Cortical Processing of Arithmetic and Simple Sentences, in an Auditory Attention Task, Linked to Behavior

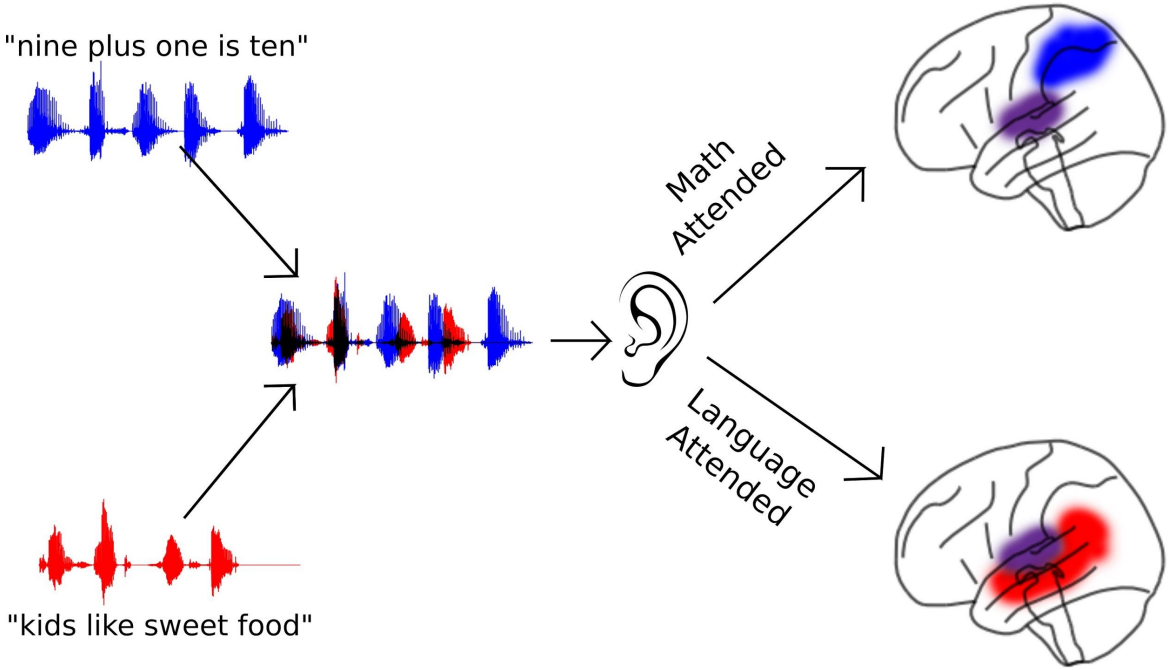
Joshua P. Kulasingham[1], Neha H. Joshi[1,2]*, Mohsen Rezaeizadeh[1,2]* & Jonathan Z. Simon[1,2,3]

[1]Department of Electrical and Computer Engineering, [2]Institute for Systems Research, [3]Department of Biology, University of Maryland, College Park, Maryland. *These authors contributed equally

Computational Sensorimotor Systems Lab

- The neural basis of arithmetic may be dissociated from that of language.
- What are the cortical areas and dynamics involved in neural processing of spoken arithmetic and language?
- How does selective attention impact these processes?

We investigate MEG responses to spoken arithmetic and language in a cocktail party paradigm



Methods

22 subjects (avg. 22.6 yrs) native English speakers.

Stimuli:

- Synthesized 4 word sentences and 5 symbol equations.
- Male and female speakers.
- Lang: Word **2.67 Hz**, Sentence **0.67 Hz**,
- Math: Symbol **2.78 Hz**, Equation **0.56 Hz**

Experiment:

- Diotic presentation of mixed speech.
- 6 mins single speaker
- 7.2 mins cocktail party

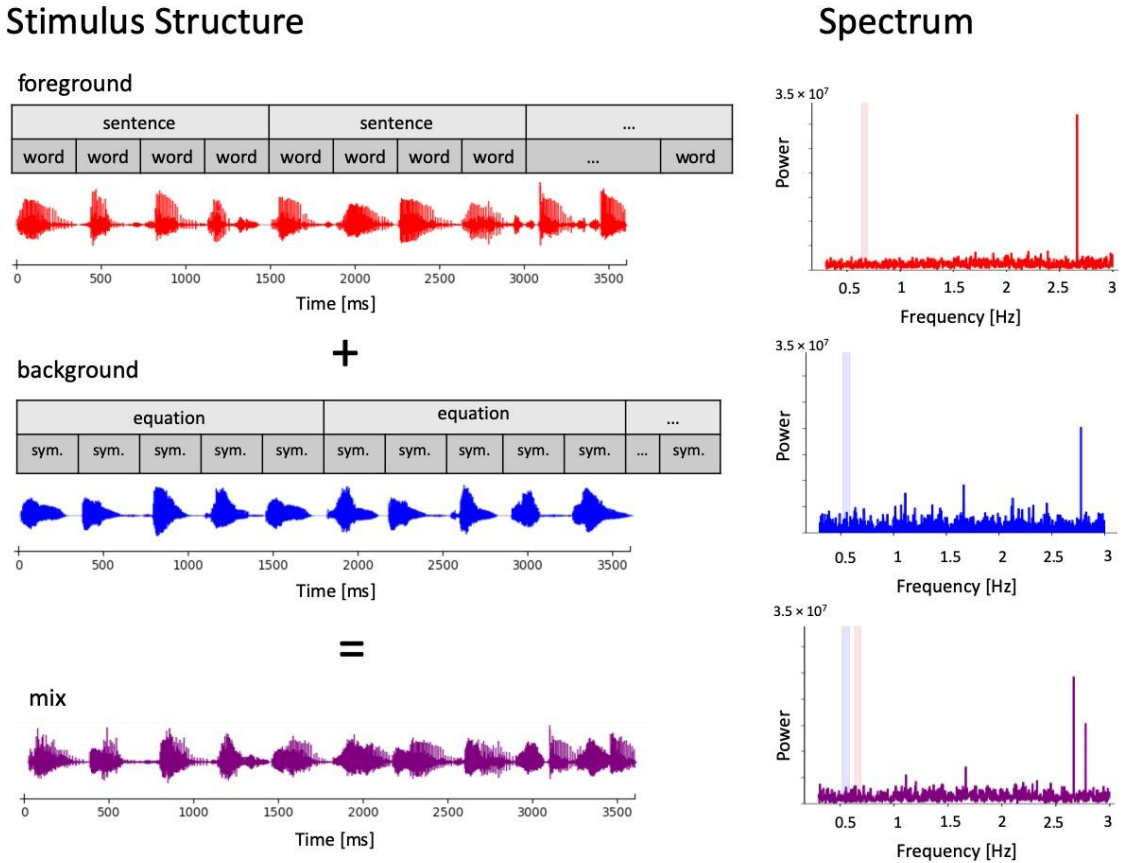
Preprocessing: TSPCA, SNS, 0.3-40 Hz, ICA

Source localization: MNE using a volume source space with 12 mm voxel spacing

Temporal Response Functions (TRFs): Using the Boosting algorithm

Decoders: Logistic Regression with 5-fold cv.

Statistical tests: Permutation tests with TFCE



Mix spectrum has both acoustic rates, but not sentence or equation rates.

Neural Tracking of Sentences and Equations

Tracking of Acoustic Rates

- Word (**2.67 Hz**) and symbol (**2.78 Hz**) rates
- For both attended and unattended speech
- Bilateral auditory areas

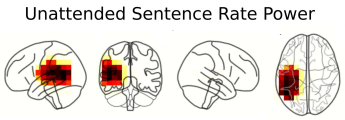
Tracking of Sentence Rate (0.67 Hz)

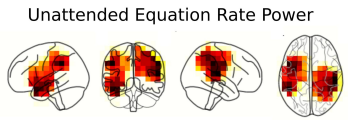
- Only for attended speech
- Left temporal areas linked to language
- Significantly left lateralized

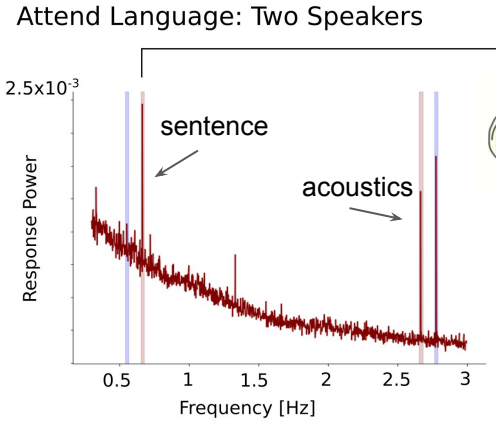
Tracking of Equation Rate (0.56 Hz)

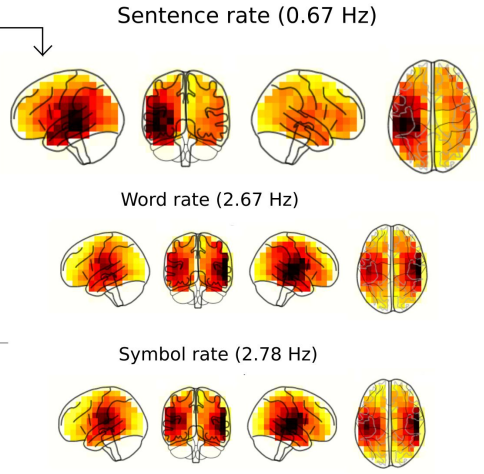
- Only for attended speech
- Parietal and occipital areas linked to arithmetic
- Overlaps with language areas
- Significantly different to sentence tracking

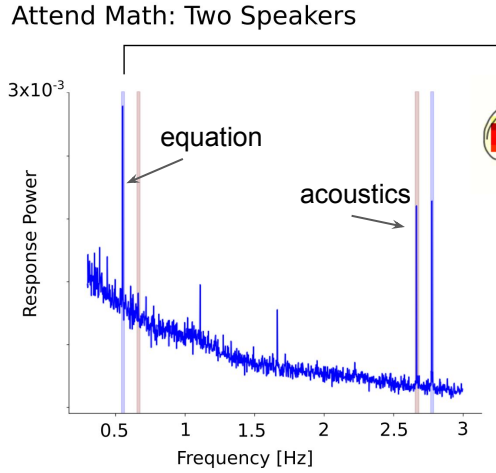
Background sentence and equation rate responses

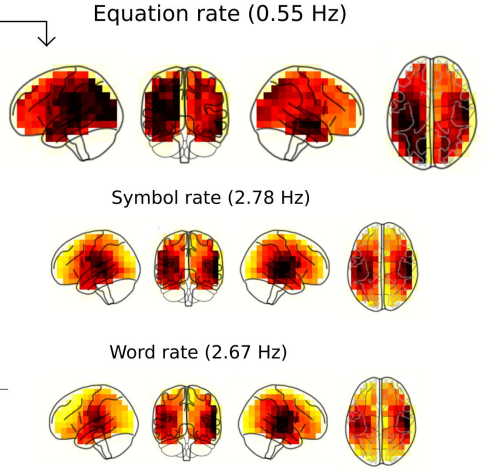












Behavior Correlates with Neural Tracking

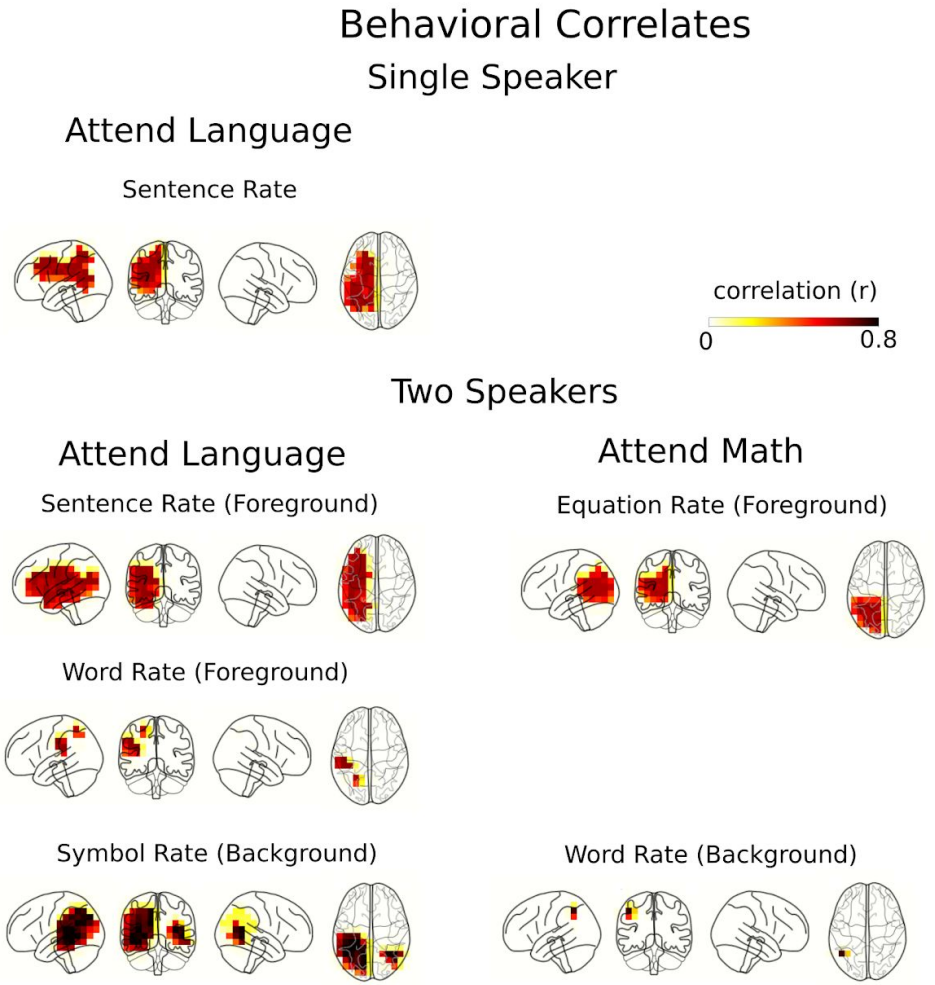
Behavior: outlier detection task

- Mathematically incorrect equations (‘one plus one is ten’)
- Semantically meaningless sentences (‘big boats eat cake’)

Correlation with cortical distribution of response frequency power

- Only attended sentence and equation rates are correlated
- Single speaker equation tracking is not correlated, perhaps due to several subjects performing at ceiling

Neural tracking may reflect comprehension



Dynamics of Cortical Processing: Temporal Response Functions (TRFs)

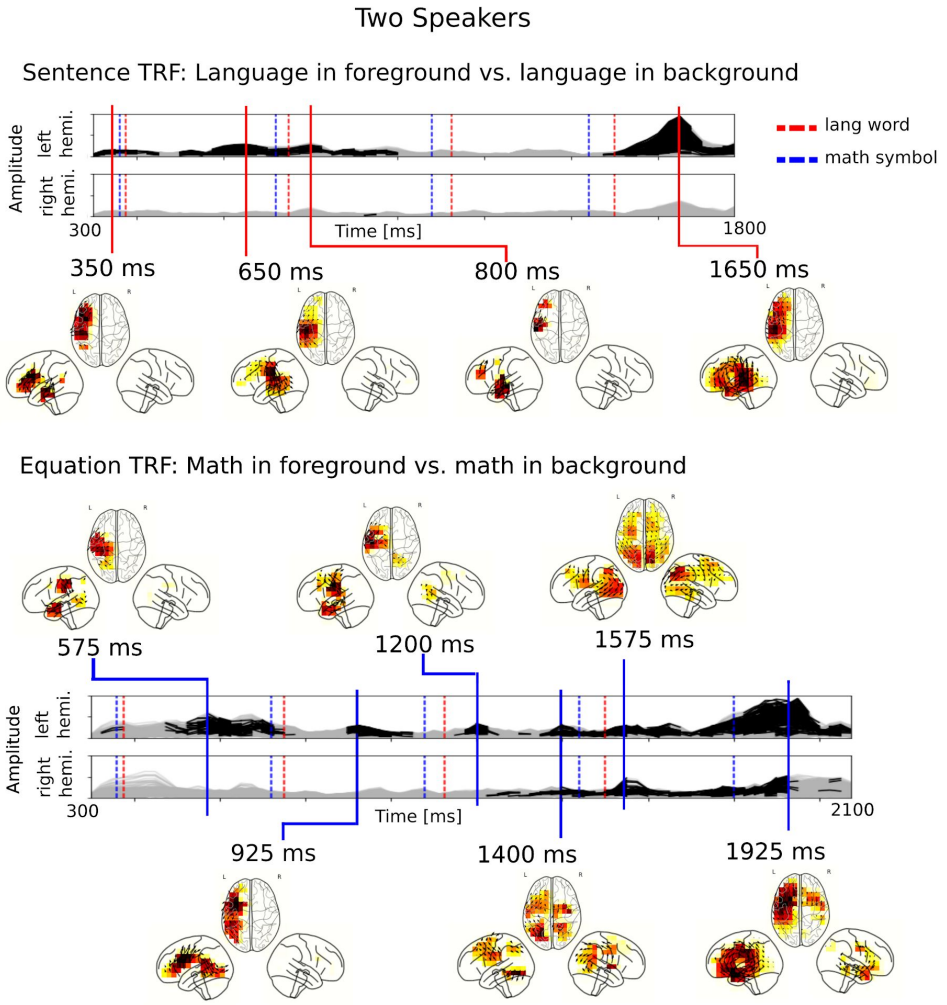
Temporal Response Functions (TRFs):

- Models the impulse response of the neural system to continuous stimuli
- TRFs fit using Boosting for:
  - speech envelopes
  - word and symbol onsets
  - sentence and equation onsets
- Minimal effect of auditory responses on sentence and equation TRFs

Spatiotemporal Patterns

- Differences in math and language processing around 1000-1600 ms
- Attentional modulation during math in parietal areas

Attentional modulation of TRFs highlights arithmetic and linguistic processing regions.



Decoding Arithmetic and Linguistic Processing from MEG Responses

Linear Decoders

- Decoders at each time point using sensor topography (left-top panel)
- Decoders at each voxel using dynamics at that voxel (other panels)

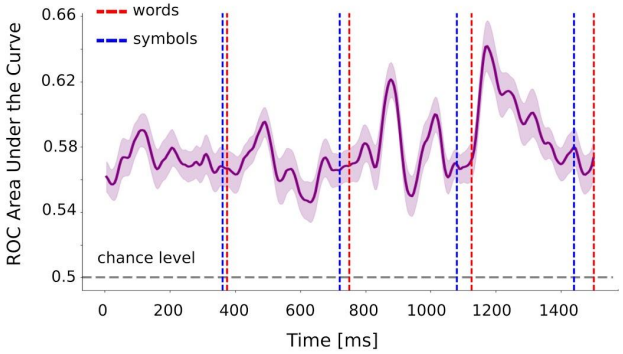
Math vs. Language

- Can be decoded from both sensor topographies and dynamics
- Discriminability best in IPS and superior parietal areas

Decoding Attention

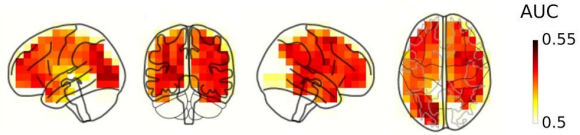
- During math: Parietal
- During language: left temporal and bilateral superior parietal

Single Speaker: Math vs. Language Decoding

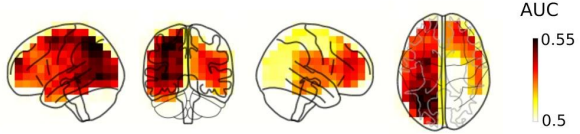


Single Speaker: Math vs. Language Decoding

Decoding based on First Word

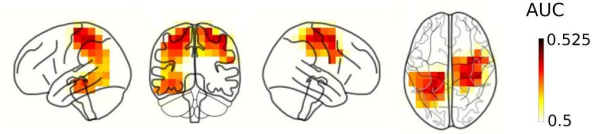


Decoding based on Last Word

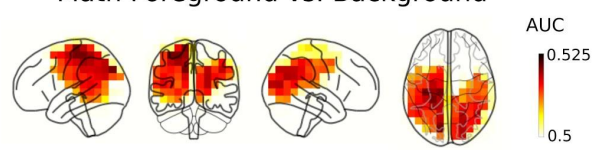


Cocktail Party: Attention Decoding

Language Foreground vs. Background

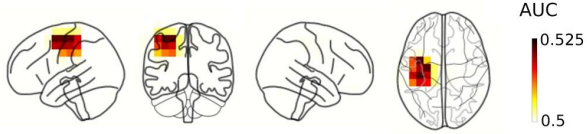


Math Foreground vs. Background

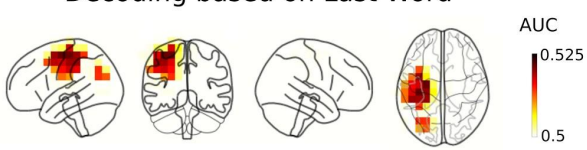


Cocktail Party: Math vs. Language Decoding

Decoding based on First Word



Decoding based on Last Word



Cortical Processing of Arithmetic and Simple Sentences, in an Auditory Attention Task, Linked to Behavior

Conclusions

Neural tracking of equations and sentences only for attended speech

Acoustic rates are tracked regardless of attention

Tracking of equations in both arithmetic and linguistic areas

- Sentences: left temporal areas
- Equations: parietal, occipital and temporal areas

Behavioral performance correlates with neural tracking

- For sentence and equation tracking only when attended
- May reflect comprehension

Dynamics of cortical processing revealed by TRFs

- Selective attention highlights differences between arithmetic and linguistic processing
- Further work needed to investigate these dynamics

Decoding math vs. language from neural responses

IPS/superior parietal areas are most discriminative

Decoding attentional state from neural responses

- During language: left temporal and bilateral superior parietal areas
- During math: bilateral parietal areas

Thank You

References

Amalric, M., Dehaene, S., 2018. Cortical circuits for mathematical knowledge: evidence for a major subdivision within the brain's semantic networks. Philosophical Transactions of the Royal Society B: Biological Sciences 373, 20160515. https://doi.org/10.1098/rstb.2016.0515

Ding, N., Melloni, L., Zhang, H., Tian, X., Poeppel, D., 2016. Cortical tracking of hierarchical linguistic structures in connected speech. Nature Neuroscience 19, 158–164. https://doi.org/10.1038/nn.4186

Ding, N., Pan, X., Luo, C., Su, N., Zhang, W., Zhang, J., 2018. Attention Is Required for Knowledge-Based Sequential Grouping: Insights from the Integration of Syllables into Words. J. Neurosci. 38, 1178–1188. https://doi.org/10.1523/JNEUROSCI.2606-17.2017

Lalor, E.C., Foxe, J.J., 2010. Neural responses to uninterrupted natural speech can be extracted with precise temporal resolution. European Journal of Neuroscience 31, 189–193. https://doi.org/10.1111/j.1460-9568.2009.07055.x

Pinheiro-Chagas, P., Piazza, M., Dehaene, S., 2019. Decoding the processing stages of mental arithmetic with magnetoencephalography. Cortex 114, 124–139. https://doi.org/10.1016/j.cortex.2018.07.018

This work was supported by DARPA (N660011824024), the National Science Foundation (SMA-1734892 and NSF #1449815), and the National Institutes of Health (R01-DC014085).