Exploring Language Network Neural Oscillations at the Single-Trial Level

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Abstract

Frequency band activity levels may offer insight into the different neurobiological processes supporting real-time language comprehension. For instance, higher frequency bands such as gamma oscillations have been linked to the prediction of upcoming words during sentence reading, while lower frequency bands may be involved in word retrieval and the integration of meaning across the sentence. Such effects have mostly been studied by group analysis of separate frequency bands across multiple participants. Given the growing body of evidence documenting interindividual differences in the functional neuroanatomy of the language network, we here investigated the stability of single sentence analysis using magnetoencephalography. Forty-two participants (half tested in English, half in Dutch) performed a well-known sentence reading paradigm. The single trial analysis robustly demonstrates that the θ, α and β band contribute to similar processing aspects of sentence reading. In addition, it opens the door for future work that relates the content of singular trials to their frequency band activation levels.

Keywords: Sentence comprehension; Frequency analysis; MEG

Introduction

Neural oscillations participate in the communication within and between cortical areas and play a significant role in cognitive processes (Ward, 2003; Marzetti et al., 2019). In the field of psycholinguistics, elevated or decreased levels of activity in neural frequency bands are leveraged to capture the intricacies of sentence comprehension (Prystauka & Lewis, 2019). While current research agrees on the involvement of neural oscillations in this cognitive task, the exact processes in which each frequency band is involved is still open to discussion (Bastiaansen & Hagoort, 2015; Lewis & Bastiaansen, 2015; Fedorenko et al., 2016; Lam, Schoffelen, Uddén, Hultén, & Hagoort, 2016). Often, findings in multiple participants are combined into group analyses to deduce the functionality of the frequency bands. However, group level estimation has been demonstrated to be less sensitive and less accurate in determining effect sizes due to not considering interindividual neuroanatomical differences (Fedorenko, Hsieh, Nieto-Castañón, Whitfield-Gabrieli, & Kanwisher, 2010; Nieto-Castañón & Fedorenko, 2012). Consequently, this work will focus on individual level analysis and more specifically, single trial analysis. The main advantage of this methodology lies in its robustness to inter-subject and inter-trial variability, as well as its capacity to relate neural oscillations to other neurolinguistic analyses of sentences, such as word predictability analysis (Shain, Blank, van Schijndel, Schuler, & Fedorenko, 2020).

Methods

Participants This study included 42 healthy young volunteers: 19 native Dutch speakers (between 19 and 29 years old, mean 23.4 years old) and 23 native English speakers (between 19 and 53 years old, mean 26.7 years old). Three participants were excluded from the English dataset due to significantly higher levels of baseline noise during the recording.

Paradigm Participants were asked to perform a sentence reading task with both correct sentences (intact syntax and semantics) and nonword lists (incorrect syntax without meaningful words). Careful consideration was taken to perceptually and phonologically match the nonword stimuli to the sentence stimuli. An example sentence trial could be: *"amy caught the ball and threw it back to her younger brother"*, while an example nonword trial could be *"anc ascan tol olsaire yav drodging dirors lus ciled cuned lugsan der"*. The words and nonwords were presented sequentially in a rapid serial visual presentation paradigm with an inter-word-interval of 385 ms in the Dutch dataset and 400 ms in the English dataset. In total, each participant was presented with 80 12-word-long sentences and 80 12-word-long nonword lists in a random order. After every trial (i.e. a 12-word-long sequence), a memory probe was presented to ensure attentiveness. For a more extensive introduction to the paradigm in question, we refer to Fedorenko et al. and Bruffaerts et al. (2010; 2023).

Preprocessing Initial preprocessing of the raw MEG recordings uses MaxFilter 2.2 (Elekta-Neuromag Oy, Helsinki Finland) to apply temporal signal space separation. Further processing of the MEG recordings is performed in MNE-Python to downsample the data to 500Hz, followed by low-pass (250 Hz), high-pass (0.1Hz) and Notch filtering (at 50Hz/60Hz for the Dutch and English dataset respectively and their subsequent higher harmonics) and artefact removal with ICA.

Frequency analysis To inspect the neural oscillations that are related to the language network, the recordings are converted to the frequency domain using Multitapers with 7 Discrete Prolate Spheroidal Sequences (DPSS). For every (non)word stimulus in each trial, we compute the power within each frequency band during its post-stimulus timeframe ([0, 400ms] for English and [0, 385ms] for the Dutch dataset). Subsequently, we normalize this data by comparing it to the power averaged over all reference pre-trial periods ([-500, -100ms] before the onset of the first (non)word of each trial). When combining these frequency-resolved power values with the chronological order in which the stimuli are presented, we can make statements about how the power evolves throughout the sentence and nonword trials for each frequency band. Each datapoint in this power progression curve originates from averaging all sensor power values (204 planar gradiometers) of that particular stimulus in the trial.

Postprocessing To objectively compare power progressions at the single trial level, we can cross-correlate the power progression curves from each frequency band to those from all other frequency bands with Pearson correlation (**Figure 1**). This way, we are able to compare the intra-trial similarity of the θ, α, β, γ_{low} and γ_{high} power progressions across multiple trials without explicitly considering their exact shape, circumventing inter-trial variability. We then apply postprocessing strategies including hierarchical agglomerative clustering on the trial correlation matrices. Here, systematic clustering of frequency bands across trials allows to isolate neurobiological processes that support sentence comprehension.

Besides single trial analysis, we can also contrast power curve increases between the sentence and nonword condition at the individual level. This analysis can reveal differences related to the processing of meaning.

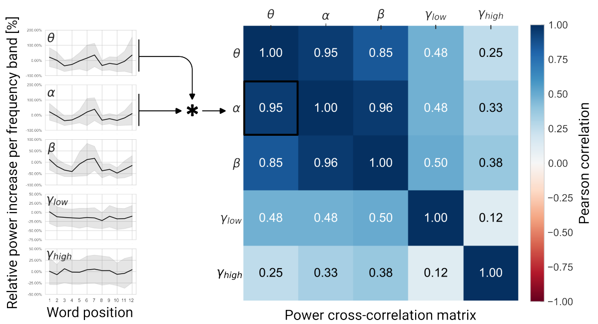

Figure 1: Power progressions over the 12 word positions (with standard deviation in grey) show similarity in the θ, α and β bands for a randomly selected sentence trial which is quantified with all-to-all cross-correlation.

Results

The power cross-correlation matrix reveals that for both the sentence and nonword condition, the lower frequency bands, θ, α and β, correlate strongly with each other at the single trial level. To demonstrate the stability of these findings across trials, we apply hierarchical clustering on the cross-correlation matrix (**Figure 2**). On average, participants in the English dataset exhibit clustering of the θ, α and β bands in $70.94 \pm 19.73\%$ of their trials. Similarly in the Dutch dataset, θ, α and β cluster together in $81.43 \pm 11.28\%$ of the trials. Further posthoc analysis can be accomplished by permutation testing of the correlation coefficients that are part of the θ, α and β cluster versus correlation coefficients that are not part of this cluster i.e. coefficients between the lower and higher frequency bands (**Figure 2**). On average, $81.77 \pm 17.54\%$ of the trials of the English participants demonstrate that the mean of the within cluster correlation coefficients is significantly greater ($p < 0.05$) than the mean of the correlation coefficients that are not part of the θ, α and β cluster. Similarly, $90.85 \pm 8.56\%$ of the trials for the average Dutch participant demonstrate the same effect.

In addition to the strong correlations in lower frequency band power progressions, we examine the contrast between the sentence condition and the nonword condition. We find that the mean relative power increase over the trials is reliably greater for the sentence condition than for the nonword condition in the lower frequencies at the individual level. We test for statistical significance between the conditions using a Wilcoxon signed-rank test in each lower frequency band. Here, for the English participants, we find for θ, α and β that the sentence condition is significantly greater than the nonword condition with p-values equal to 0.00059, 0.0012 and

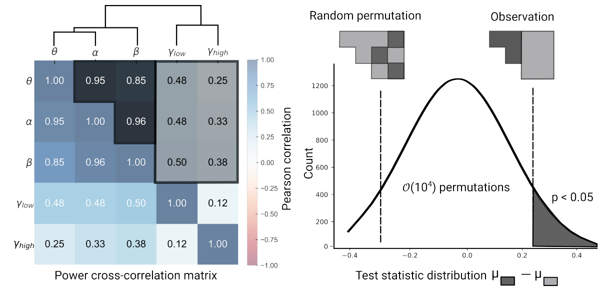

Figure 2: Hierarchical clustering of a randomly selected sentence trial reveals that θ, α and β cluster together in the power cross-correlation matrix. Posthoc permutation testing of within cluster coefficients vs. coefficients that correlate lower frequency with higher frequency bands demonstrate significance of the observation with respect to random permutations.

0.0027 respectively (**Figure 3A**). At an individual level, we see that 16/20 participants have an increased effect size for the sentence condition than for the nonword condition in these frequency bands. Similarly, we test for significance in the Dutch participants and see for the lower frequency bands that the effect sizes are significantly greater for the sentence condition than for the nonword condition with all p-values < 0.0001 (**Figure 3B**). At an individual level, we see that nearly all participants (18/19) exhibit an increased response for the sentence condition in comparison to the nonword condition.

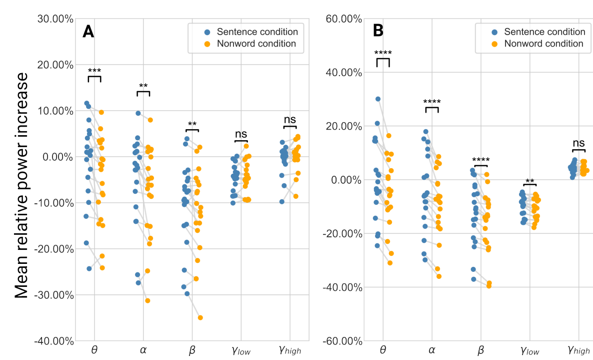

Figure 3: A-B. Effect size comparison for the lower frequency bands between sentence condition and nonword condition in the English dataset and Dutch dataset respectively.

Discussion

Through single trial analysis of a language localizer paradigm in two independent (different language) MEG datasets, we demonstrate that the power in the lower frequency bands, θ, α and β, progresses similarly over the course of a singular trial. In addition, we find that the mean power increase is significantly larger over the sentence trials than over the nonword trials in the lower frequency bands. These findings suggest that there appears to be some incremental tracking of the trial information modulated similarly by the θ, α and β band but to a greater degree in the sentence than in the nonword condition. To expand on these findings, additional analysis can be performed to investigate how the content of trials is connected to the single-trial power progressions.

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