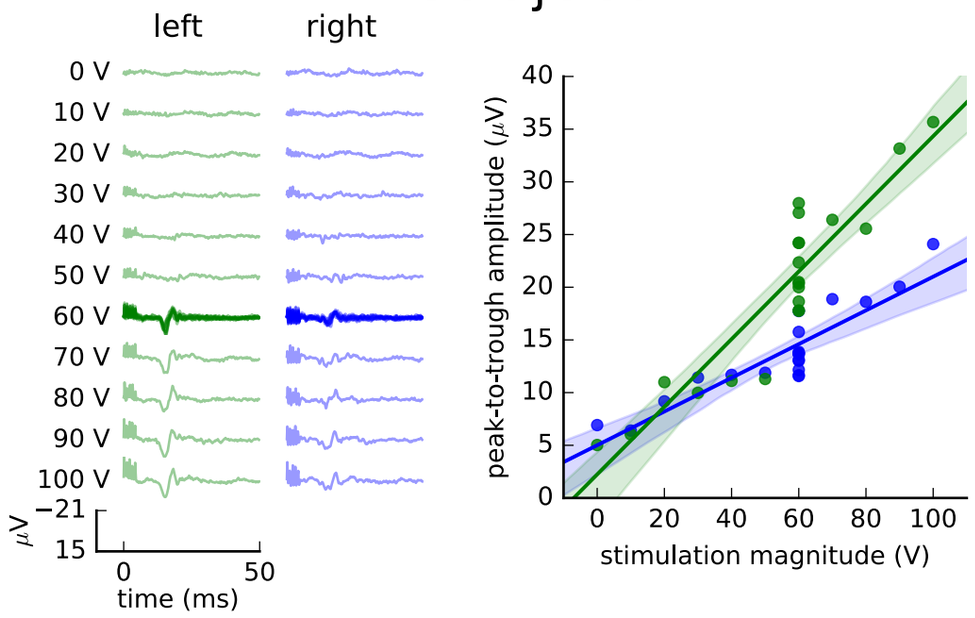




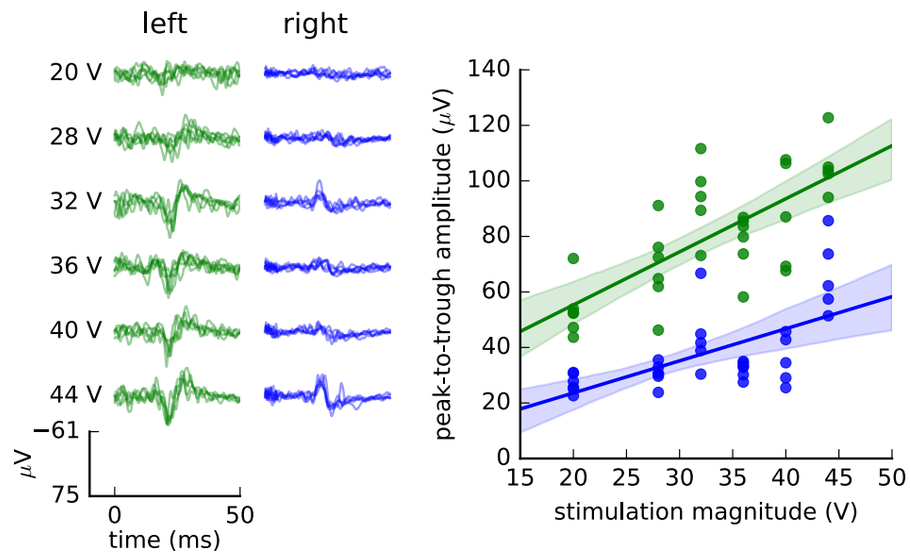
(Chang, Niziolek et al. 2013)

Individual stimulation EMG results

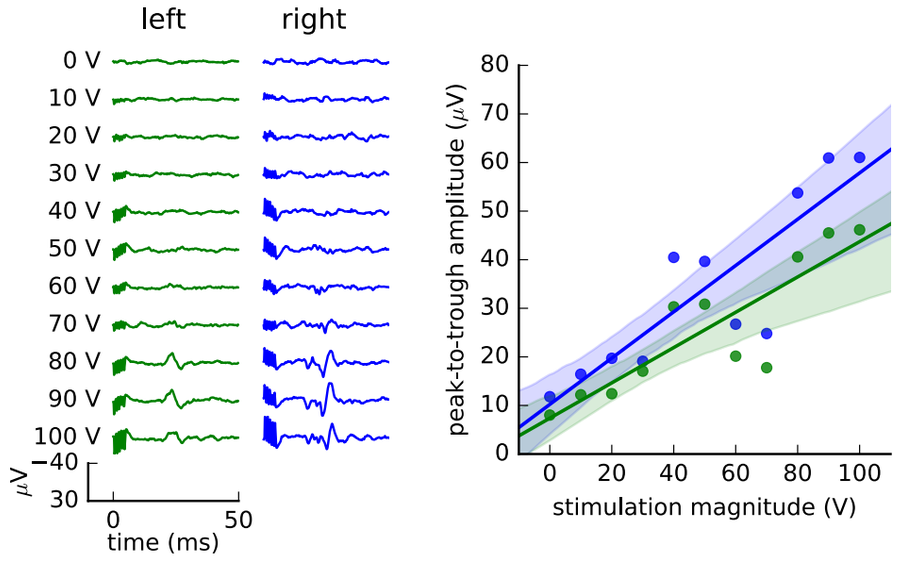
subject 1



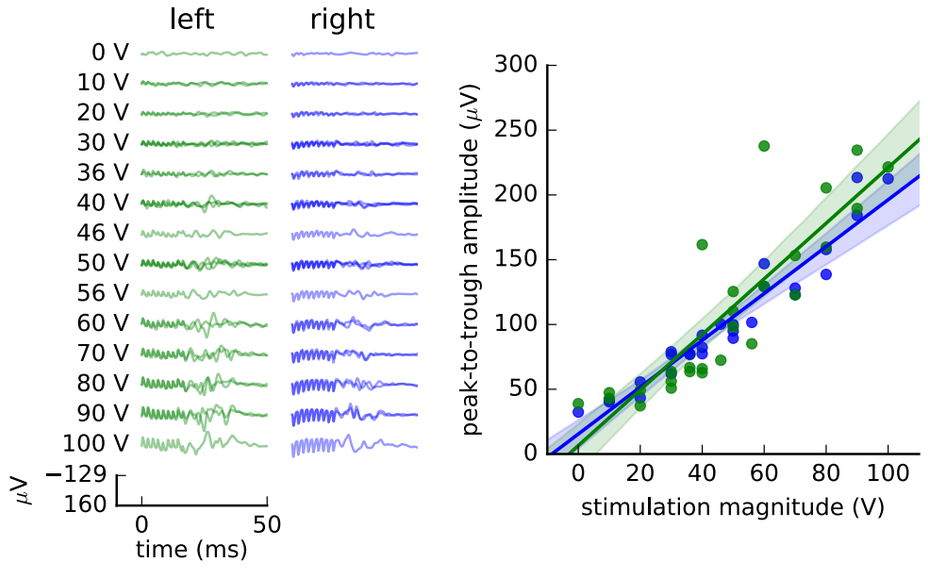
subject 2

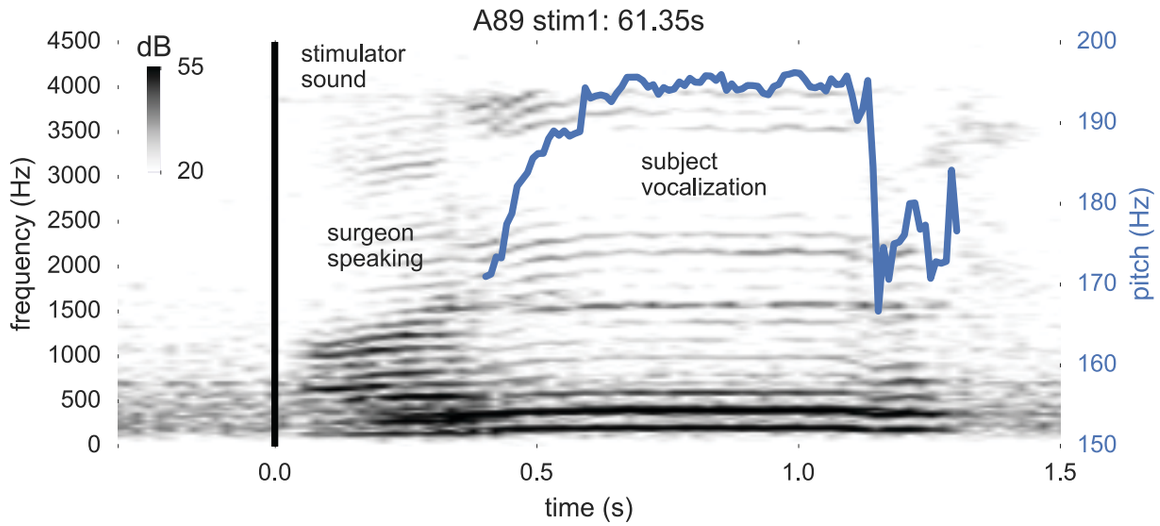


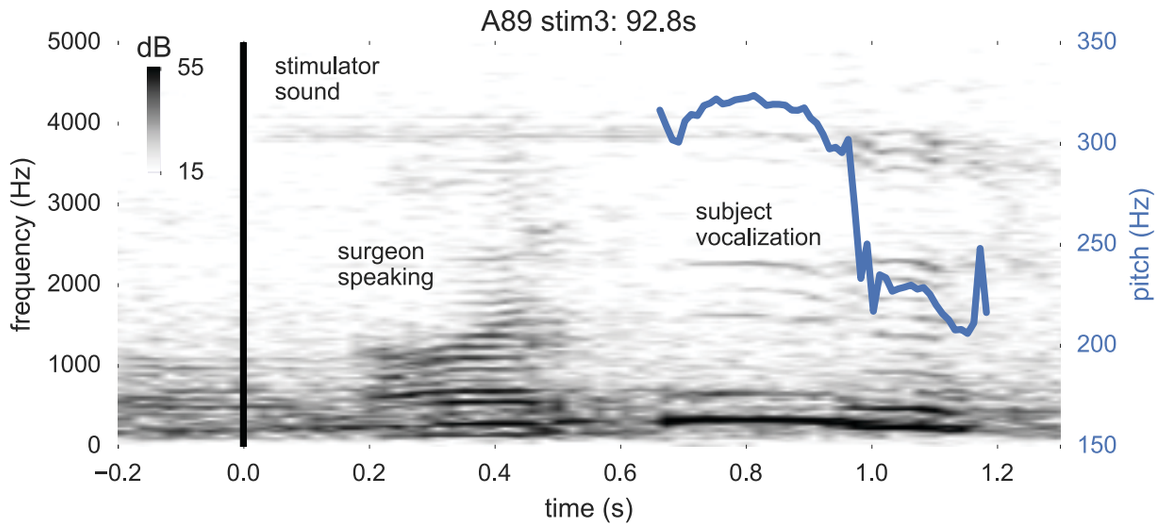
subject 3

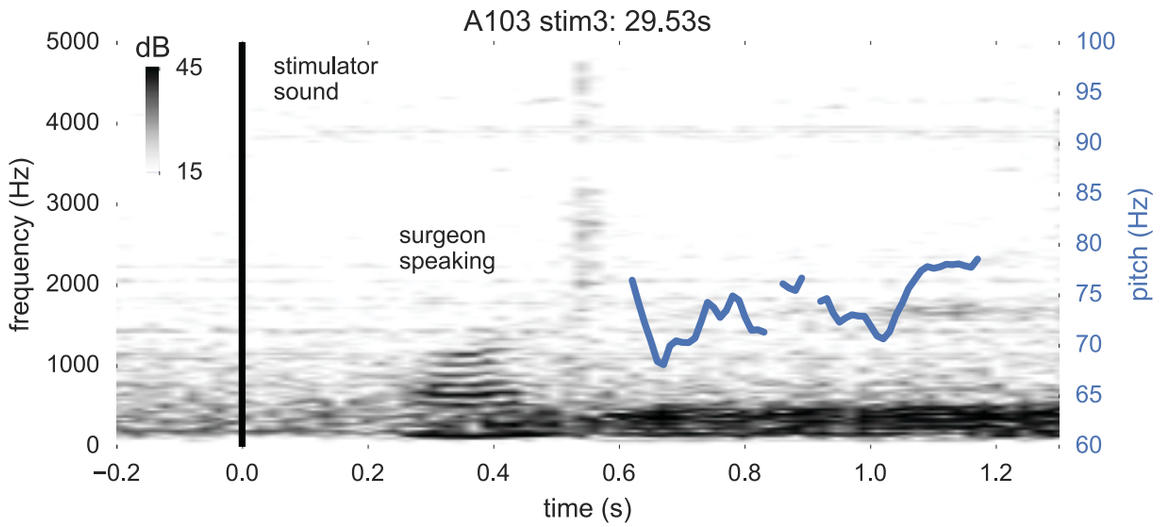


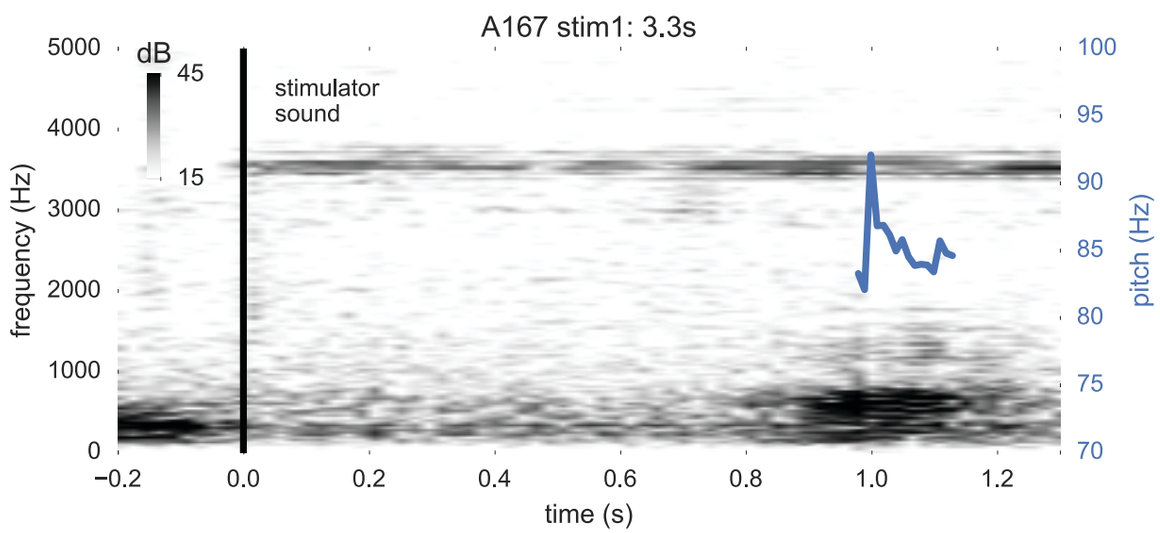
subject 4

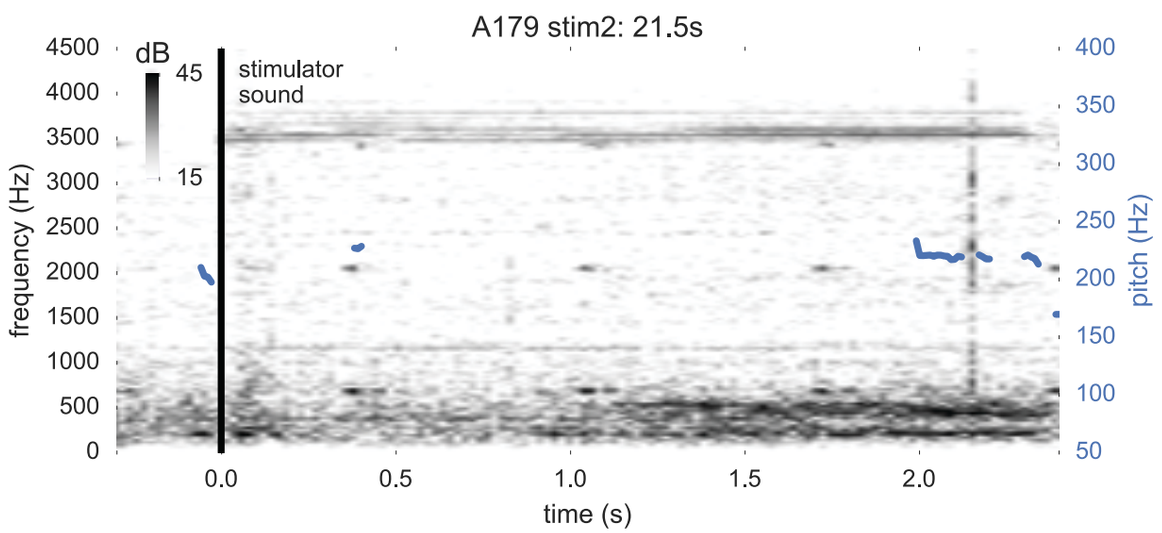


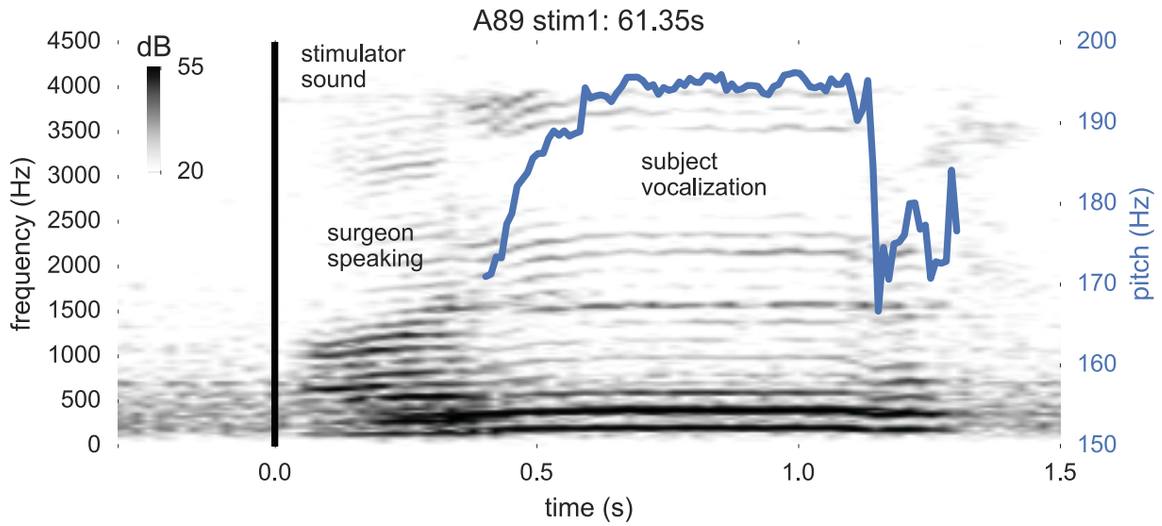

A89 stim1: 61.35s
dB
55
20
stimulator sound
subject vocalization
surgeon speaking
frequency (Hz)
pitch (Hz)
time (s)

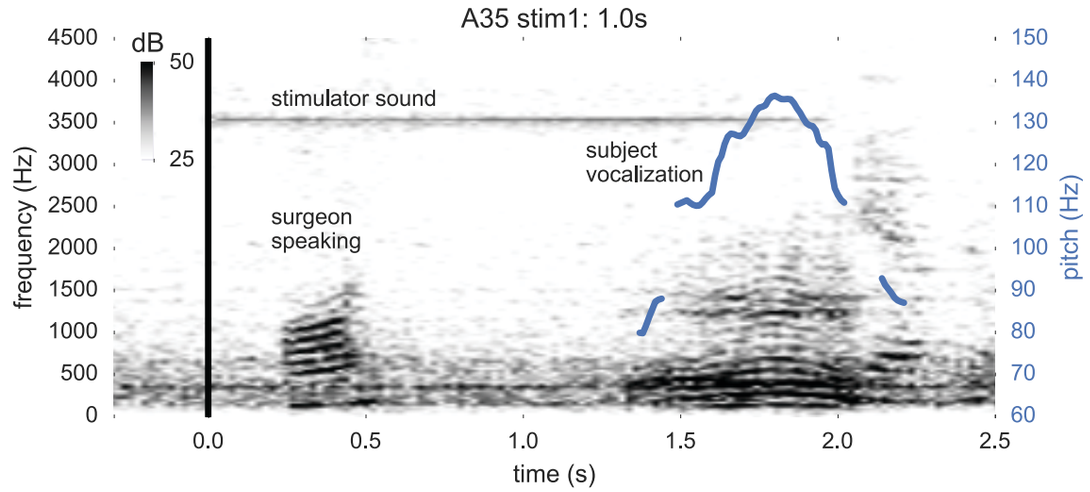

A89 stim3: 92.8s
dB
55
15
stimulator sound
surgeon speaking
subject vocalization
frequency (Hz)
pitch (Hz)
time (s)

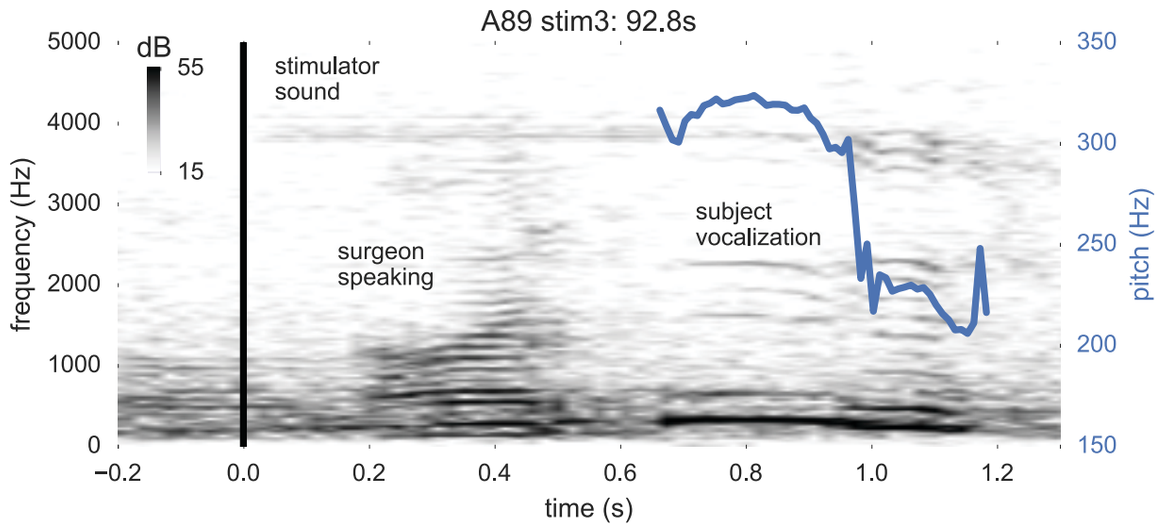

A103 stim3: 29.53s
dB
45
15
stimulator sound
surgeon speaking
frequency (Hz)
pitch (Hz)
time (s)

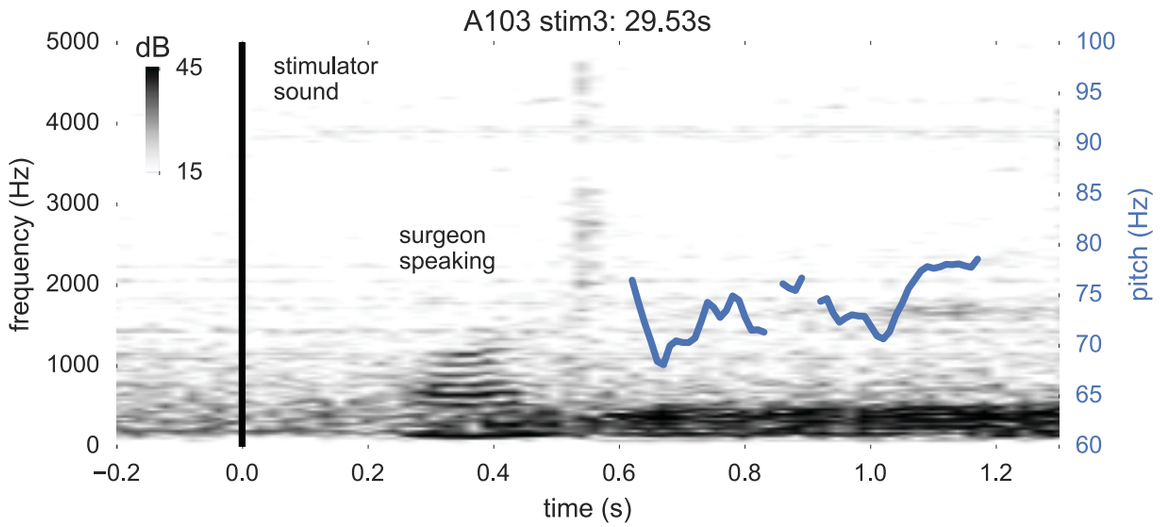

A167 stim1: 3.3s
dB
45
15
stimulator sound
frequency (Hz)
pitch (Hz)
time (s)

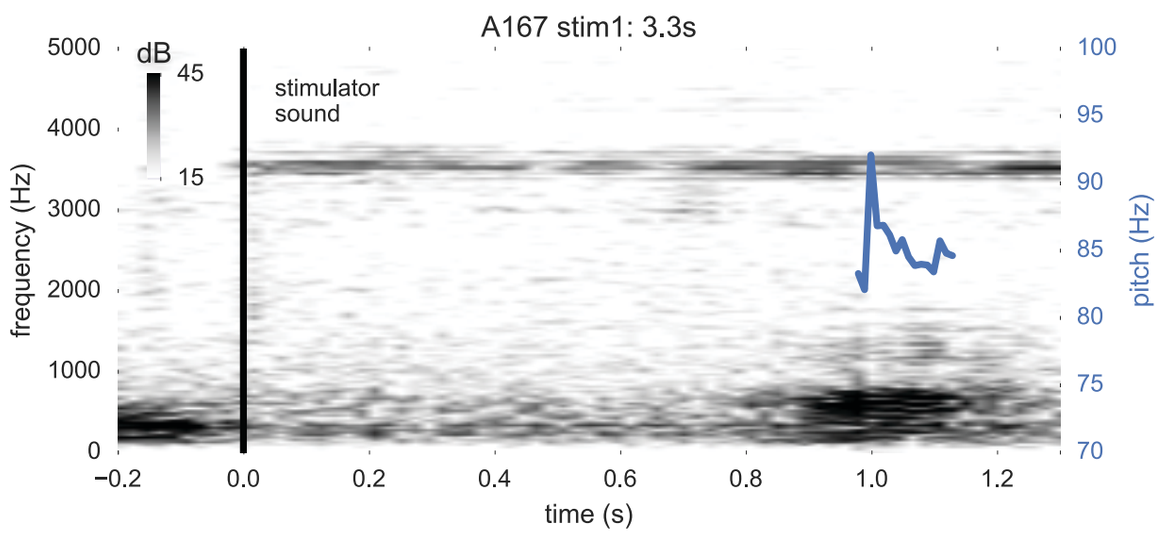

A179 stim2: 21.5s
dB
45
15
stimulator sound
frequency (Hz)
pitch (Hz)
time (s)

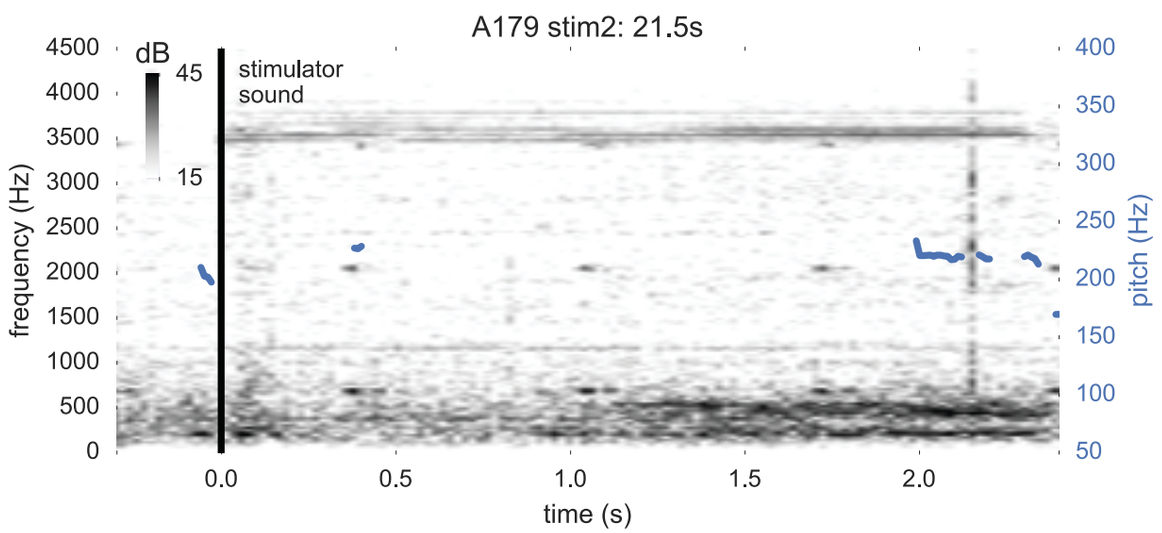

A89 stim1: 61.35s
dB
55
20
stimulator sound
subject vocalization
surgeon speaking
frequency (Hz)
pitch (Hz)
time (s)

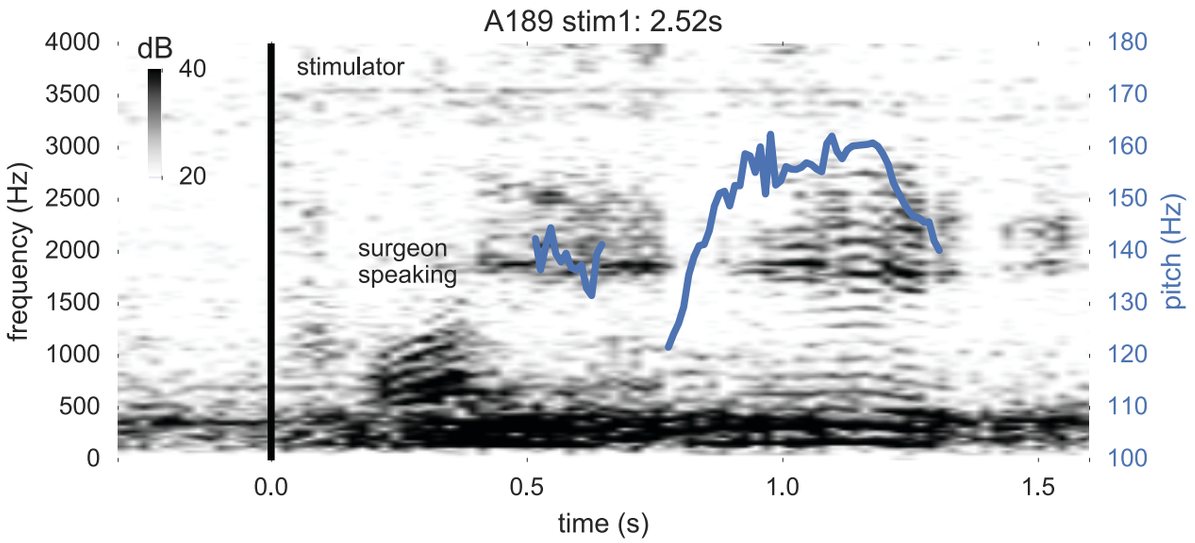

A35 stim1: 1.0s
dB
50
25
stimulator sound
subject vocalization
surgeon speaking
frequency (Hz)
pitch (Hz)
time (s)

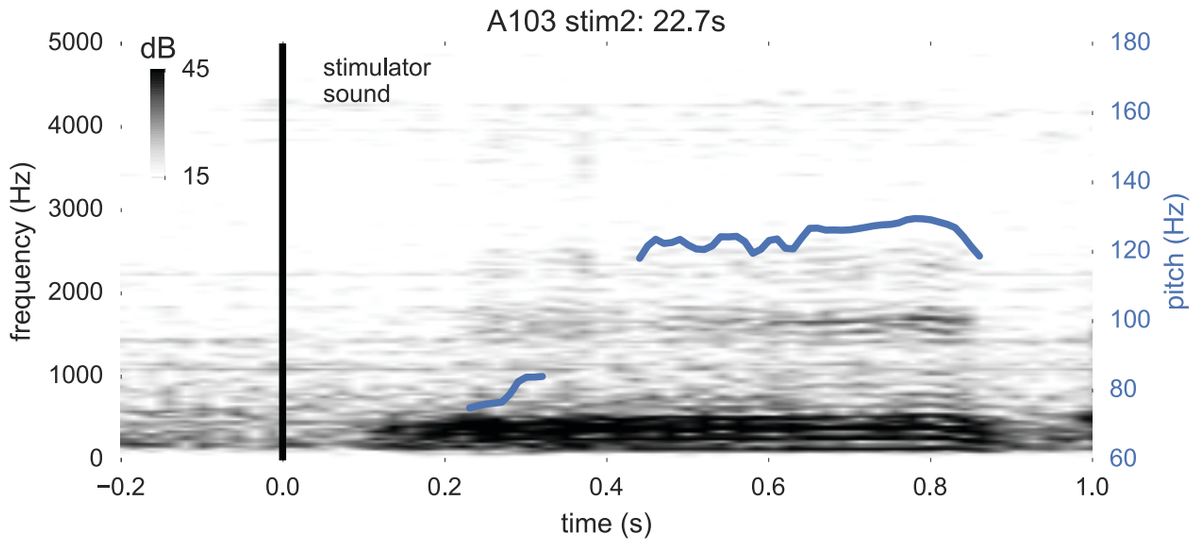

A89 stim3: 92.8s
dB
55
15
stimulator sound
subject vocalization
surgeon speaking
frequency (Hz)
pitch (Hz)
time (s)

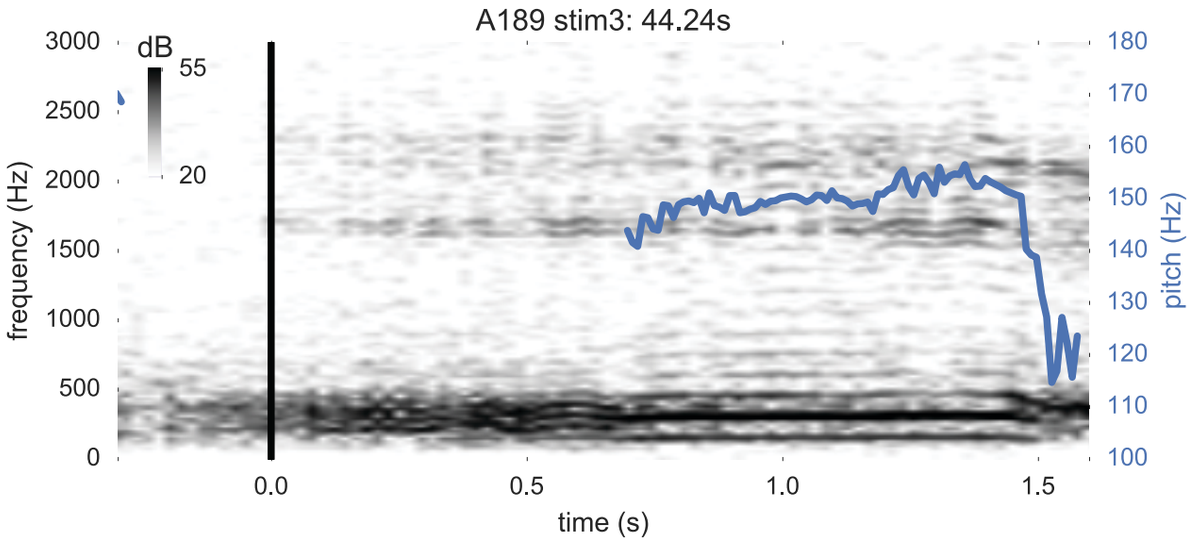

A103 stim3: 29.53s
dB
45
15
stimulator sound
surgeon speaking
frequency (Hz)
pitch (Hz)
time (s)

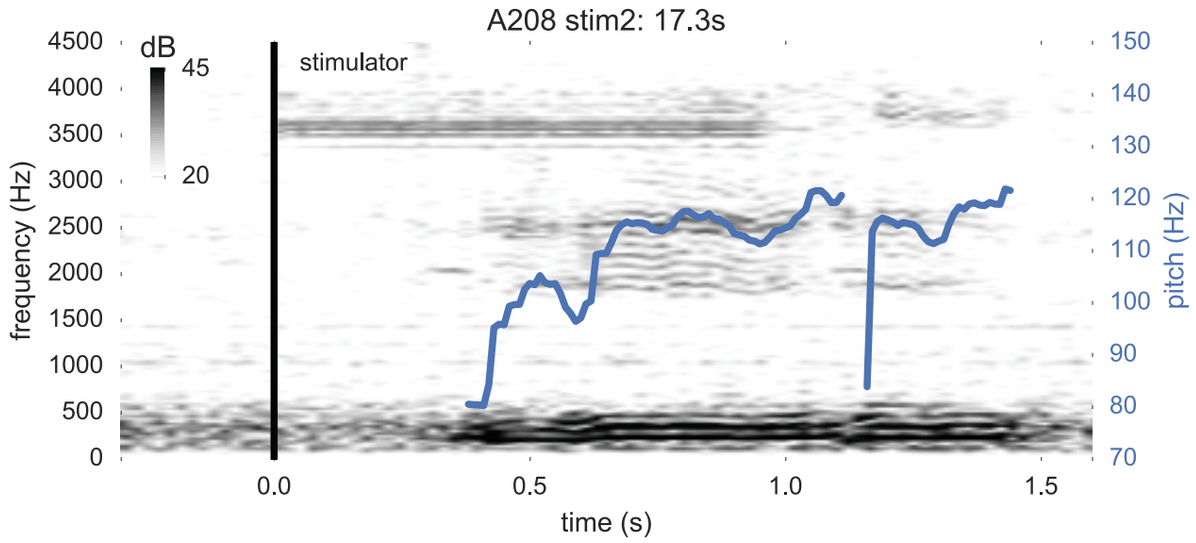

A167 stim1: 3.3s
dB
45
15
stimulator sound
frequency (Hz)
pitch (Hz)
time (s)

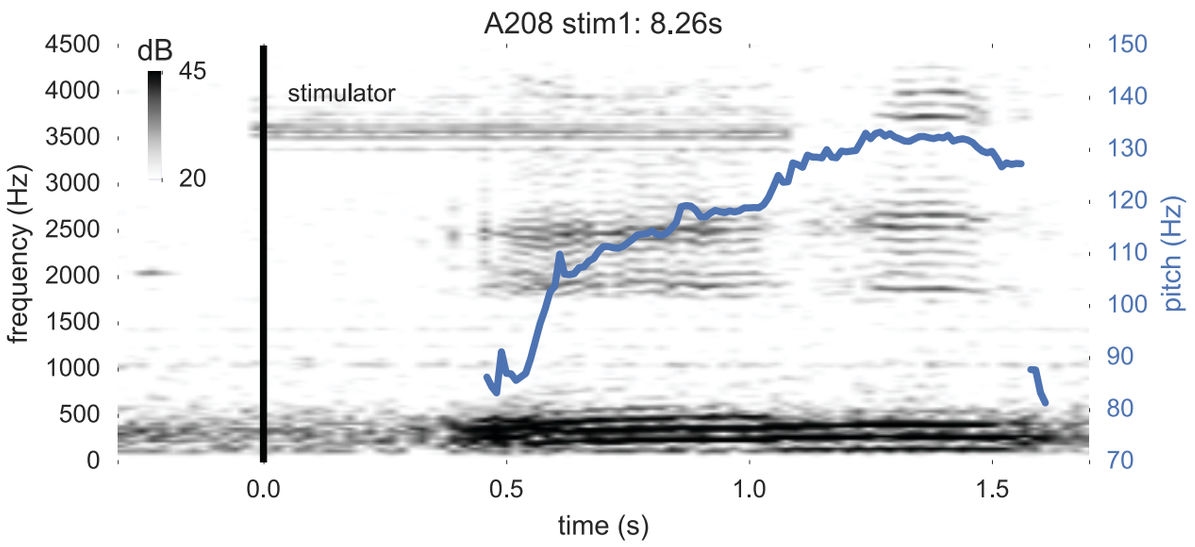

A179 stim2: 21.5s
dB
45
15
stimulator sound
frequency (Hz)
pitch (Hz)
time (s)

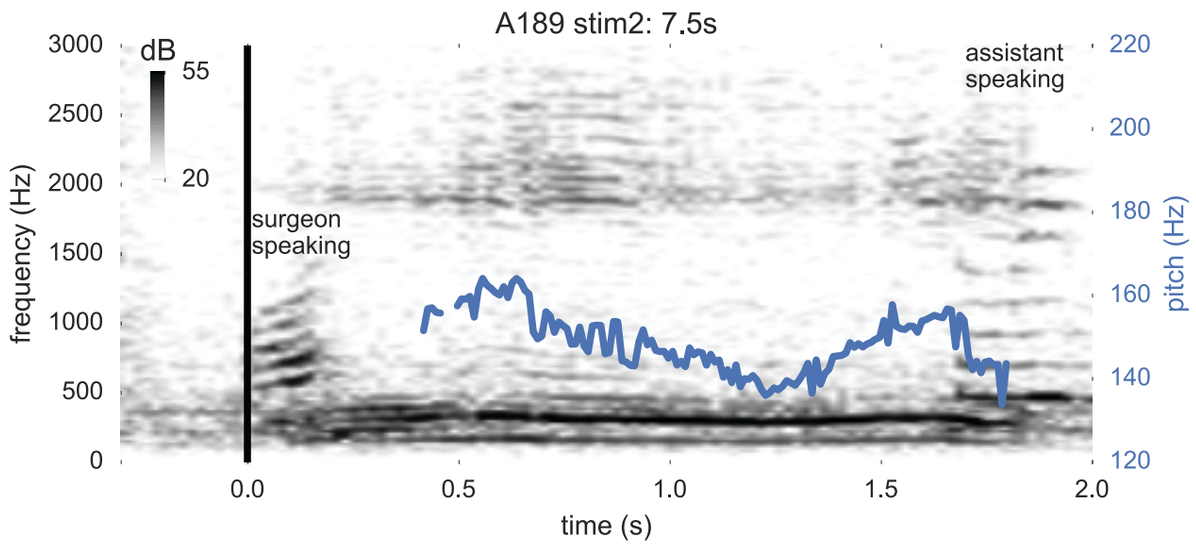

A189 stim1: 2.52s
dB
40
20
stimulator
surgeon
speaking
frequency (Hz)
pitch (Hz)
time (s)


A103 stim2: 22.7s
dB
45
15
stimulator
sound
frequency (Hz)
pitch (Hz)
time (s)

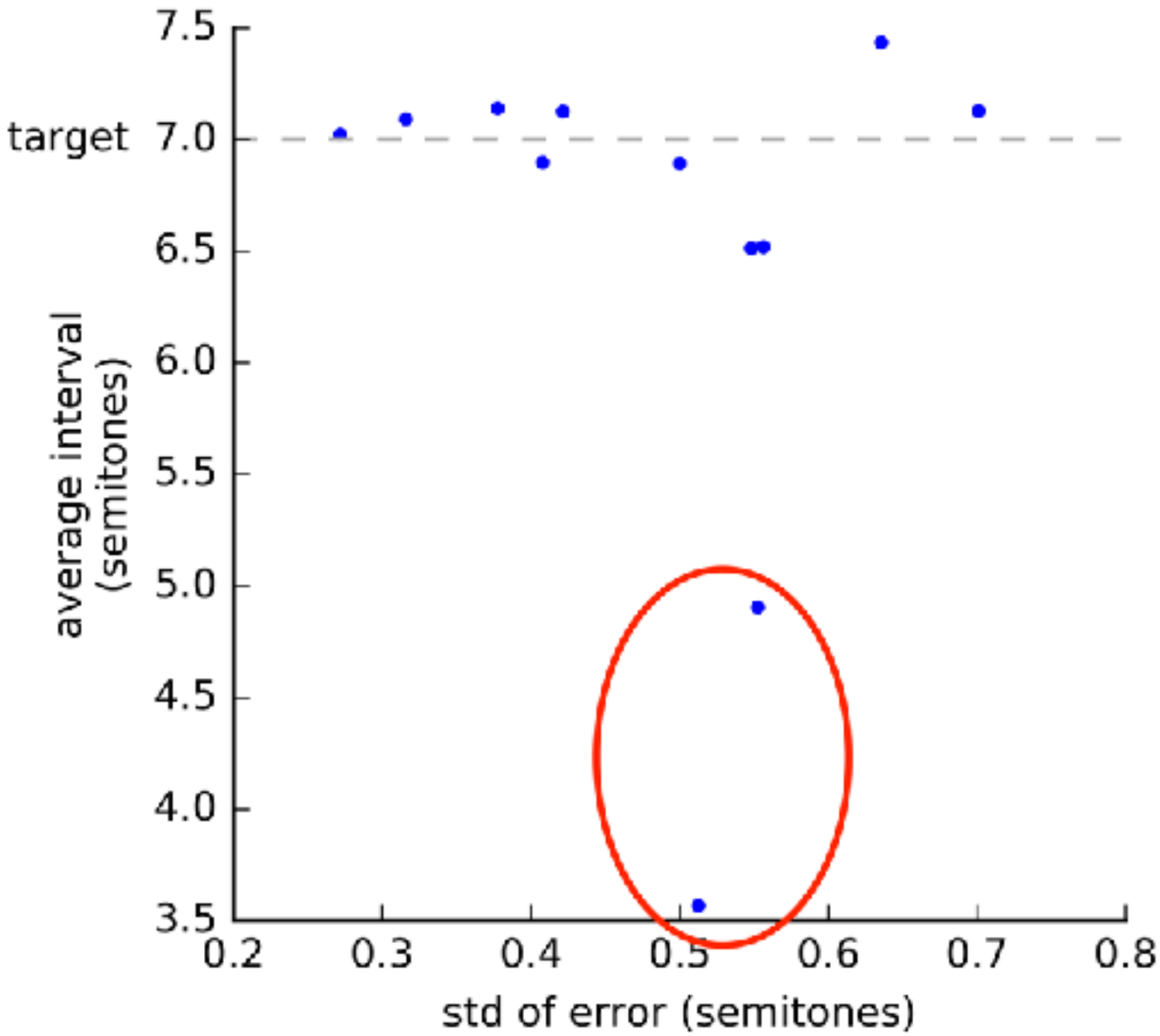

A189 stim3: 44.24s
dB
55
20
frequency (Hz)
pitch (Hz)
time (s)


A208 stim2: 17.3s
dB
45
20
stimulator
frequency (Hz)
pitch (Hz)
time (s)

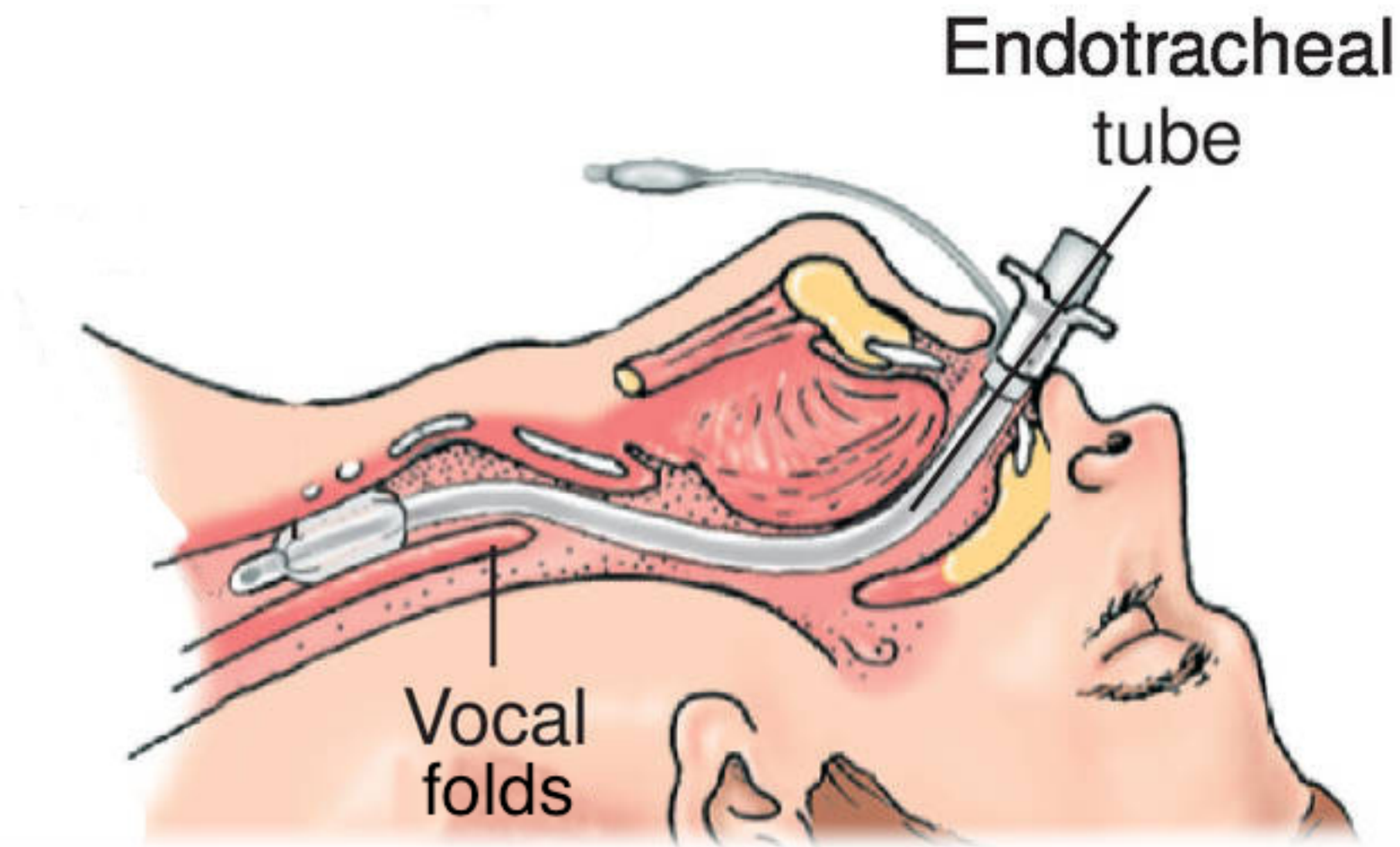

A208 stim1: 8.26s
dB
45
20
stimulator
frequency (Hz)
pitch (Hz)
time (s)


A189 stim2: 7.5s
dB
55
20
assistant
speaking
surgeon
speaking
frequency (Hz)
pitch (Hz)
time (s)

Singing behavior



Endotracheal tube with EMG



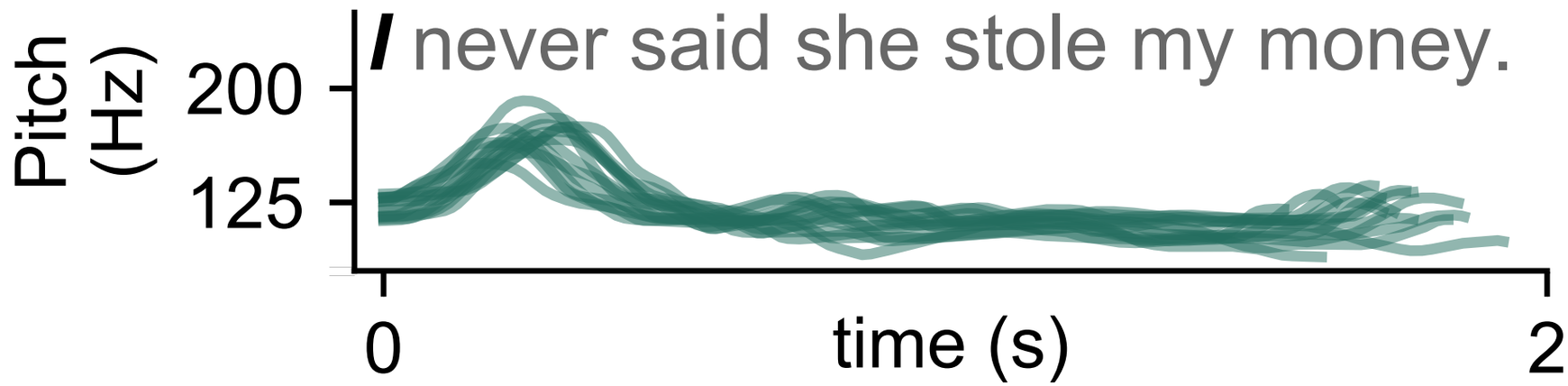
Contrastive emphasis task: vocal pitch encoding

I never said she stole my money.

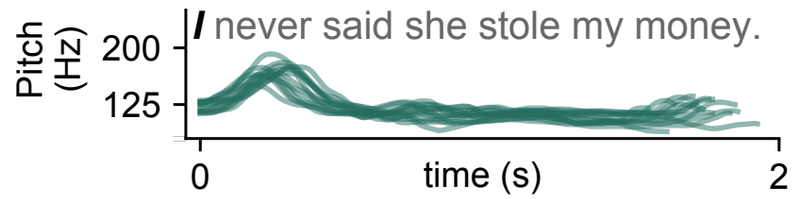
Contrastive emphasis task: vocal pitch encoding

I never said she stole my money.

Contrastive emphasis task: vocal pitch encoding



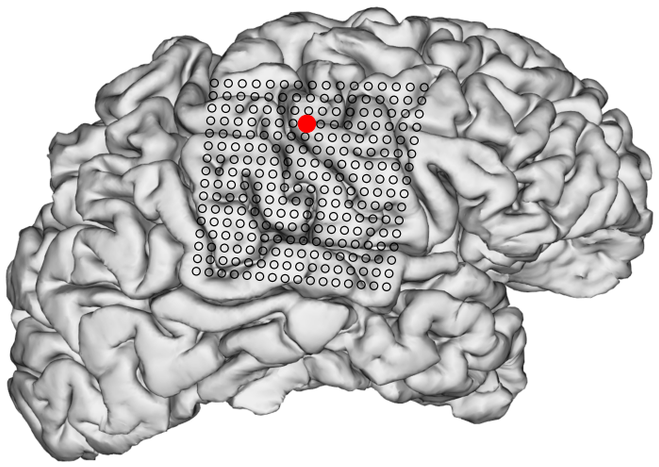
Contrastive emphasis task: vocal pitch encoding



Contrastive emphasis task: vocal pitch encoding

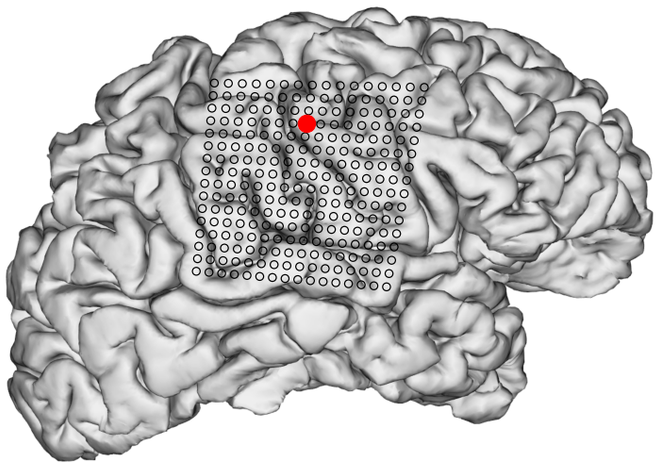
Contrastive emphasis task: vocal pitch encoding

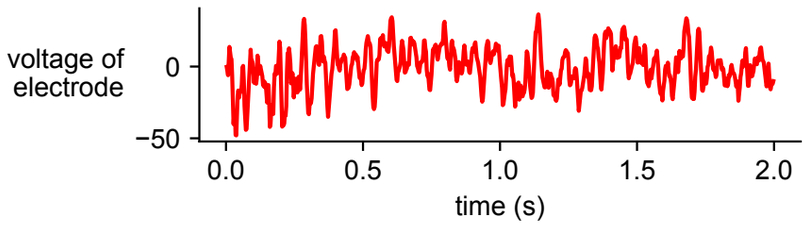
ECoG

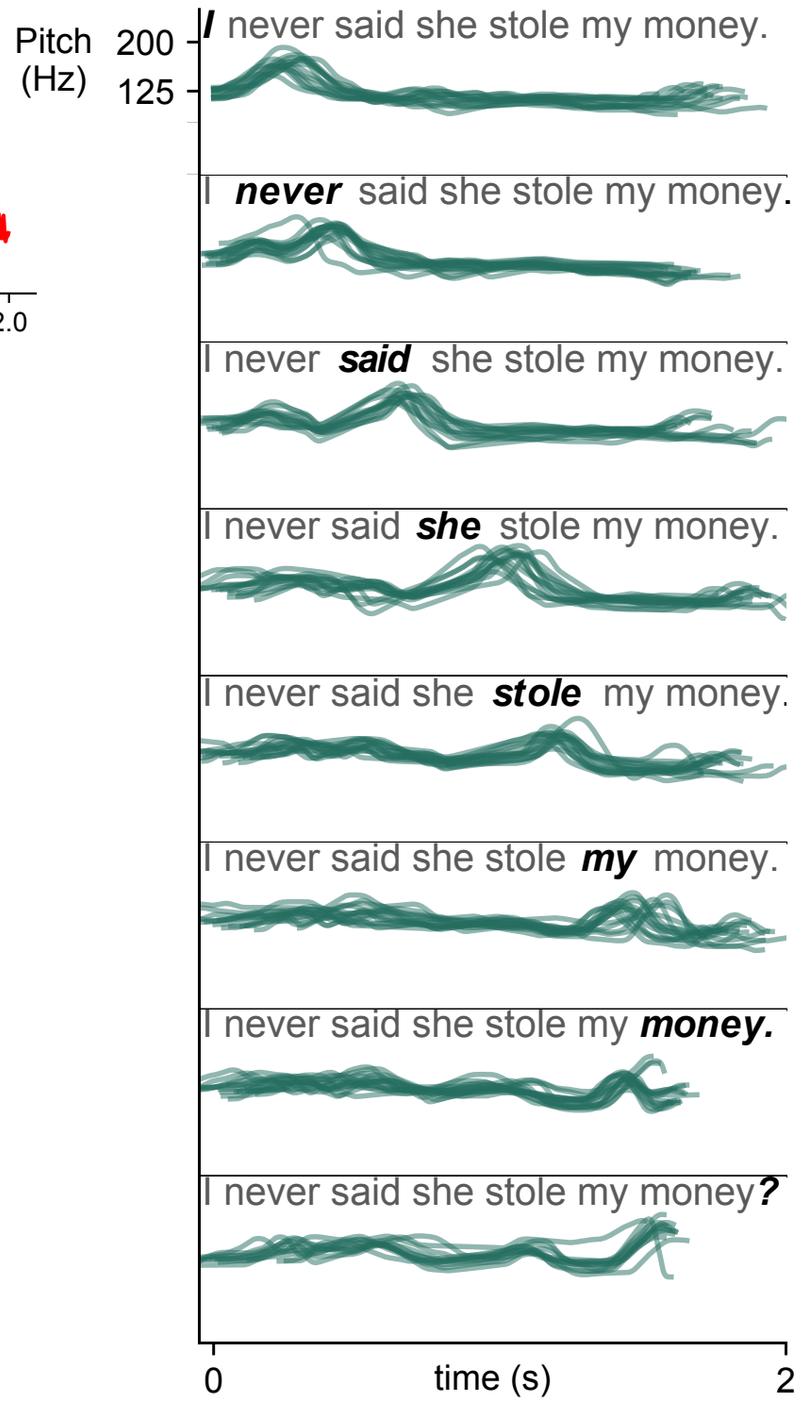


Contrastive emphasis task: vocal pitch encoding

ECoG

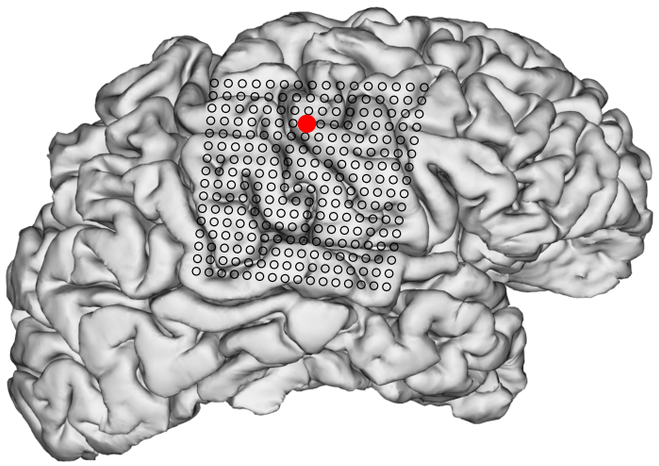


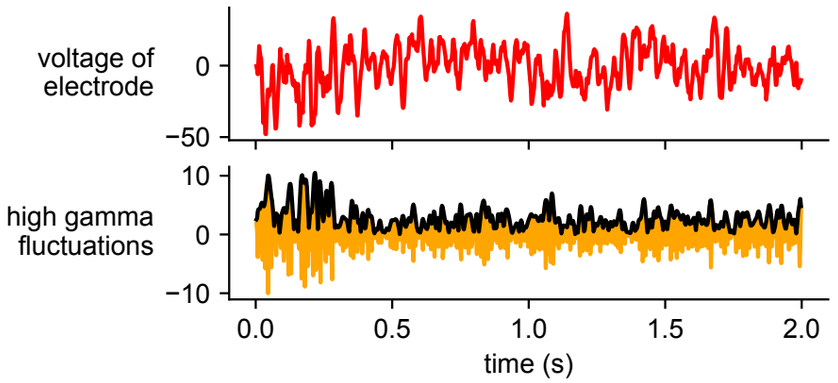




Contrastive emphasis task: vocal pitch encoding

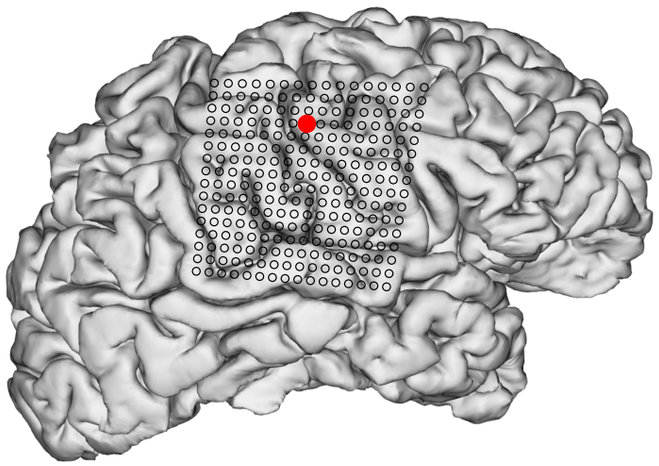
ECoG

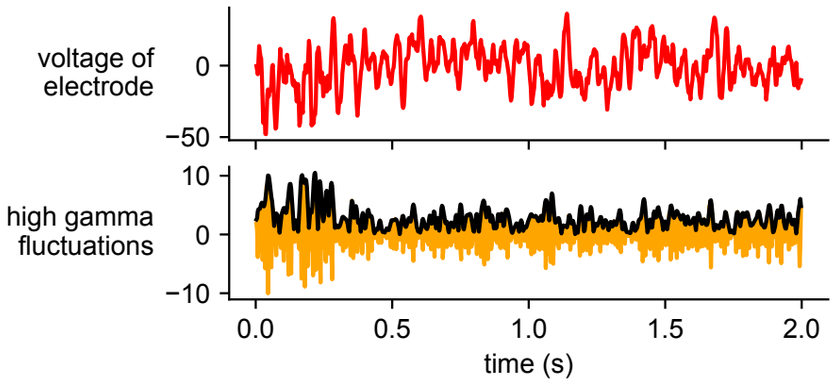




Contrastive emphasis task: vocal pitch encoding

ECoG

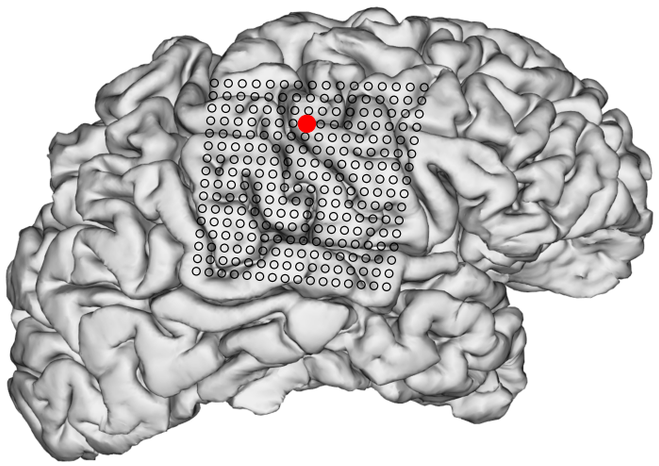


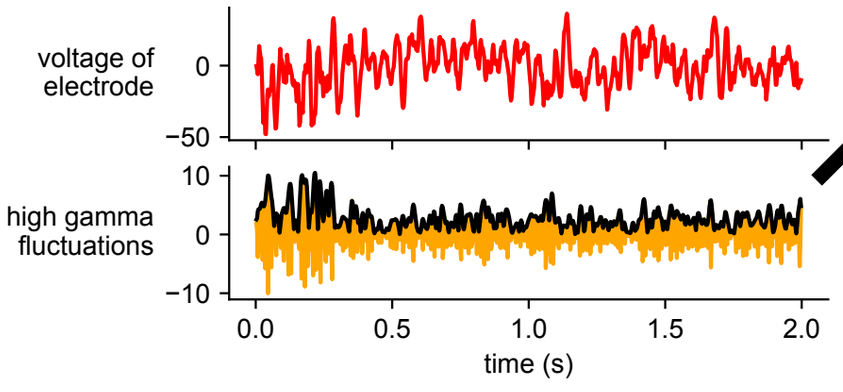


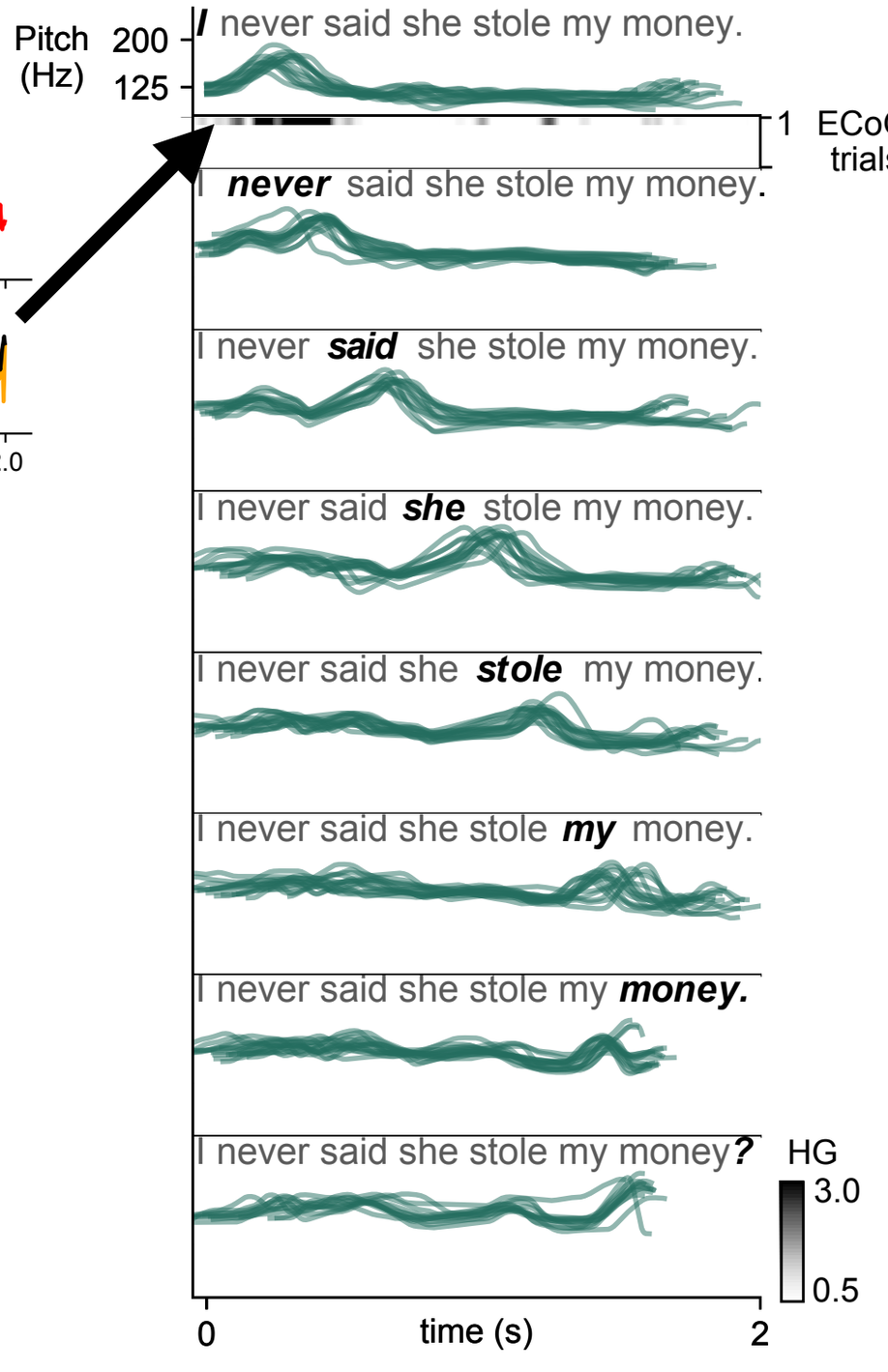
Correlates with firing rate of neuron (Ray and Mansell, 2011) and speech movements (Bouchard et al. 2013)

Contrastive emphasis task: vocal pitch encoding

ECoG



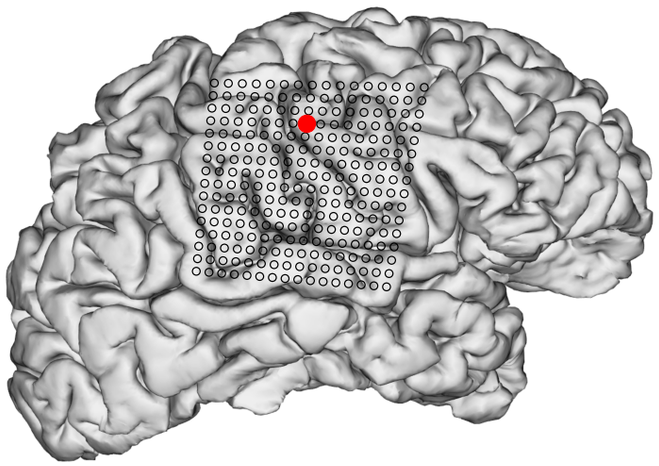


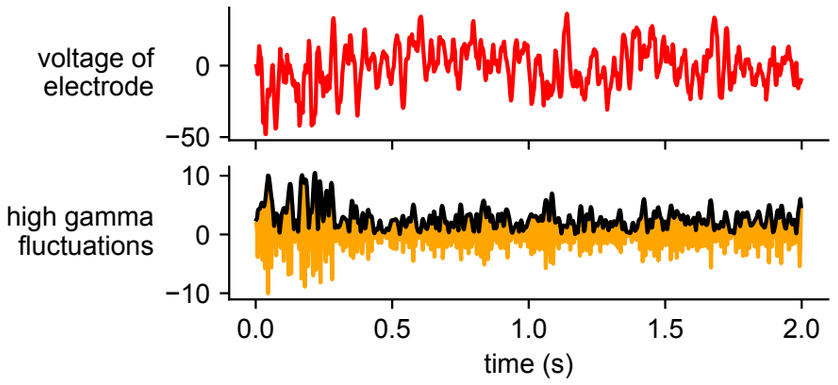


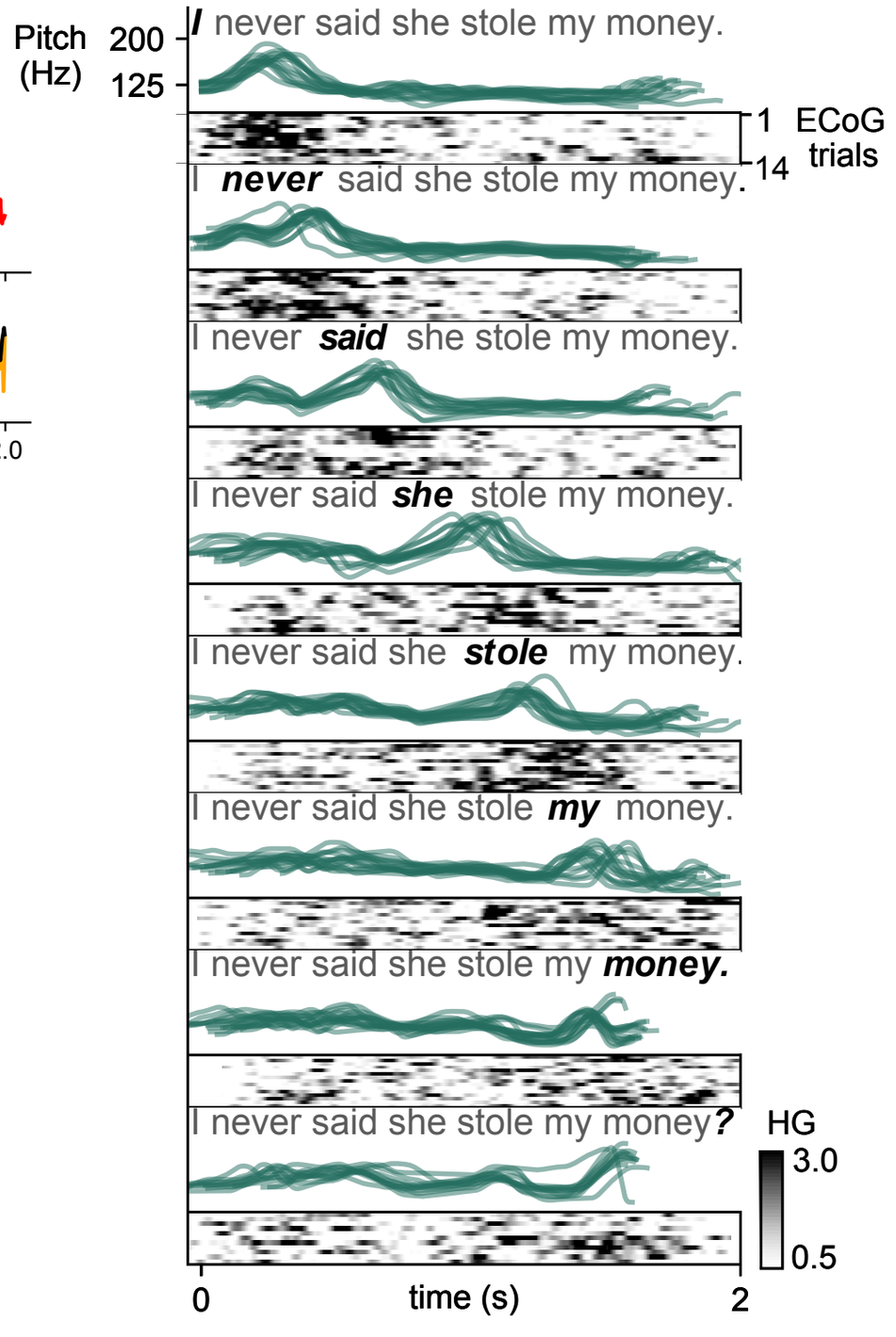
Correlates with firing rate of neuron (Ray and Mansell, 2011) and speech movements (Bouchard et al. 2013)

Contrastive emphasis task: vocal pitch encoding

ECoG





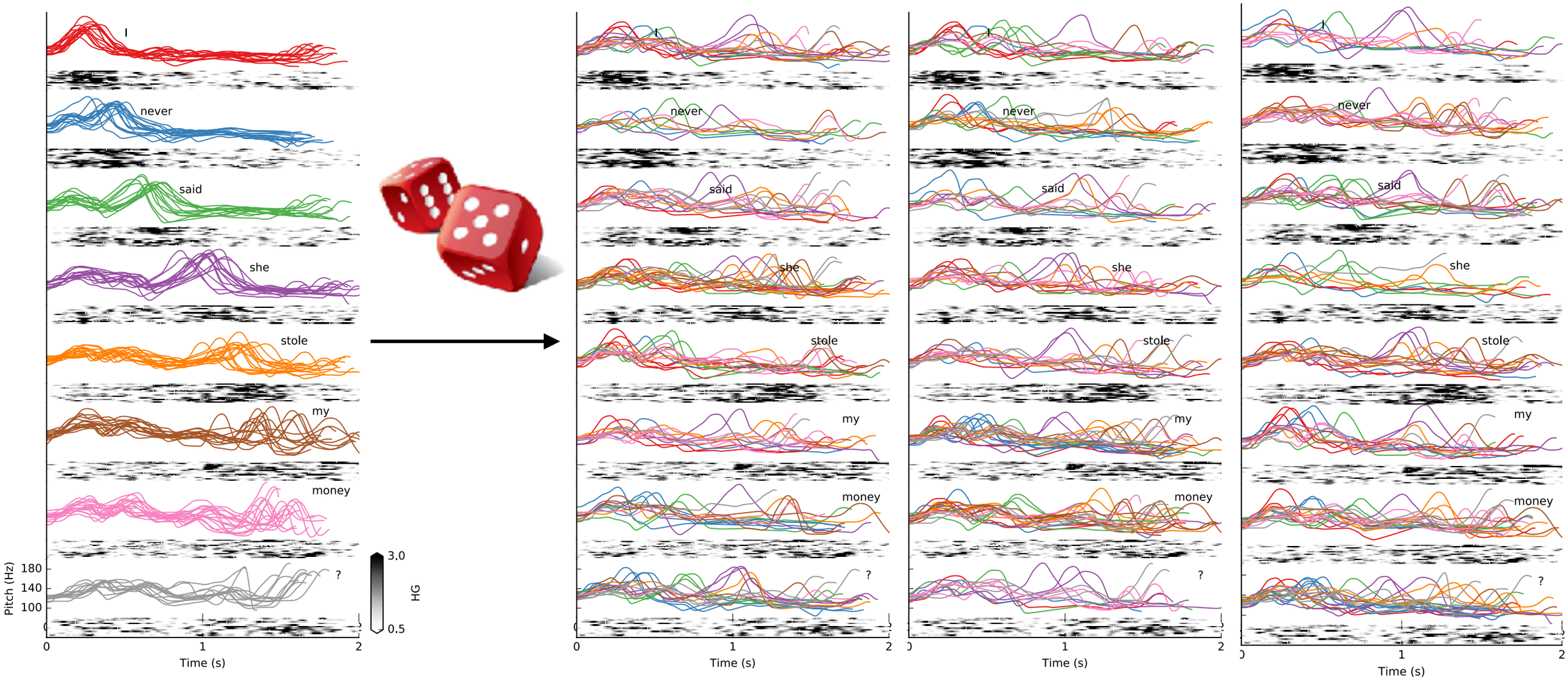


Correlates with firing rate of neuron (Ray and Mansell, 2011) and speech movements (Bouchard et al. 2013)

Roadmap for representation of pitch

- Control of vocal pitch production
  - In speech
  - In song
    - Cortical stimulation
- Pitch intonation perception in speech

Sentence timing: permutation test



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