Cortical Processing of Arithmetic and Simple Sentences in an Auditory Attention Task

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Introduction

Cortical Processing of Arithmetic and Language
- May rely on both shared and task specific mechanisms (Amalric & Dehaene 2018, 2019)
- Language processing predominantly activates left temporal areas (Hickock and Poeppel 2007)
- Arithmetic processing activates bilateral parietal areas, as well as occipital, temporal and frontal areas (Dehaene et. al.,2003)

Isochronous Stimulus Paradigm
- Pioneered by Ding et. al., 2016
- 4 word spoken sentences presented at fixed rhythmic word and sentence rates
- Neural activity tracks the word rate, which is also the dominant acoustic rate
- Neural activity also tracks the sentence rate, which is not present in the acoustics.
- Hierarchical tracking of sentence structures

Selective Attention: **Cocktail party paradigm**
- Attention to one of two simultaneous speakers
- Attention modulates linguistic responses
- Sentence tracking of isochronous speech occurs only for attended stream (acoustic tracking occurs regardless of attention) (Ding et. al., 2018)

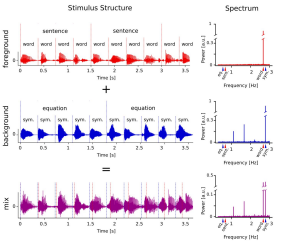
We use an **Isochronous Speech Cocktail Party Paradigm** with fixed word, symbol, sentence and equation rates

Research questions
- Does isochronously presented speech allow dissociating symbol-level from equation-level processing in the frequency domain?
- Does equation and sentence level processing show shared or distinct cortical networks?
- Can the cocktail party paradigm further differentiate between these networks?

Methods

MEG data was collected from 22 young subjects listening to **two simultaneous speakers, diotically** presented. The speakers were of opposite sex and alternated between spoken **equations** and **sentences.**

Stimulus Design
- Fixed word, symbol, sentence, equation rates
- Word, symbol peaks present in stimulus spectrum (but sentence, equation peaks not present)
- Example sentence: "kids like sweet food"
- Example equation: "three plus five is eight"
- Subjects were asked to attend to one speaker and detect deviants (incorrect equations or meaningless sentences)



Frequency Domain Analysis
- Analyzed MEG responses at the frequencies of interest after subtracting the average of neighboring 5 frequency bins on either side
- MEG frequency response peaks were source localized using minimum norm estimation (Gramfort et.al., 2014)

Temporal Response Functions (TRFs)
- Investigated response dynamics using source localized TRFs estimated with boosting (David et. al., 2007) using Eelbrain (Brodbeck et. al., 2020)
- Simultaneous estimation of envelope, word, symbol, sentence & equation TRFs to regress out auditory responses

$$y_r(t) = \sum_{p=1}^{P} \sum_{d} r_{p,r}(d)\, x_p(t-d) + n_r(t)$$

TRF model: The response $y_r(t)$ at voxel r and time t is given by lagged products of the TRF $r_{p,r}(d)$ (for predictor p and time lag d) and the predictor $x_p(t-d)$, summed across all P predictors, plus noise $n_r(t)$

Linear Decoders at each voxel trained on dynamics of MEG responses to detect if subject attended to equations or sentences

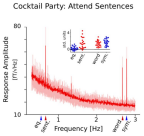
Statistical Tests in source space were performed using TFCE (Smith and Nichols 2009) and permutation tests to control for multiple comparisons

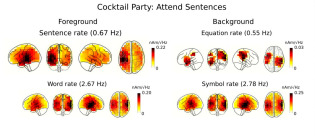
Statistics are not reported here, but are available in the preprint https://doi.org/10.1101/2021.01.31.429030

Results

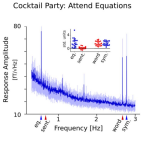
Frequency Analysis
- Neural response spectra show clear peaks at acoustic rates (word and symbol) for both attended and unattended speech
- Equation and sentence rate peaks are seen only for the attended speech

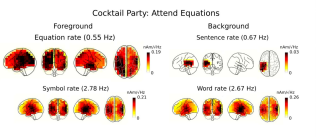
Equation and sentence responses are modulated by selective attention





Cortical response patterns
- Word/symbol: bilateral auditory areas
- Sentence: left temporal areas (consistent with language processing)
- Equation:
  - bilateral parietal areas (consistent with arithmetic processing)
  - left temporal areas (may indicate language processing, arithmetic fact retrieval)
  - occipital areas (may indicate visualization)

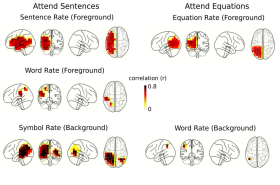




Distinct cortical networks are involved in sentence and equation processing

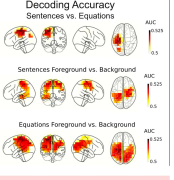
Behavioral Correlations
- Neural responses are correlated with behavioral accuracy in deviant detection task
- Sentence and equation rate responses only correlated when attended
- Spatial patterns of significant correlations are consistent with language and arithmetic processing for each case

Indicates that neural responses may be linked to comprehension or correct calculations



Decoding Attention from Neural Response Dynamics
- Linear Decoders trained on the response dynamics at each source voxel
- Decoding of attention condition (sentences or equations) significantly above chance
- Highest decoding accuracy in superior parietal areas consistent with arithmetic processing

Decoding attention from cortical responses reveals distinct areas with equation vs. sentence responses

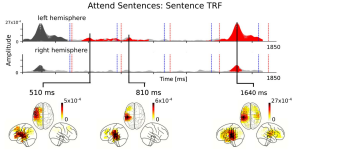


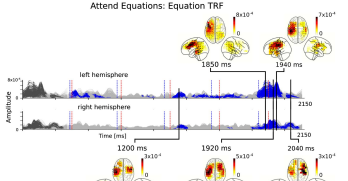
Discussion & Conclusions
- Auditory responses occur regardless of attention, while sentence and equation responses occur only when attended
- Sentence and equation processing involves cortical networks that are both shared (left temporal areas) and distinct (bilateral parietal and occipital areas for equations)
- Dynamics of sentence and equation processing involve distinct spatiotemporal patterns
- Superior parietal areas are most important for decoding attention to sentences vs. equations
- Cortical networks involved in arithmetic and language processing naturally segregate during selective attention
- Attended sentence and equation responses are correlated with behavior, and may be linked to comprehension or correct calculations

Preprint: https://doi.org/10.1101/2021.01.31.429030, **Poster**: http://ter.ps/simonpubs

Spatiotemporal Dynamics of Cortical Processing
- Temporal Response Functions (TRFs) for sentences and equations
- Significant activity towards the end of the sentence/equation
- Auditory responses are regressed out

TRFs reveal distinct spatiotemporal patterns of arithmetic and sentence processing





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