

Guiding auditory neuroscience through in-silico experiments

Sam Norman-Haignere

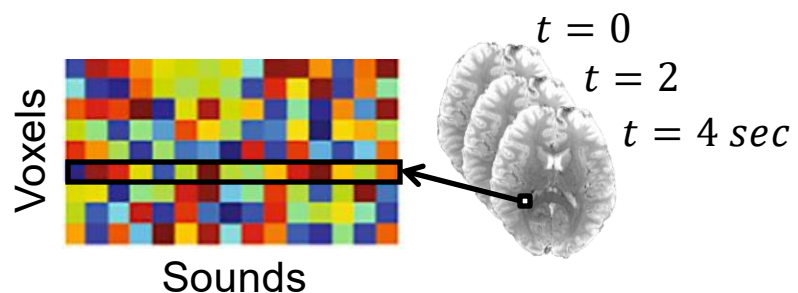
Associate Professor, University of Rochester Medical Center

Biostatistics & Computational Biology (Primary), Neuroscience (Primary)

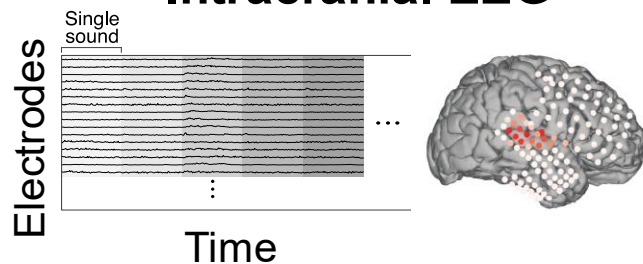
Brain & Cognitive Sciences, Biomedical Engineering

Neural recordings

Functional MRI



Intracranial EEG

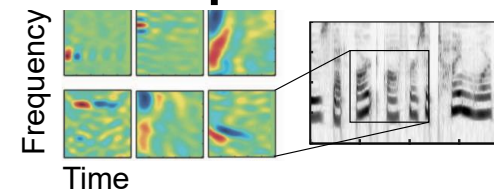


Experimental measures

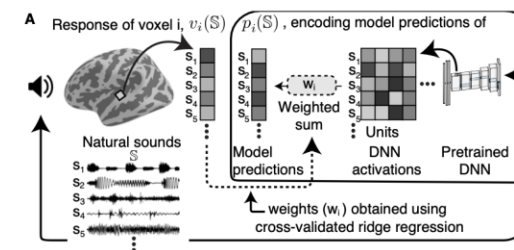
Temporal integration
Acoustic invariance
...

Computational models

Spectrotemporal receptive field



Deep neural networks



In-silico experimentation

Key properties:

1. Cheap, large-scale, noise-free
2. Full model access and knowledge (e.g., weights, gradients)
3. Experiments can be performed on virtually any model or brain response

Benefits:

1. Supportive of scientific curiosity & exploration
2. Validation of new experimental methods
3. Hypothesis generation
4. Entirely new kinds of experiments (e.g., synthesis, population control)
5. Enables direct brain-model comparisons (also model-model comparisons)
6. Experiments = scientific understanding

In-silico experimentation

Key properties:

1. **Cheap, large-scale, noise-free**
2. Full model access and knowledge (e.g., weights, gradients)
3. Experiments can be performed on virtually any model or brain response

Benefits:

1. **Supportive of scientific curiosity & exploration**
2. **Validation of new experimental methods**
3. **Hypothesis generation**
4. Entirely new kinds of experiments (e.g., synthesis, population control)
5. Enables direct brain-model comparisons (also model-model comparisons)
6. Experiments = scientific understanding

In-silico experimentation

Key properties:

1. Cheap, large-scale, noise-free
2. **Full model access and knowledge (e.g., weights, gradients)**
3. Experiments can be performed on virtually any model or brain response

Benefits:

1. Supportive of scientific curiosity & exploration
2. Validation of new experimental methods
3. Hypothesis generation
4. **Entirely new kinds of experiments (e.g., synthesis, population control)**
5. Enables direct brain-model comparisons (also model-model comparisons)
6. Experiments = scientific understanding

In-silico experimentation

Key properties:

1. Cheap, large-scale, noise-free
2. Full model access and knowledge (e.g., weights, gradients)
3. **Experiments can be performed on virtually any model or brain response**

Benefits:

1. Supportive of scientific curiosity & exploration
2. Validation of new experimental methods
3. Hypothesis generation
4. Entirely new kinds of experiments (e.g., synthesis, population control)
5. **Enables direct brain-model comparisons (also model-model comparisons)**
6. Experiments = scientific understanding

In-silico experimentation

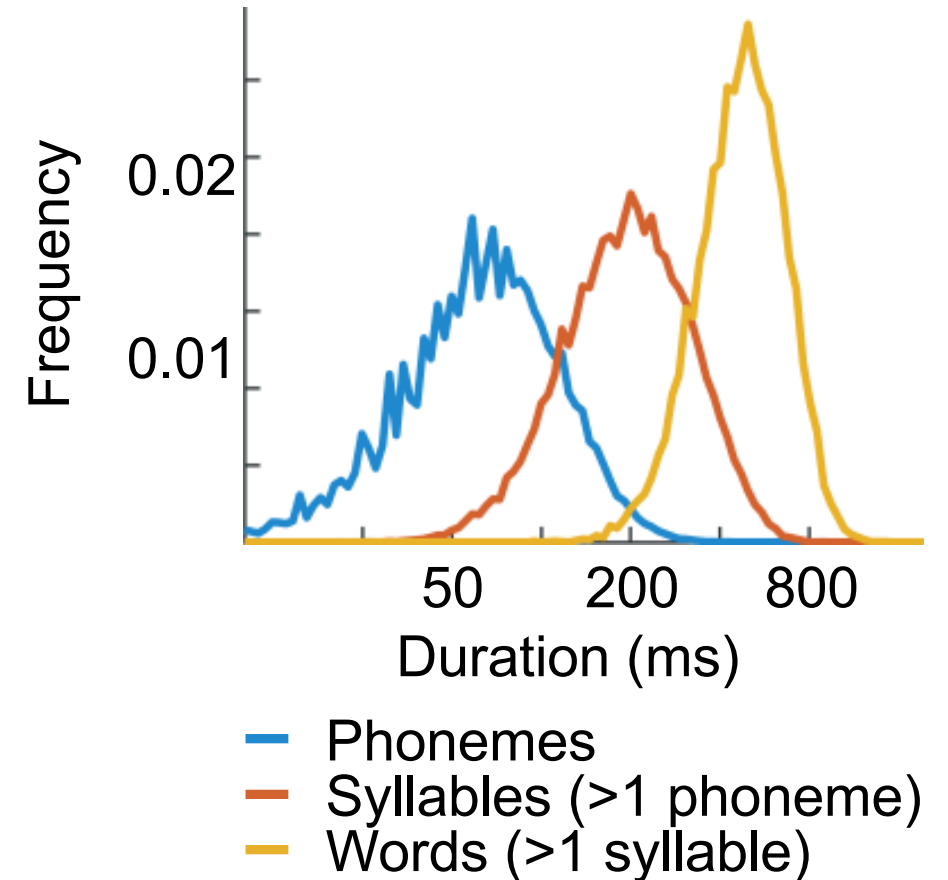
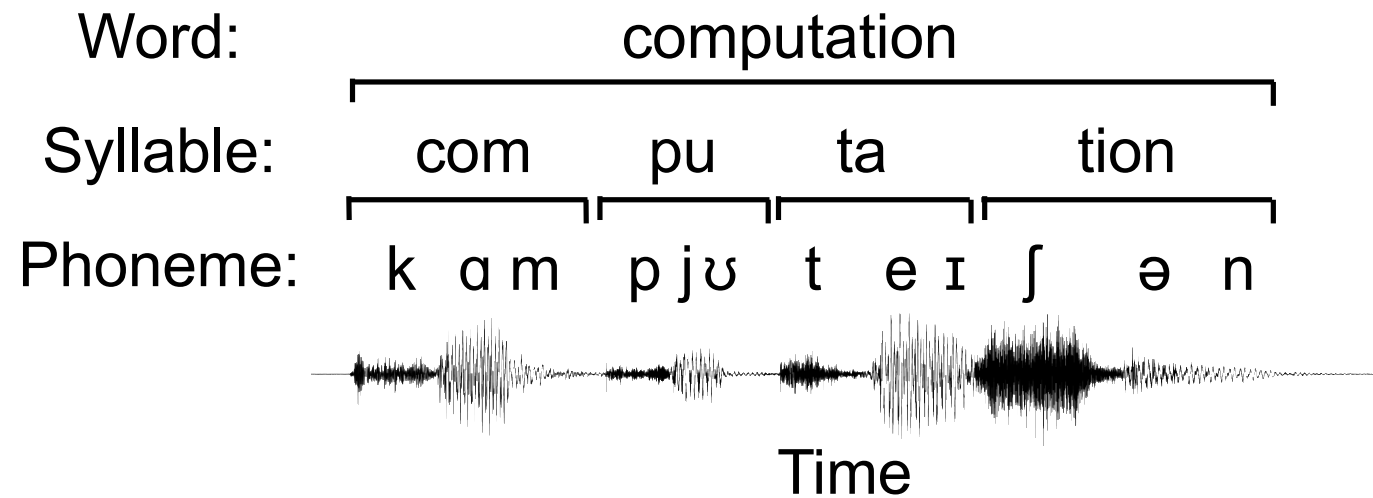
Key properties:

1. Cheap, large-scale, noise-free
2. Full model access and knowledge (e.g., weights, gradients)
3. Experiments can be performed on virtually any model or brain response

Benefits:

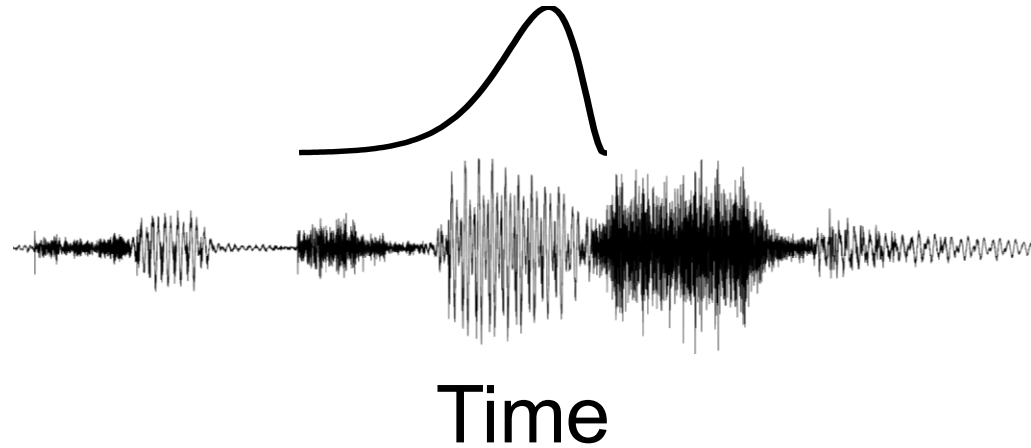
1. Supportive of scientific curiosity & exploration
2. Validation of new experimental methods
3. Hypothesis generation
4. Entirely new kinds of experiments (e.g., synthesis, population control)
5. Enables direct brain-model comparisons (also model-model comparisons)
6. **Experiments = scientific understanding**

Multiscale temporal integration



Integration window

Time window when stimuli alter the neural response
(Theunissen & Miller, 1995)

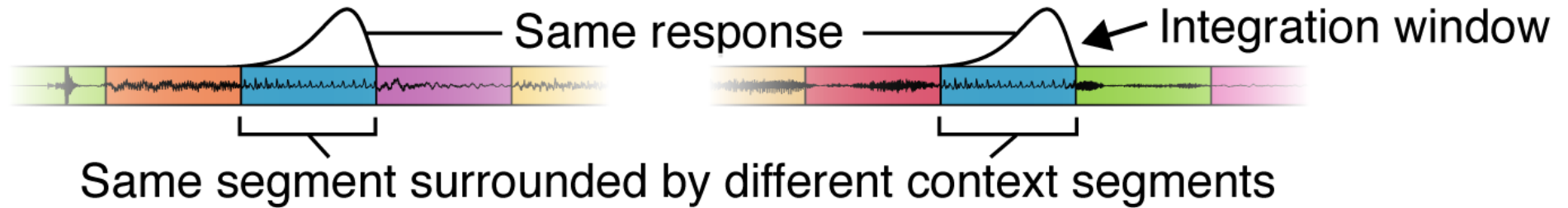


Temporal context invariance paradigm

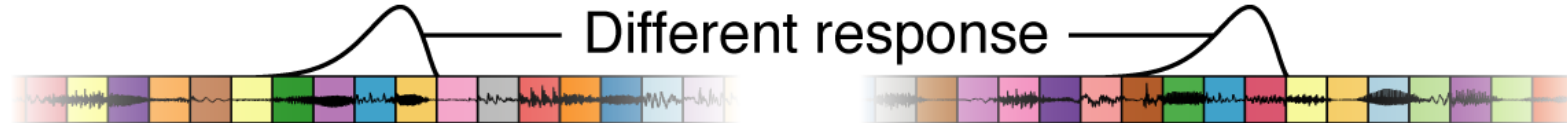


Temporal context invariance paradigm

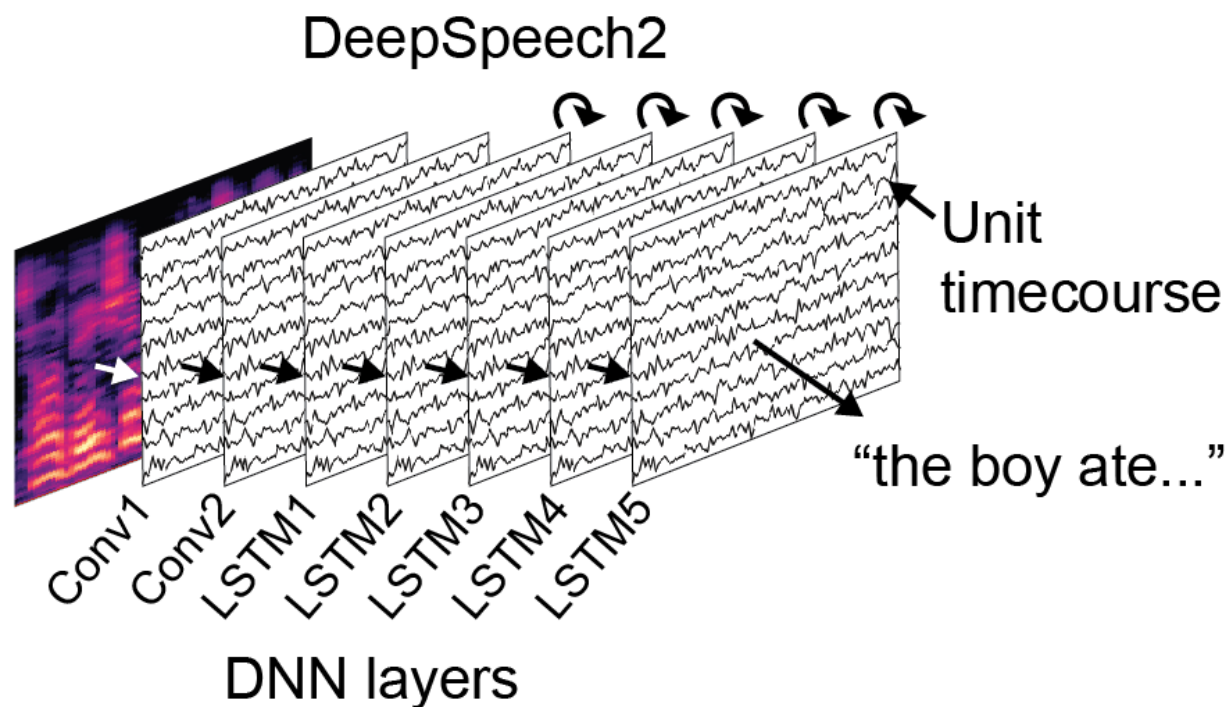
Segment duration > Integration window



Segment duration < Integration window



Develop Methods & Hypotheses using Deep Artificial Neural Networks (DANNs)

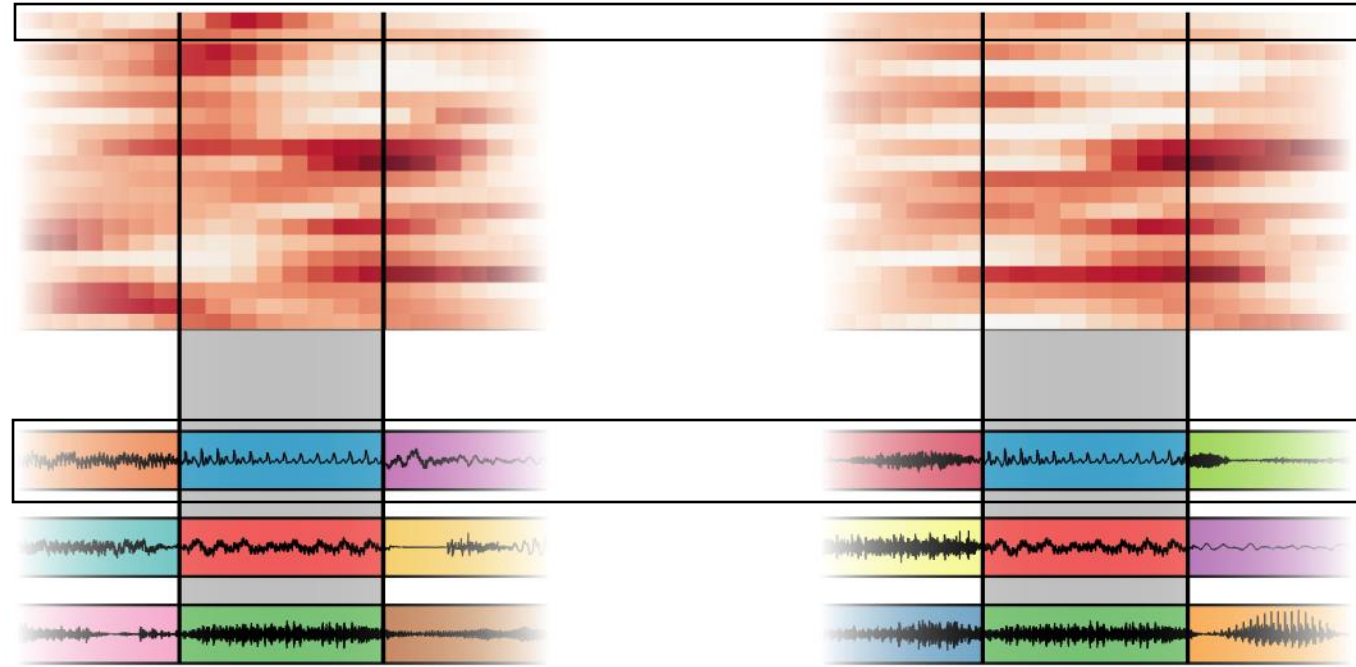


Menoua Keshishian

Keshishian et al., 2021, *NeurIPS*

Cross-context correlation (CCC)

All segments of a single duration

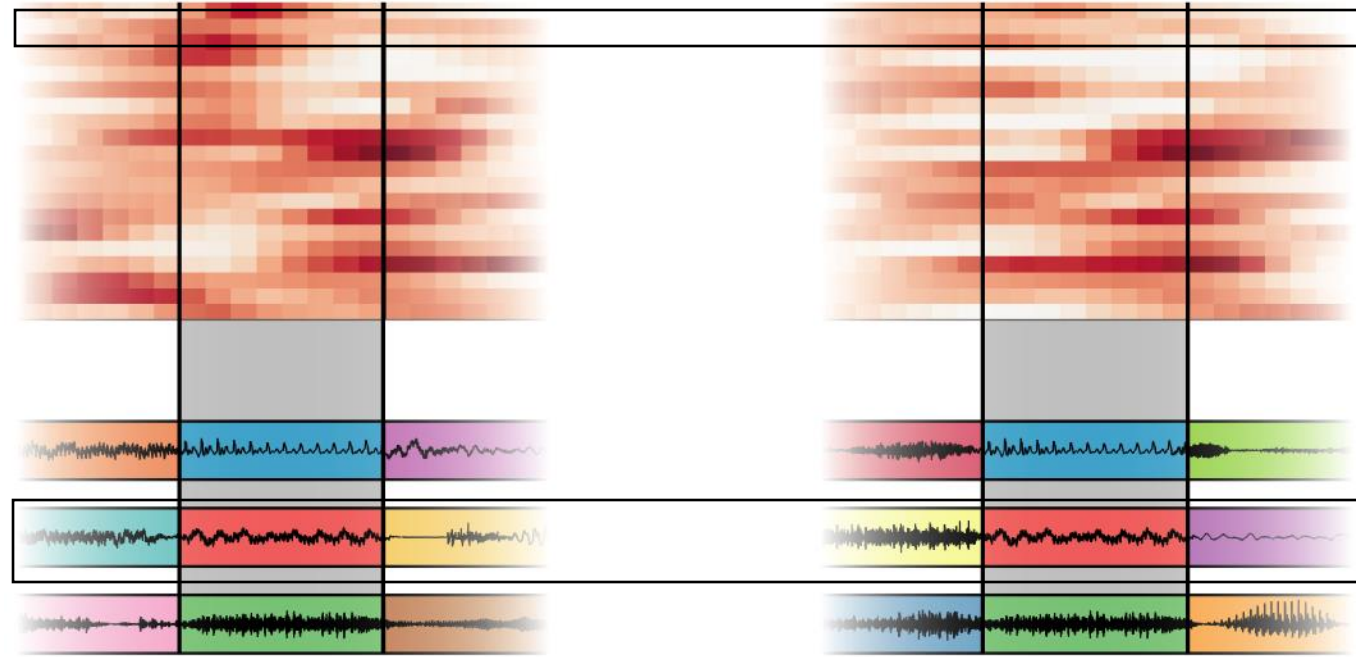


Same segments in different contexts

Response magnitude: 

Cross-context correlation (CCC)

All segments of a single duration

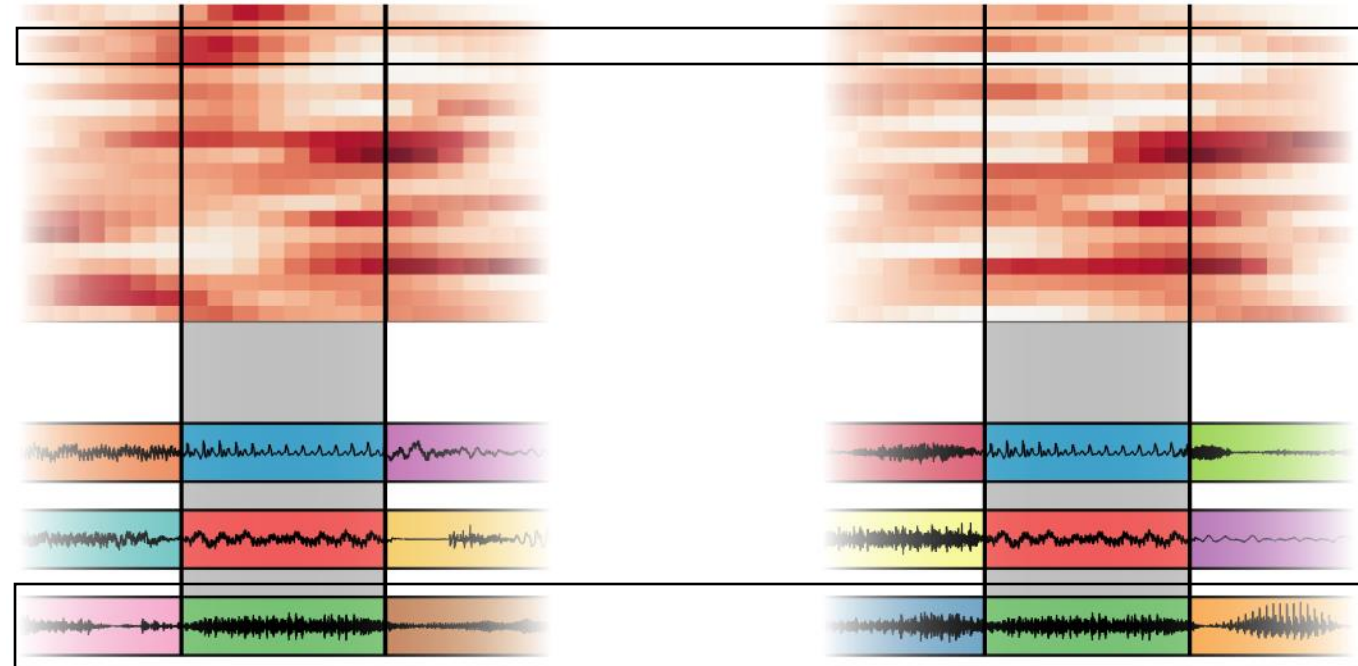


Same segments in different contexts

Response magnitude: 

Cross-context correlation (CCC)

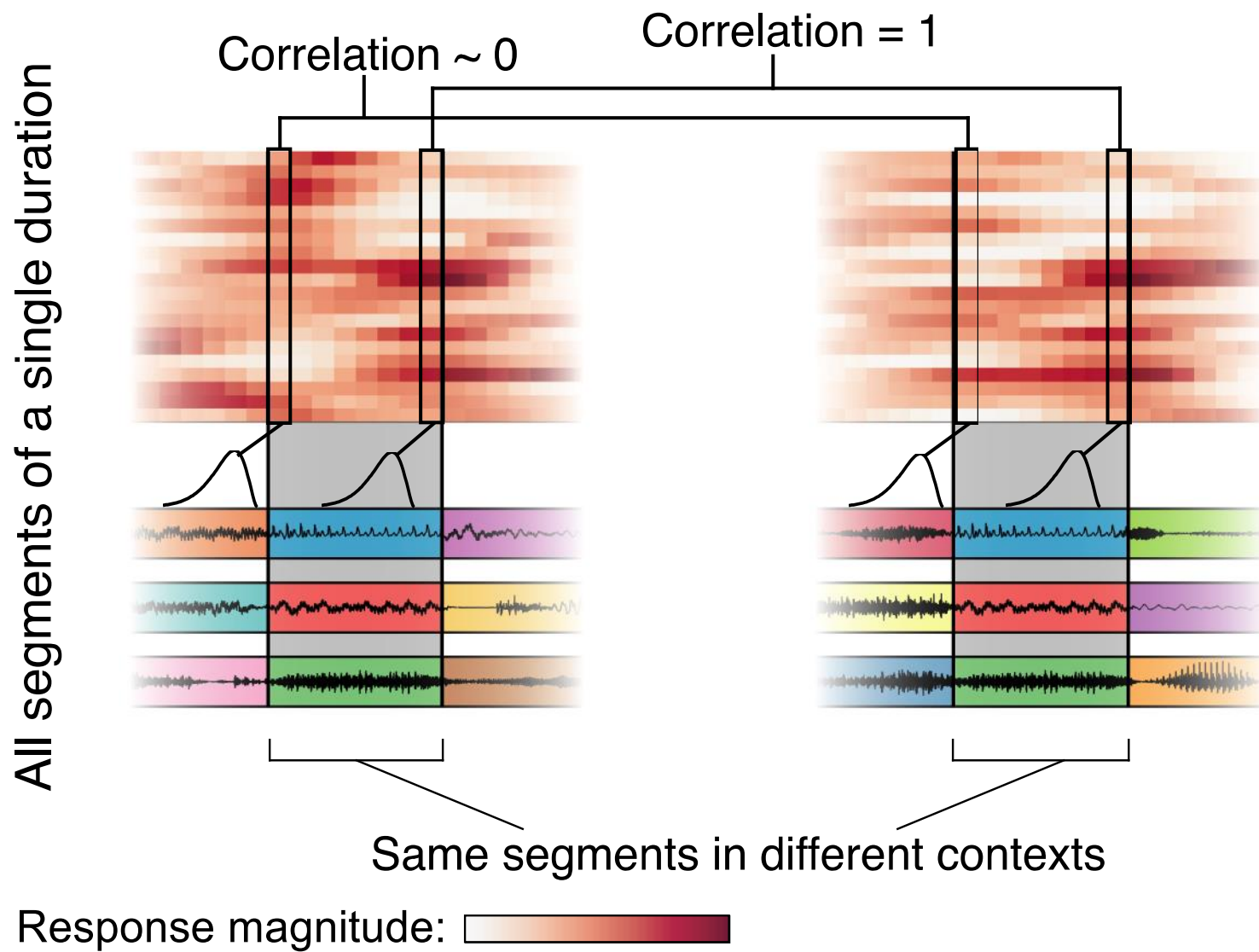
All segments of a single duration



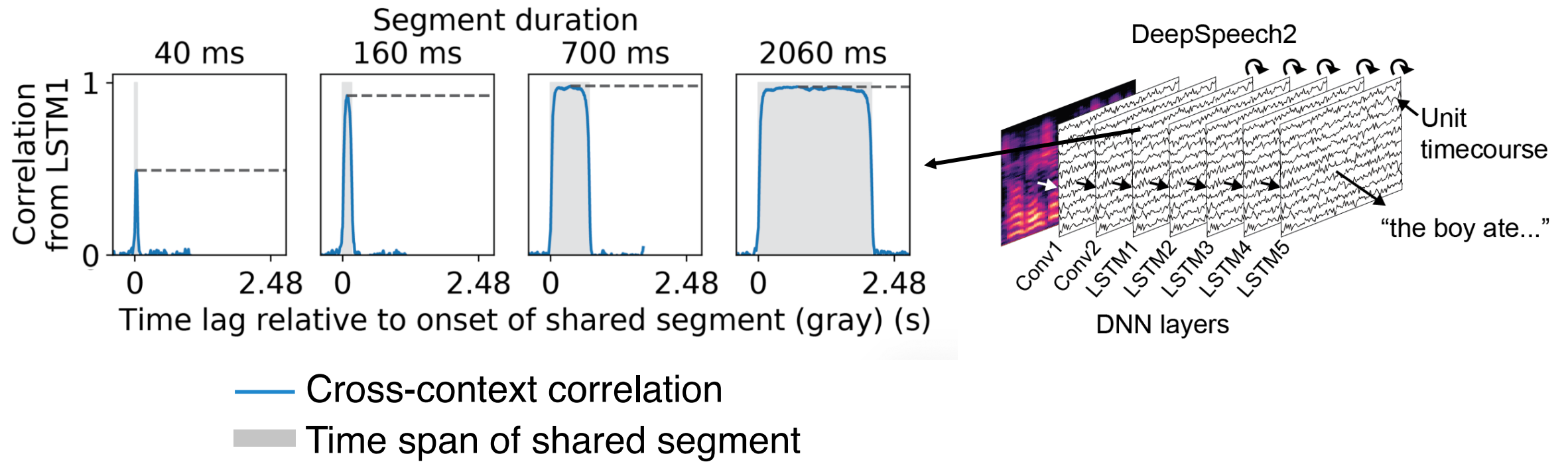
Same segments in different contexts

Response magnitude: 

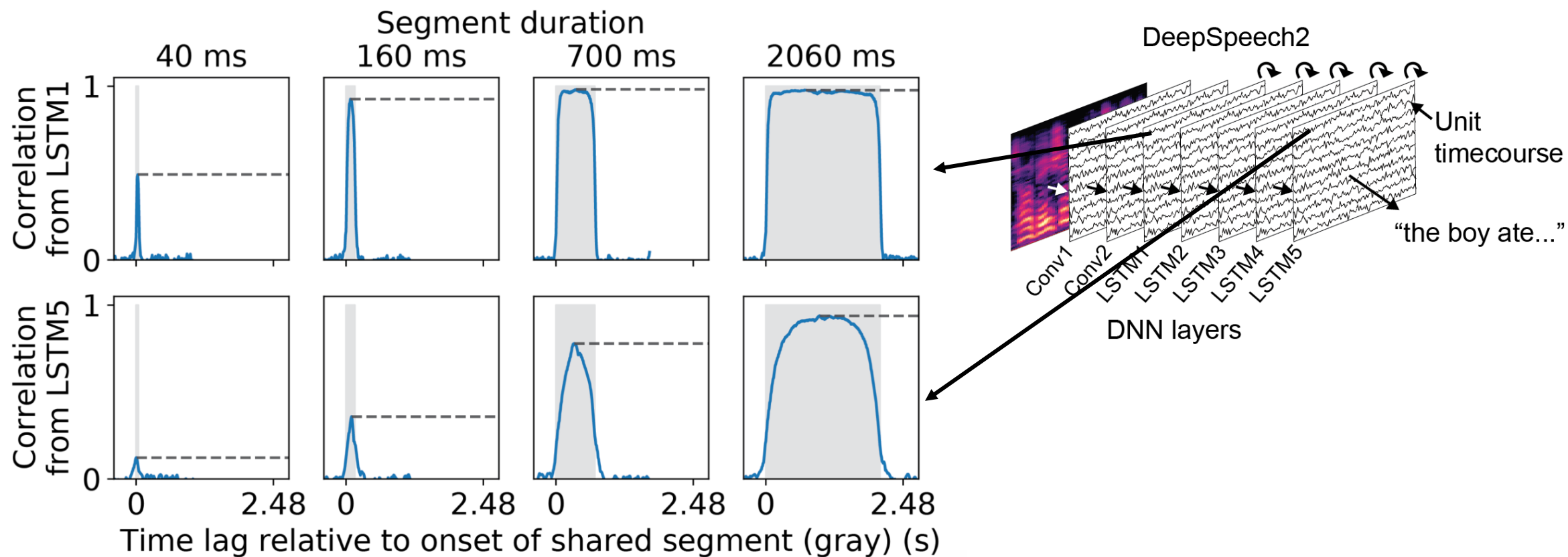
Cross-context correlation (CCC)



Cross-context correlation (CCC) from individual DANN units

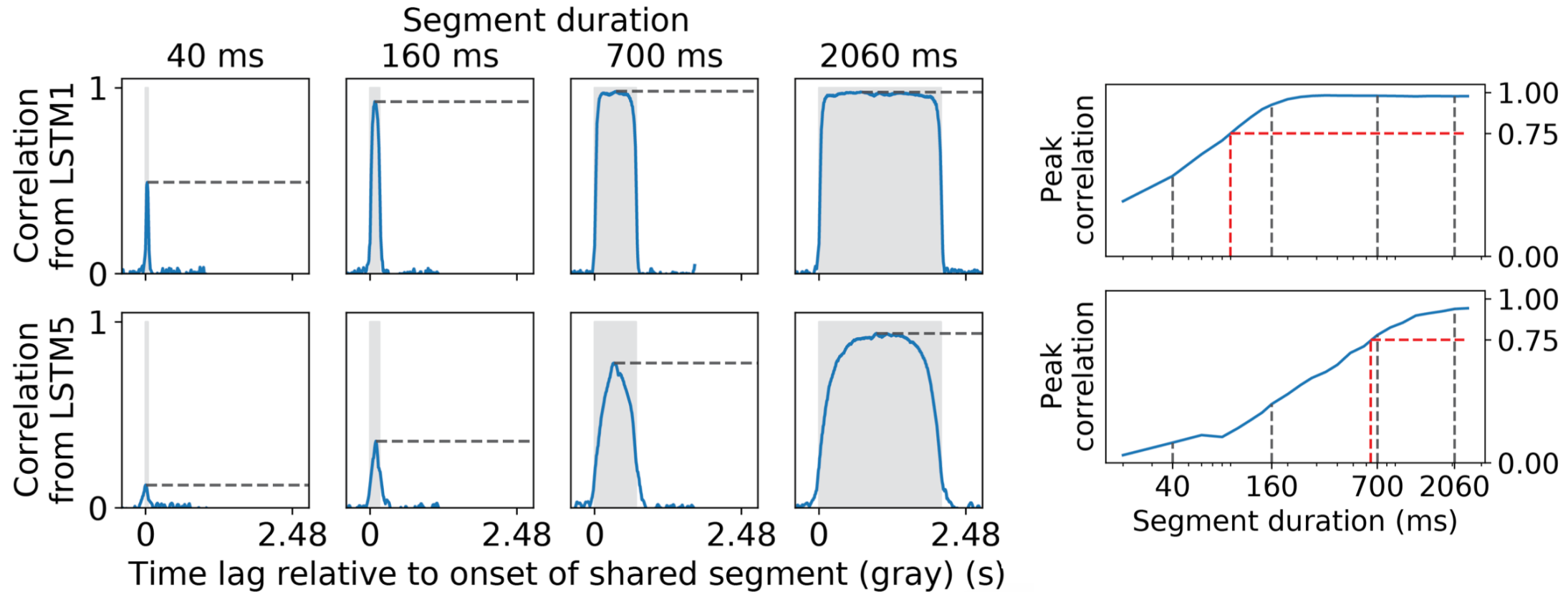


Cross-context correlation (CCC) from individual DANN units



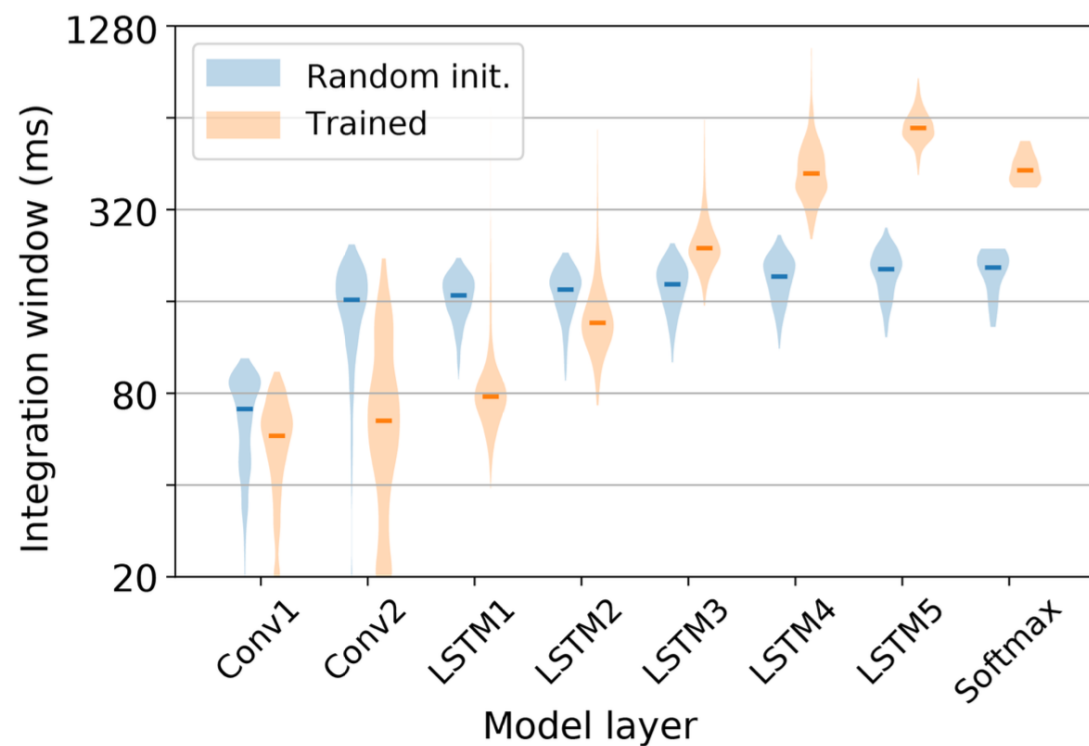
- Cross-context correlation
- Time span of shared segment

Cross-context correlation (CCC) from individual DANN units



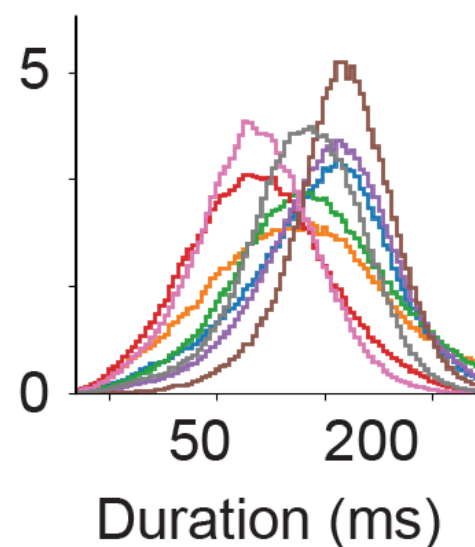
Integration window: smallest segment that achieves threshold invariance level (CCC=0.75)

DANN integration windows



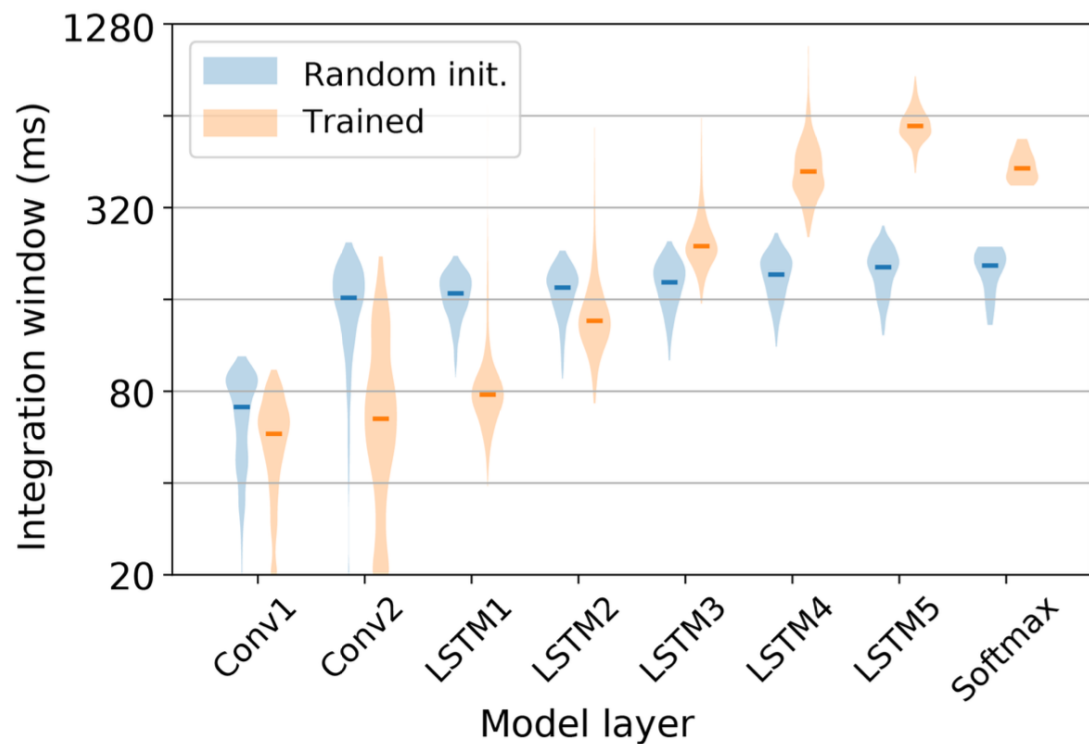
Time- or structure-yoked?

Histogram of phoneme durations

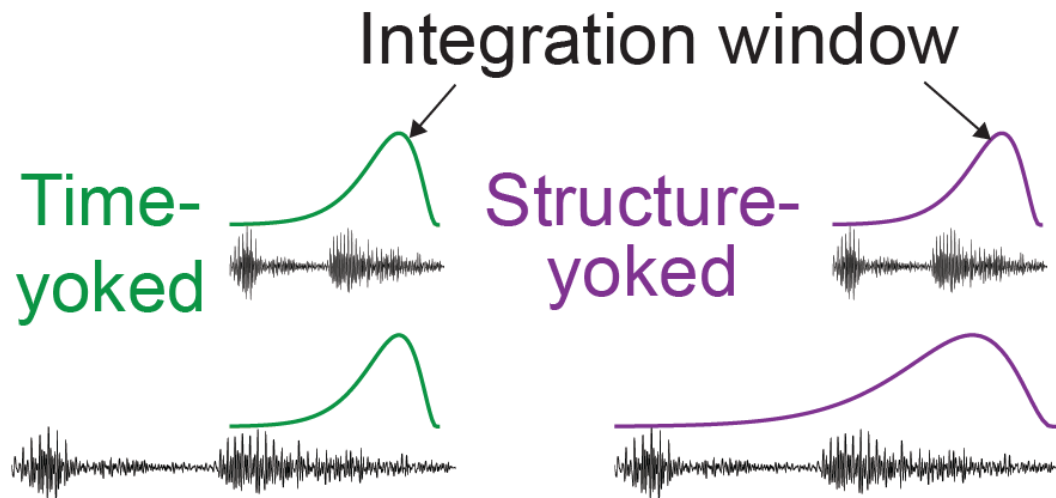


DNN ***learns*** to integrate hierarchically across layers for natural speech

DANN integration windows

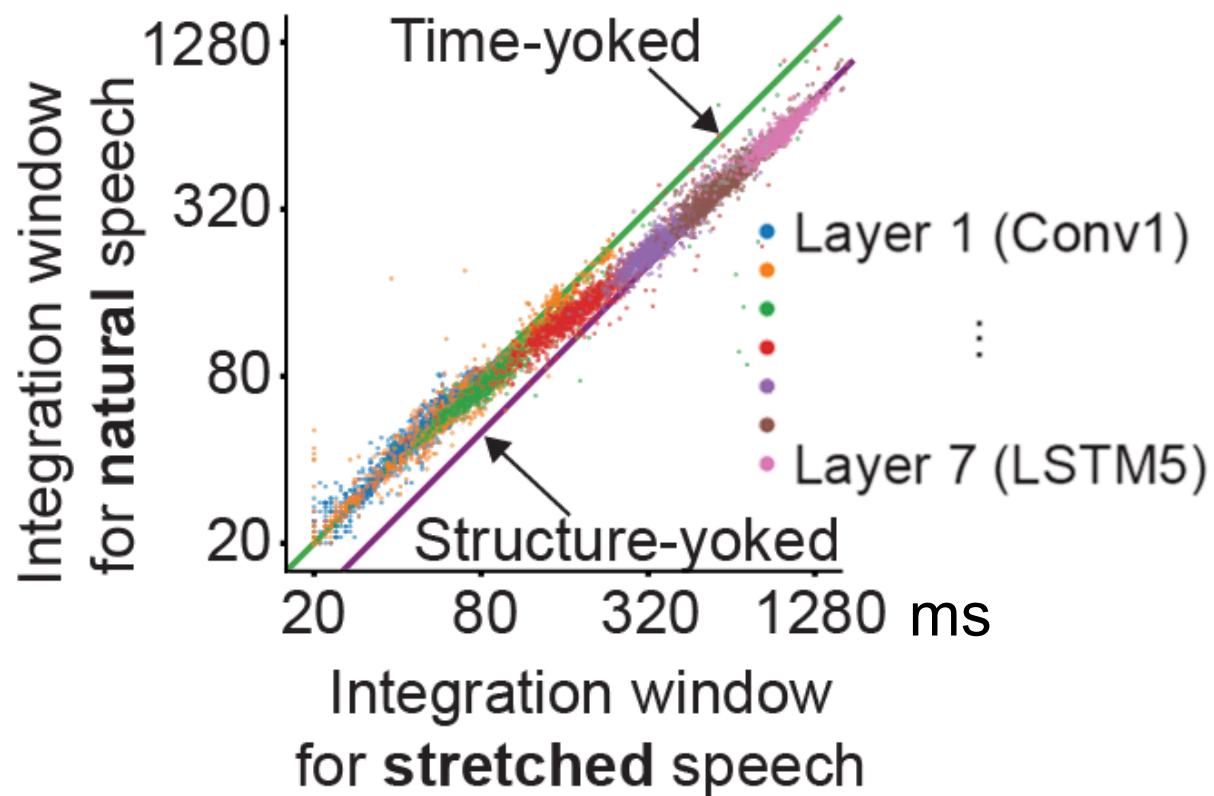


Time- or structure-yoked?

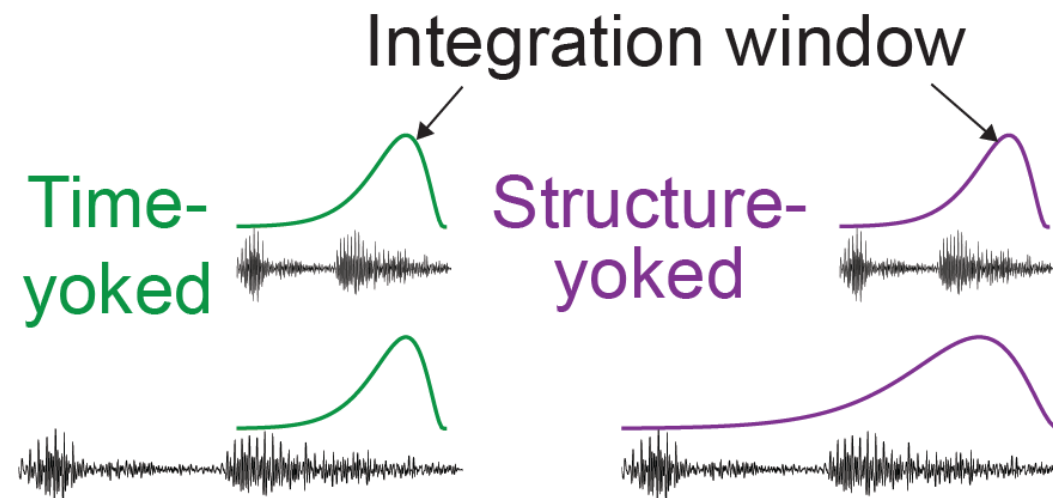


DNN ***learns*** to integrate hierarchically across layers for natural speech

DANN integration windows

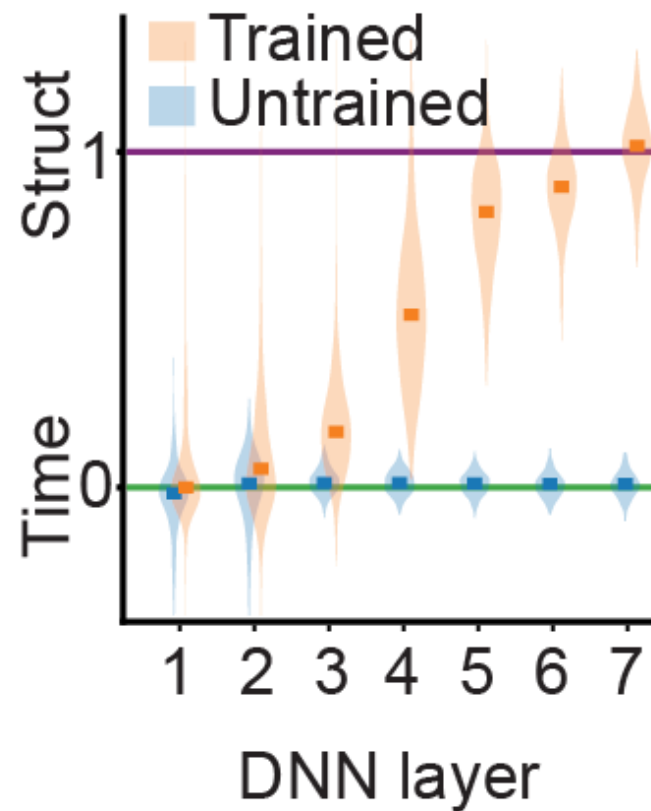
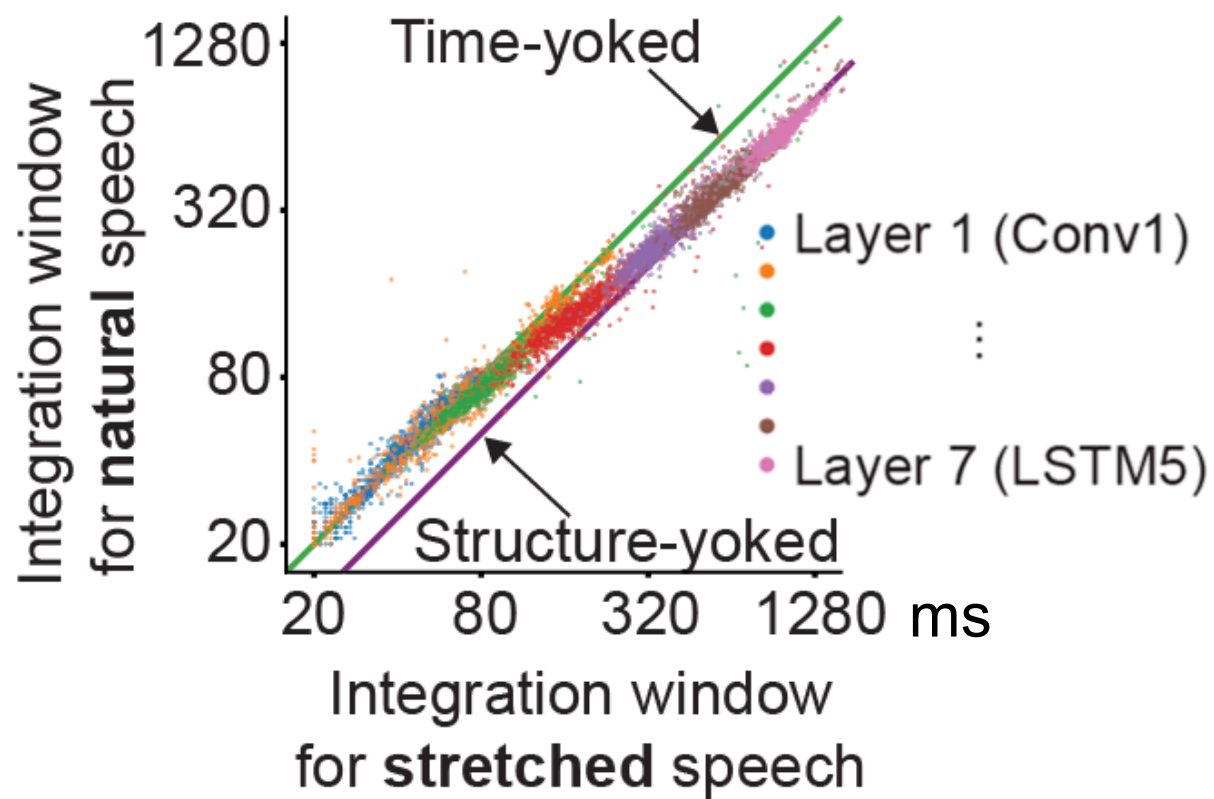


Time- or structure-yoked?



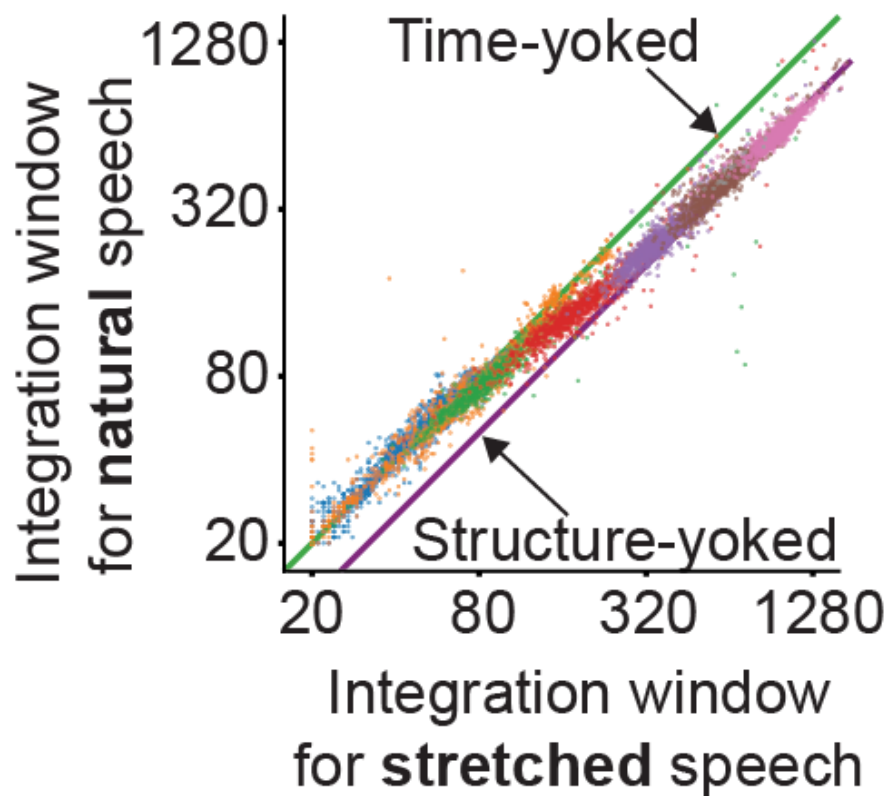
Transition from time- to structure-yoked integration across DNN layers

DANN integration windows

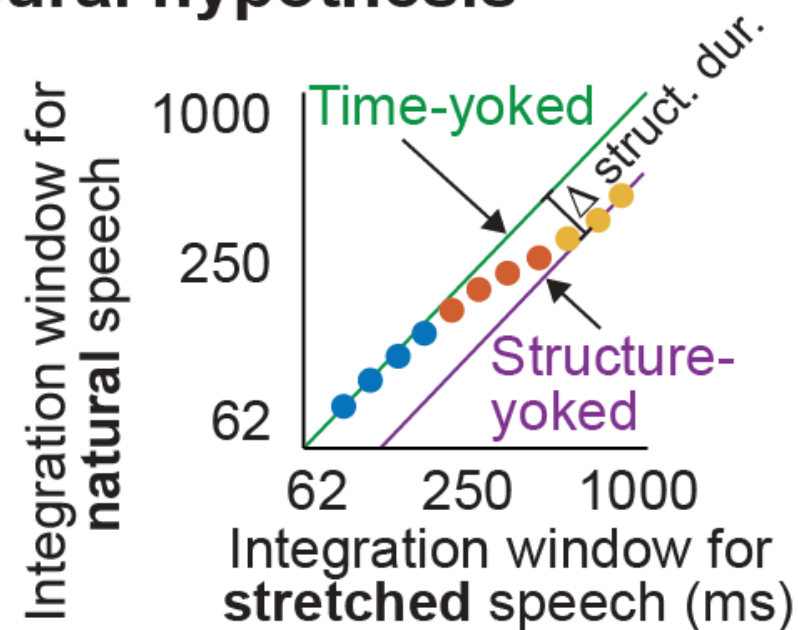
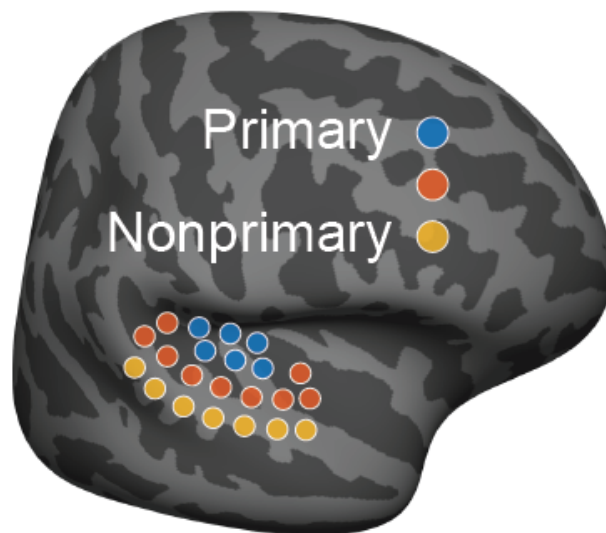


Transition from time- to structure-yoked integration across DNN layers

DANN integration windows

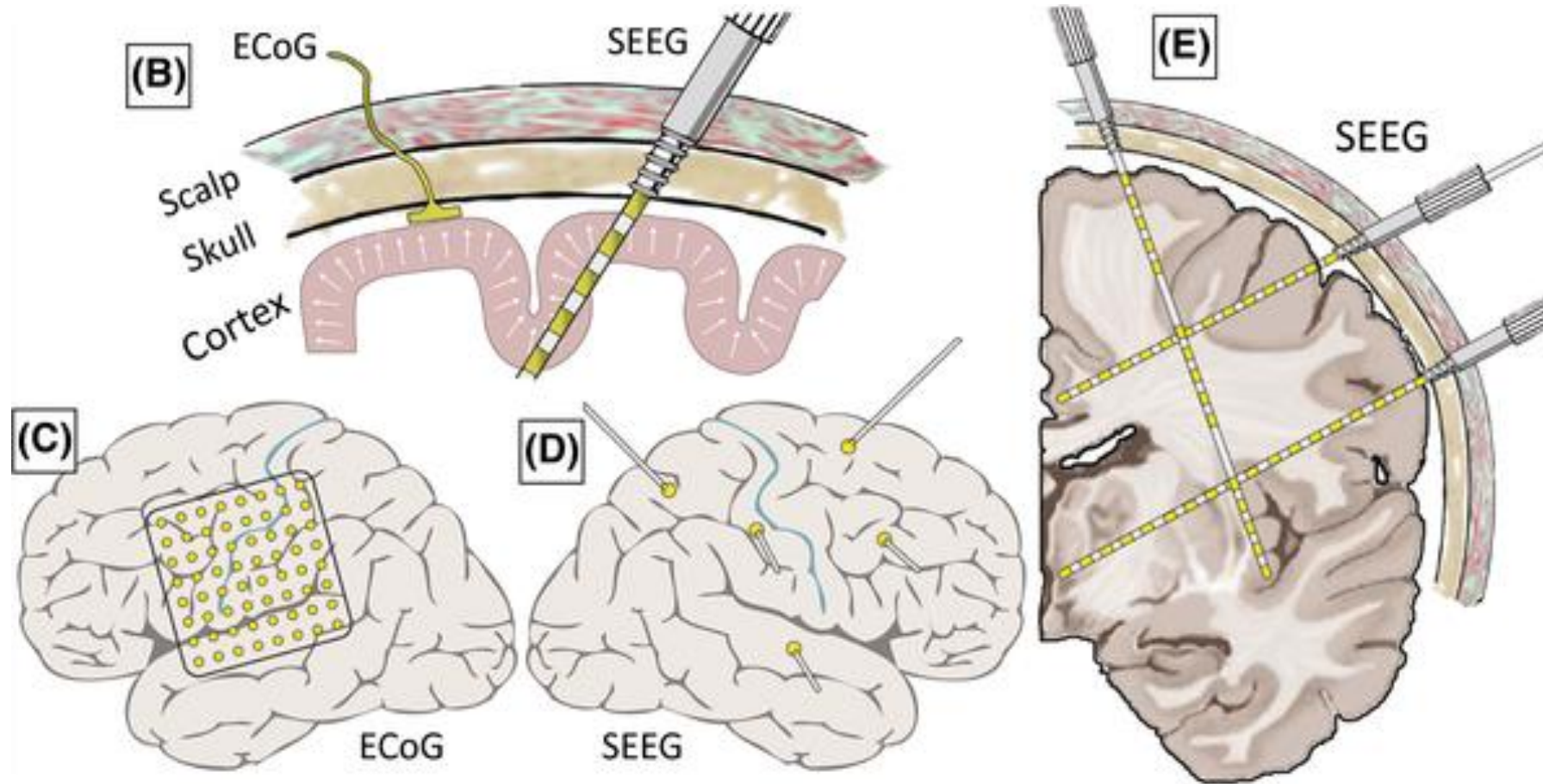


DNN-motivated neural hypothesis

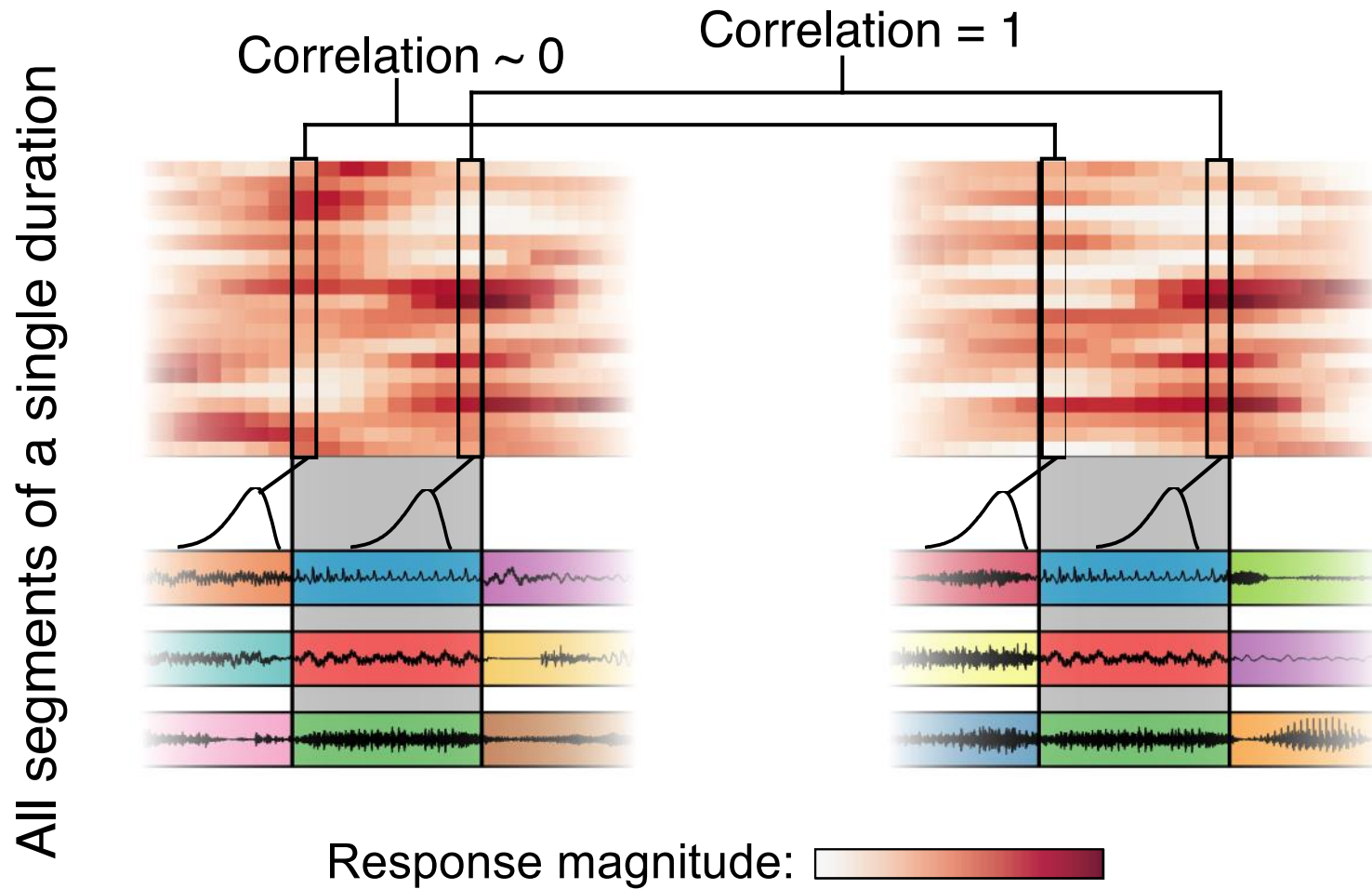


Similar organization in the auditory cortex?

Intracranial EEG

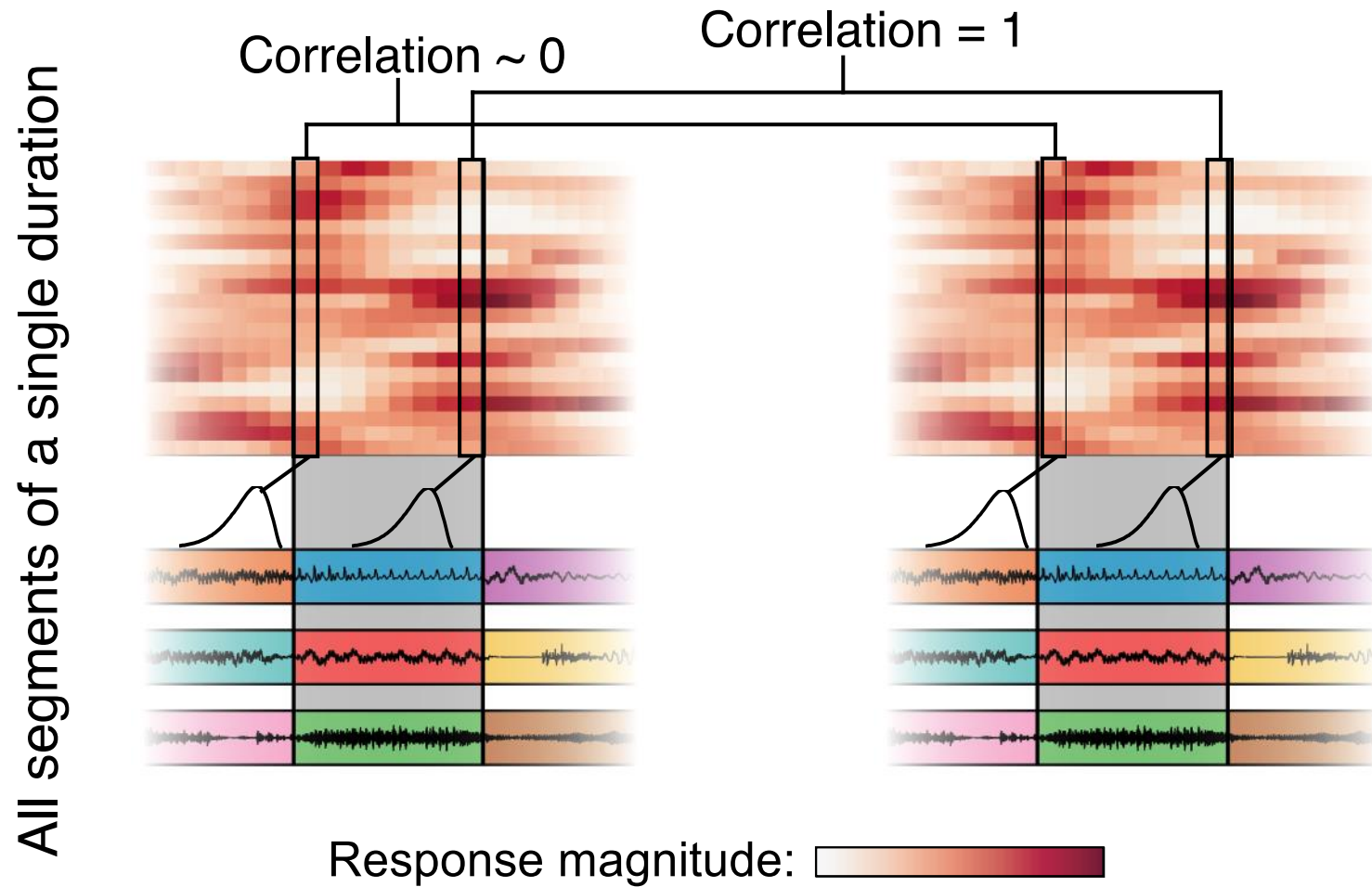


Cross-context correlation



Diverse natural sounds: ferret vocalizations, speech, & music

Noise ceiling



Diverse natural sounds: ferret vocalizations, speech, & music

Cross-context correlation

Electrode in Heschl's gyrus (HG)

31 ms

63 ms

125 ms

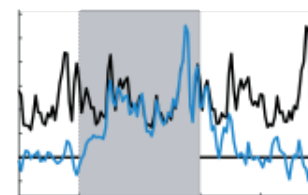
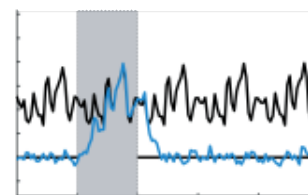
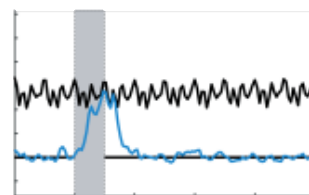
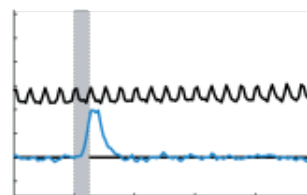
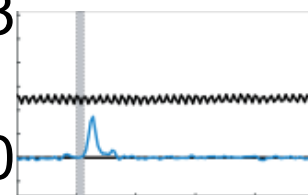
250 ms

500 ms

Correlation

0.3

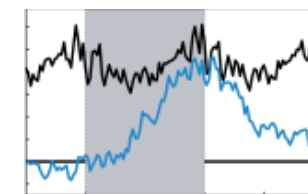
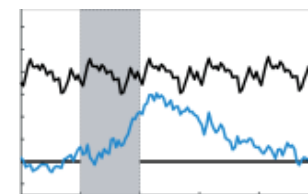
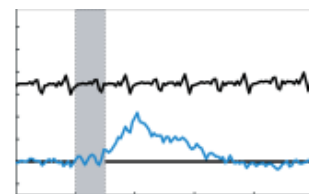
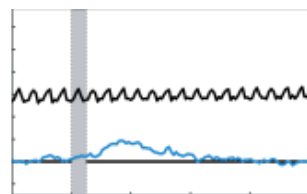
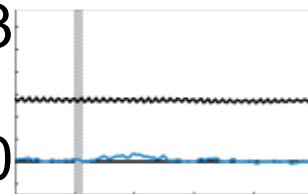
0



Electrode in superior temporal gyrus (STG)

0.3

0

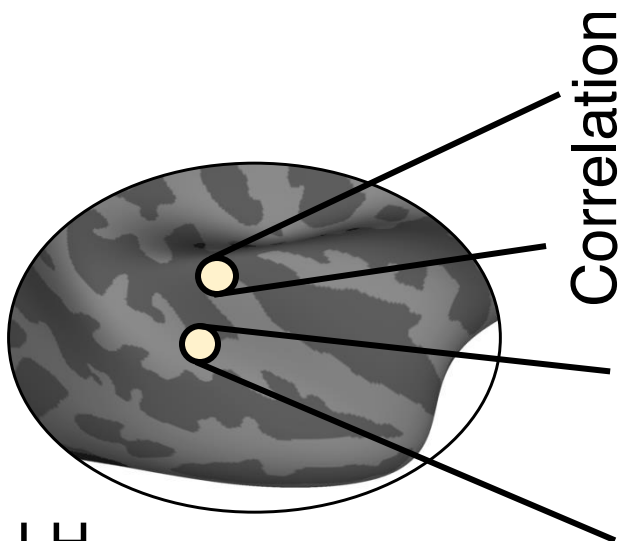


0 500 1000

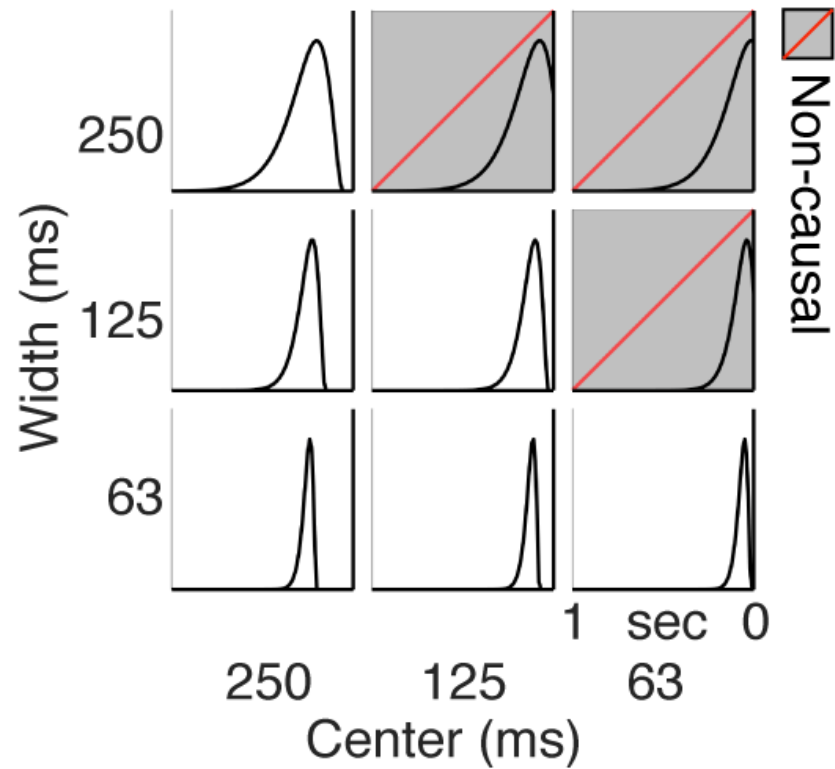
Time lag from onset of shared segment (ms)

- Cross-context correlation
- Noise ceiling
- Time span of shared segment

LH



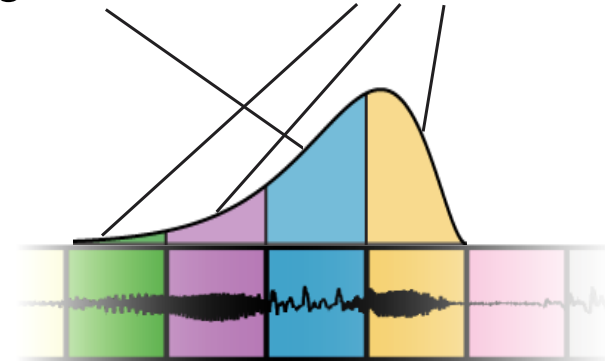
Model window



Model prediction of cross-context correlation

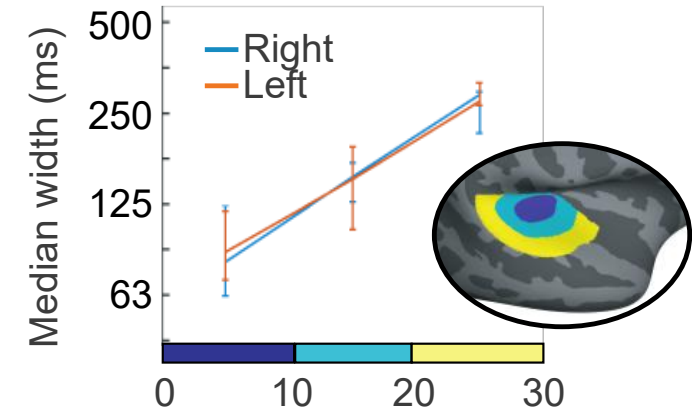
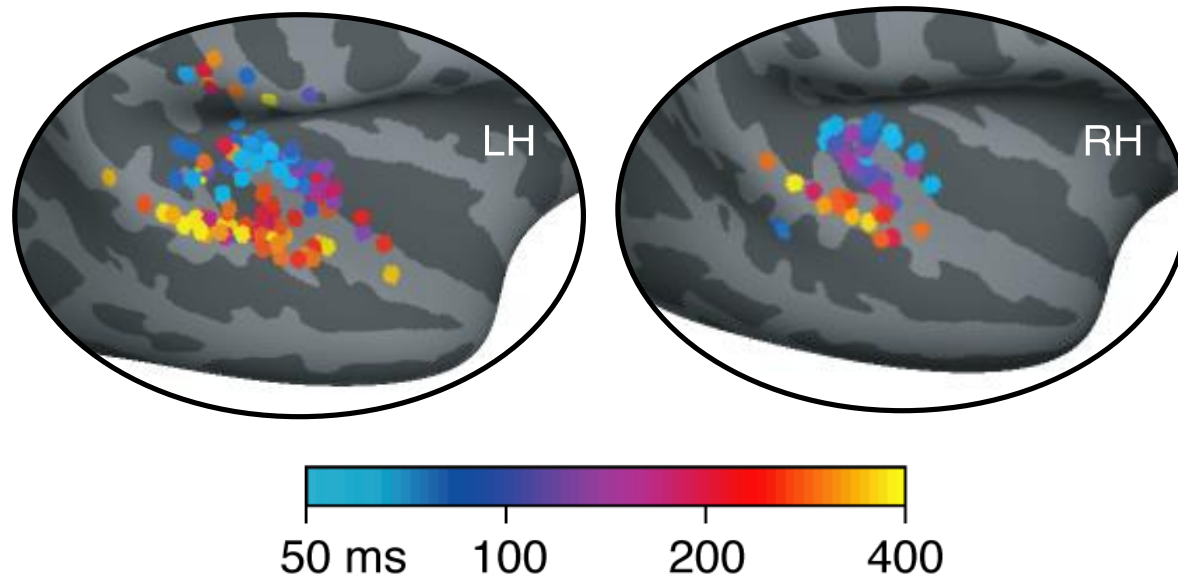
Overlap with shared segment (w)

Overlap with surrounding segments (β_n)



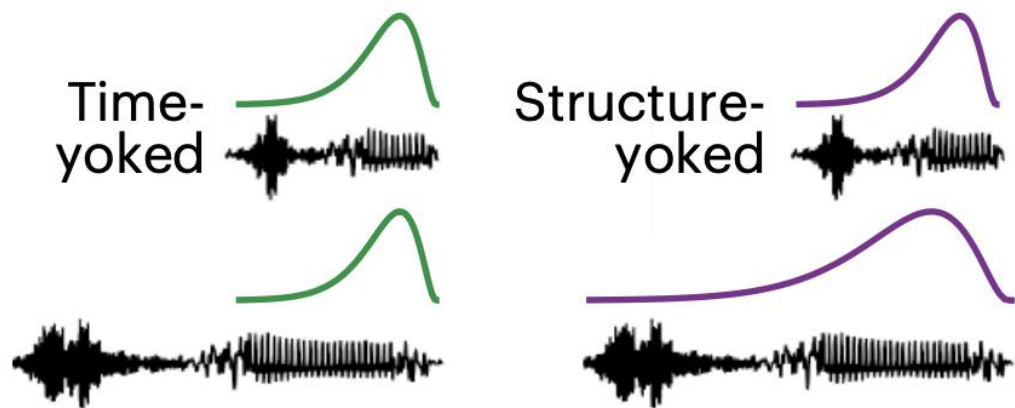
prediction: $r_{ceil} \frac{w^2}{w^2 + \sum_n \beta_n^2}$

Organization of integration windows in human auditory cortex



Hierarchical organization: ~3-fold increase from primary to non-primary regions

No hemispheric difference



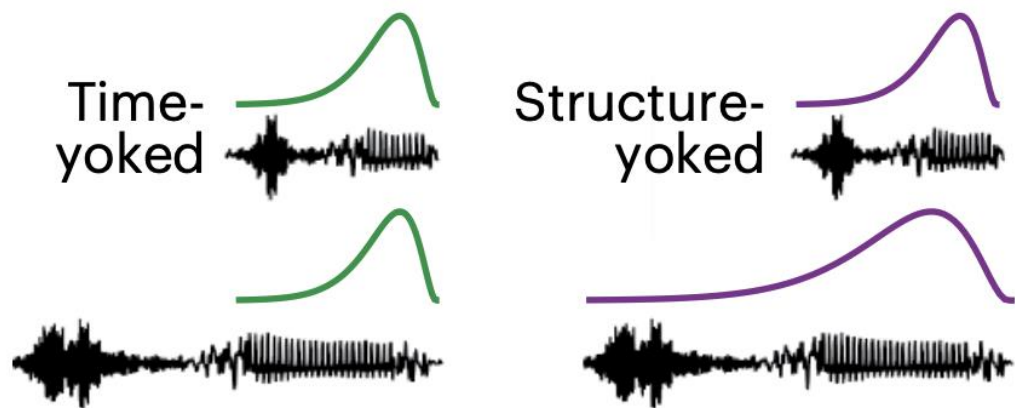
Engaging spoken story from “The Moth”

Compressed or stretched by $\sqrt{3}$

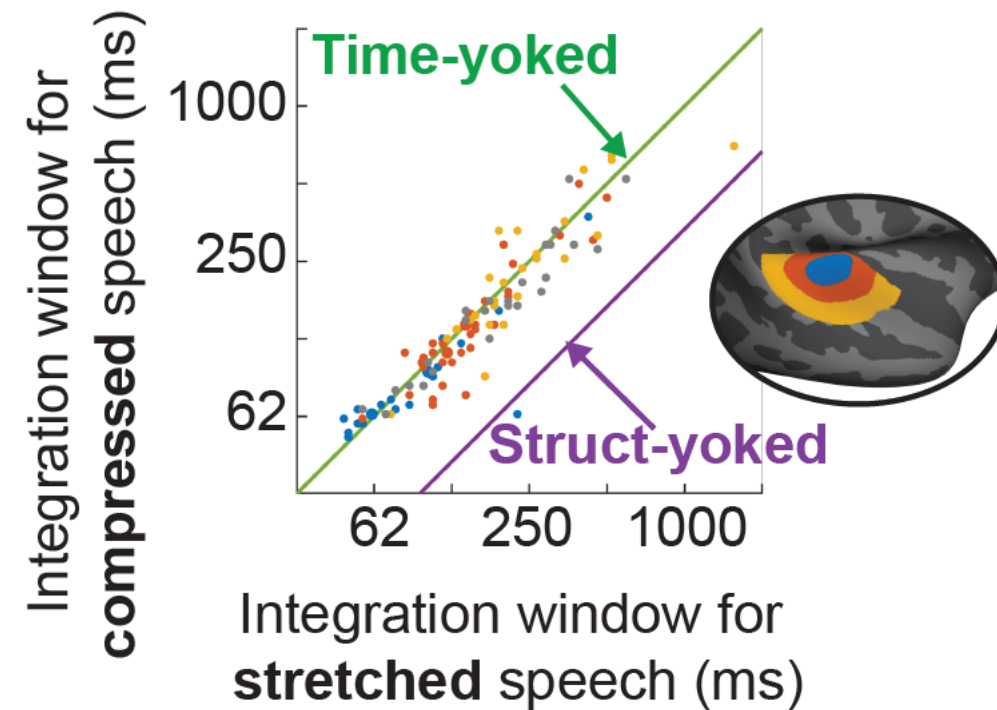
 Stretched  Compressed

3x difference in structure durations

Maintains intelligibility

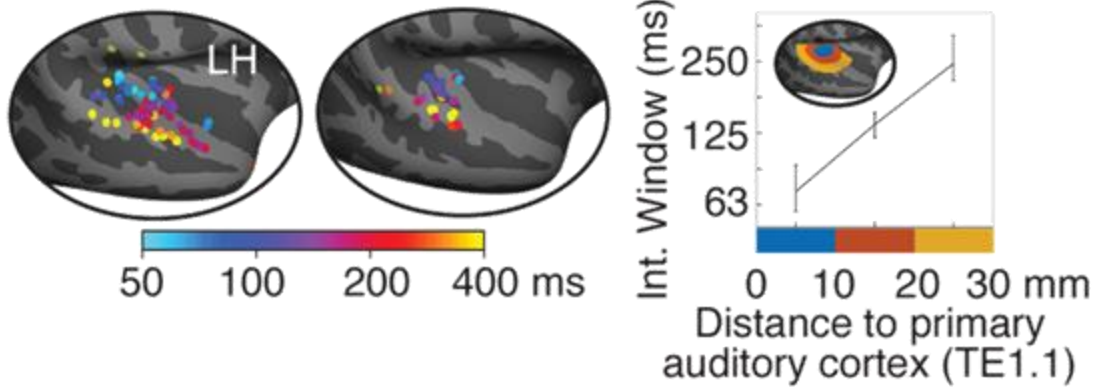


Human auditory cortex

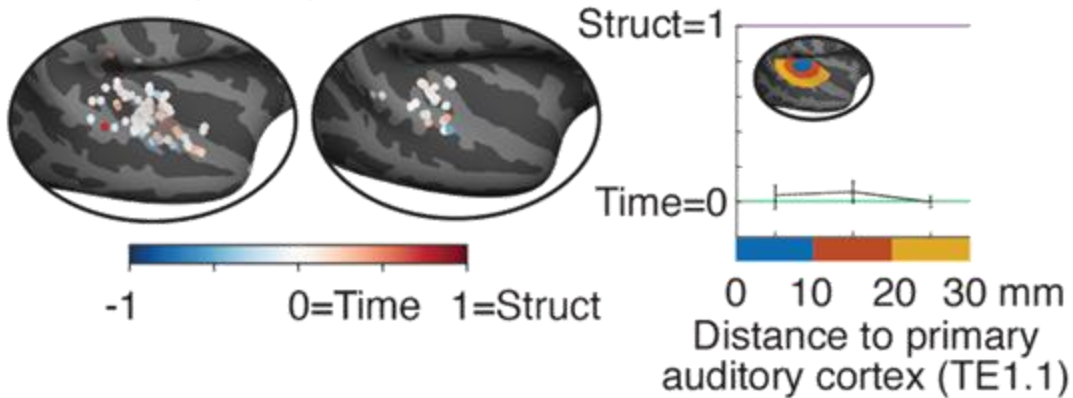


Integration windows **time-yoked** throughout hierarchy

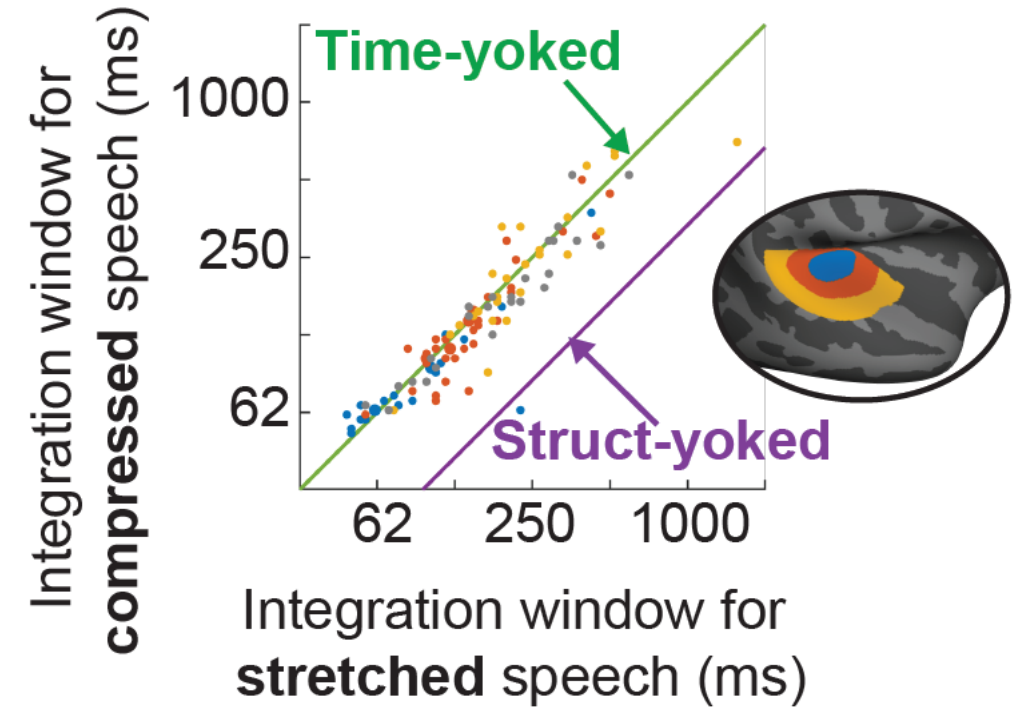
Overall integration window



Structure yoking

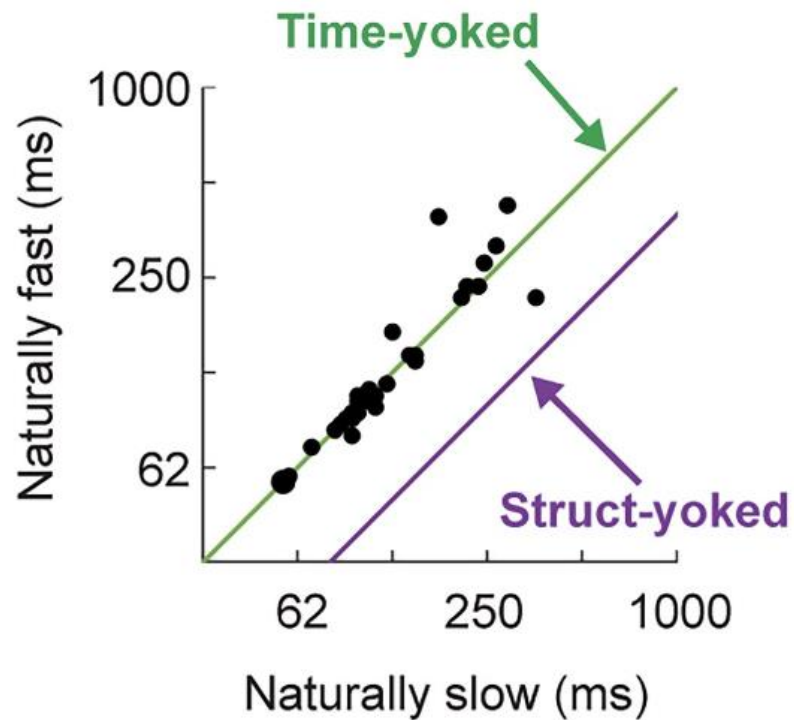


Human auditory cortex

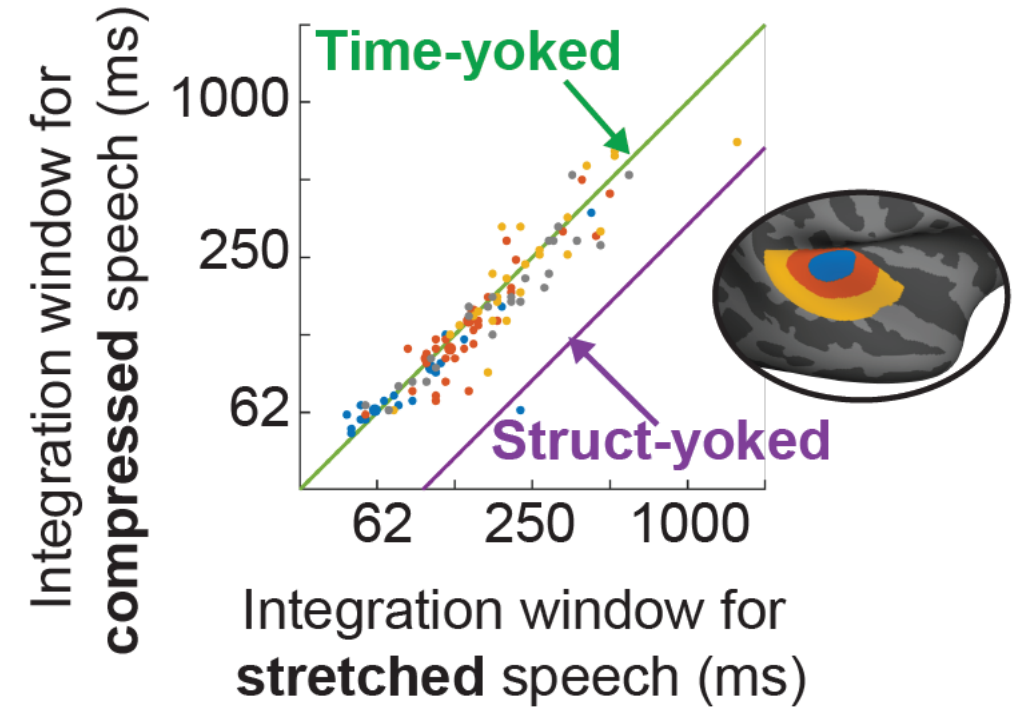


Integration windows **time-yoked** throughout hierarchy

Model-estimated integration windows
for naturally fast and slow speech



Human auditory cortex



Integration windows **time-yoked** throughout hierarchy