Testing temporal boundaries of composition in low-frequency neural oscillations

Chia-Wen Lo & Jonathan R. Brennan (University of Michigan)
chiawenl@umich.edu

Introduction Human language has the unique characteristic where we can create infinite and novel phrases or sentences; this stems from the ability of composition, which allows us to combine smaller units into a bigger meaningful unit. However, it is not yet clear about "how" neural oscillations carry out the operation of composition and how neural circuits reflect structure-building processes. This study aims to investigate the temporal dynamics of information integration reflected in low-frequency delta oscillations (0.5-3 Hz) by conducting an EEG experiment.

In the current study, temporal properties of stimuli were manipulated: time-compressed speech was used, and the irregularity between syllables was controlled. These manipulations aim to address the following questions. First, whether composition is driven by delta oscillations is still unknown. Previous studies focus more on syllable processing in neural oscillations. For example, the TEMPO model, proposed by Ghitza and Greenberg (2009), suggests that syllables are matched in a theta cycle (~ 200ms). Ghitza (2017) generalized the TEMPO to the word/phrasal processing level by demonstrating behavioral evidence with a context-free digit recall task, suggesting that speech is not comprehensible when the compositional rate of phrase/sentence falls out of the delta range. Based on TEMPO, we expect that neurons fail to entrain to speech if the syllable rate falls out of theta or the compositional rate falls out of delta. However, whether evidence from language comprehension in neural oscillations can be aligned with the prediction from the model remains unclear.

Second, the relationship between language comprehension and delta brainwaves is unclear. Previous studies have shown that the positive correlation between speech intelligibility and the cortical responses (Luo and Poeppel, 2007; Howard and Poeppel, 2010). On the other hand, Nourski et al. (2009) have shown that the low-frequency components of ECoG failed to match with the stimulus envelope of sentences when the ratio of compressed speech is below 0.4, where the subjects' performance is below 0.5. However, these studies focus on syllable processing in theta (4-8 Hz) and there is a lack of evidence for how composition reflected in delta correlates to language comprehension.

Third, whether rhythmicity at the phrasal level affects the processing of composition and how rhythm variations interact with this process in delta oscillations is also still unclear (Ghitza 2017). Ghitza (2017) has observed similar error rates in the conditions where the digits are inserted with gaps and the digits recorded as chunks, as long as the chunking rate of phrase falls in the delta range. The current study aims to see how regularity affects language comprehension in delta oscillations.

Methods N=27 Native speakers of Mandarin Chinese listened to trials consisting of ten 4-syllable sentences and judged whether each trial is plausible or not, following the experimental paradigm in Ding et al. (2016). Each sentence consistent of 4 monosyllabic Mandarin words generated individually using a computer speech program. Five conditions that vary the length of syllable and the regularity between syllables were included (Table 1). Three different lengths of syllables were included (i.e. 250ms, 200ms, 100ms). Semi-regular condition included two different syllable lengths in a fixed order (i.e. 200ms 300ms 200ms 300ms). The irregular condition included random syllable length (either 200ms or 300ms). The sentence length in both semi-regular and irregular condition is 1 second. In each condition, 20 grammatical 4-syllable sentence trials and 10 implausible 4-syllable sentence trials were included. The first sentence from each trial was excluded to avoid potential EEG responses to sound onset. Data were manually cleaned of artifacts, filtered from 0.1-25 Hz, and re-referenced offline to common average. Following the analysis in Ding et al. (2017), for each condition, we compute normalized Evoked Power (EPn) and Inter-trial phase coherence (ITPC) from 0.1 to 20 Hz in increments of 0.1 Hz and a Hanning taper was applied after adding 10 seconds of zero-padding to each condition. Conditions were compared via one-way ANOVA for each measure in each frequency of interest.

Results As a baseline, we replicated the findings in Ding et al. (2017): peaks at the sentence, phrase, and syllable rate were observed in the regular 250ms/syl for both EPn (Fig.1) and ITPC (Fig.2). Peaks for both EPn and ITPC were also shown in the 200ms/syl but not in the 100ms/syl. As for regularity, peaks were also observed in both semi-regular and irregular conditions (Fig.1&2). All subjects show high accuracy overall (Mean = 0.98), even in the 100ms/syl (Mean = 0.97). The current results suggest that delta oscillations are responsible for phrase/sentence chunking, as long as the syllable rate falls within the theta range. However, a high accuracy of comprehension with the absence of cortical tracking in 100ms/syl raised the possibility that there is a delay in comprehension and thus it needs sufficient time for delta to entrain with fast speech.

Table 1. Experimental conditions and frequency of interest

Condition	Regular: 4Hz/syl (250 ms/syl)	Regular: 5Hz/syl (200 ms/syl)	Regular: 10Hz/syl (100 ms/syl)	Semi-regular: 300 200 300 200	Irregular: 300 200 300 200, 300 300 200 200...
Frequency of interest	Sentence: 1 Hz Phrase: 2 Hz Syllable: 4 Hz	Sentence: 1.25 Hz Phrase: 2.5 Hz Syllable: 5 Hz	Sentence: 2.5 Hz Phrase: 5 Hz Syllable: 10 Hz	Sentence: 1 Hz Phrase: 2 Hz Syllable: 4 Hz	Sentence: 1 Hz Phrase: 2 Hz Syllable: 4 Hz

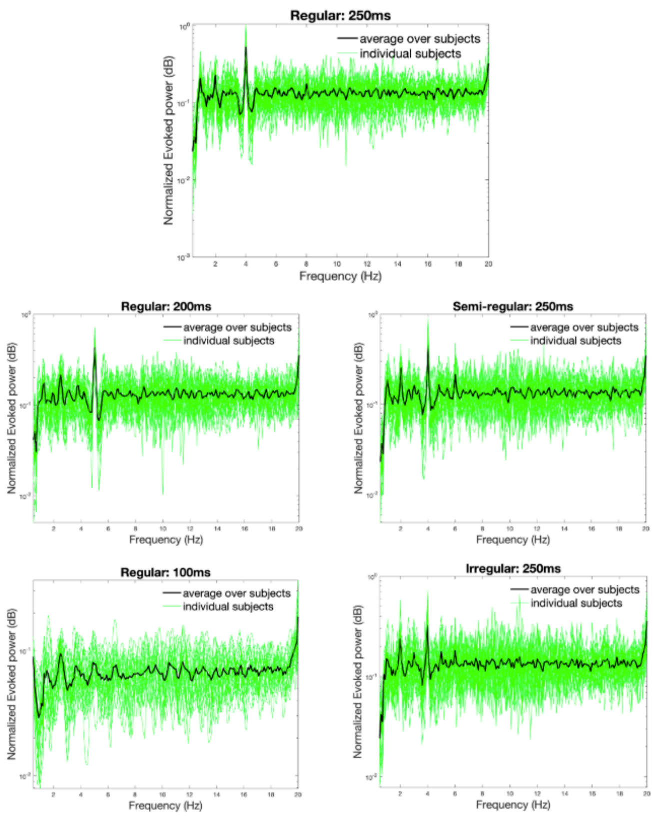

Figure 1. Normalized evoked power

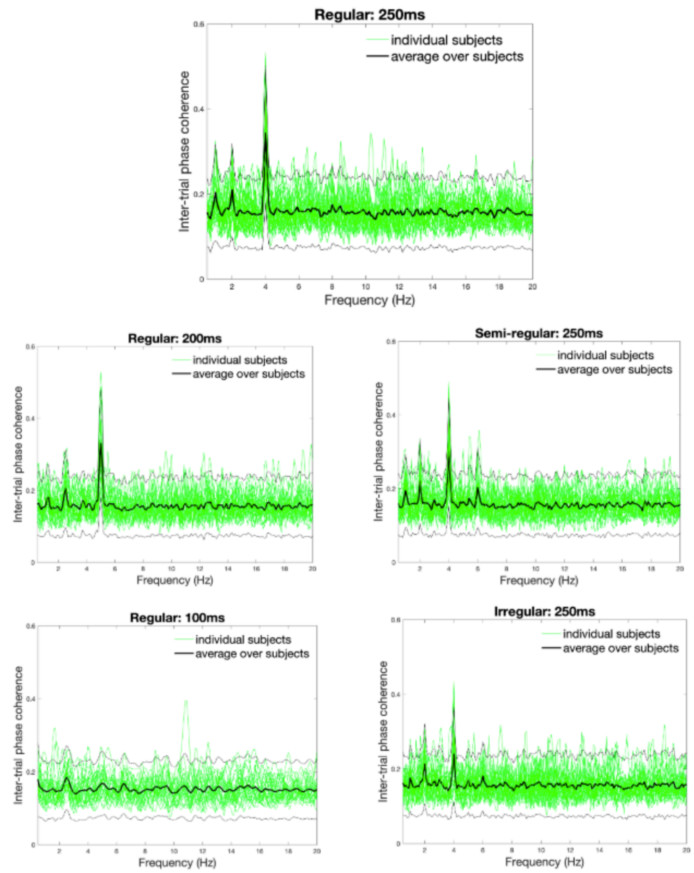

Figure 2. Inter-trial phase coherence

References

Ding, N., Melloni, L., Zhang, H., Tian, X., and Poeppel, D. (2016). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature Neuroscience*, 19:158–164.

Ding, N., Melloni, L., Yang, A., Wang, Y., Zhang, W., and Poeppel, D. (2017). Characterizing neural entrainment to hierarchical linguistic units using electroencephalography (eeg). *Frontiers in human neuroscience*, 11:481.

Ghitza, O. (2017). Acoustic-driven delta rhythms as prosodic markers. *Language, Cognition and Neuroscience*, 32(5):545–561.

Ghitza, O. and Greenberg, S. (2009). On the possible role of brain rhythms in speech perception: Intelligibility of time-compressed speech with periodic and aperiodic insertions of silence. *Phonetica*, 66(1-2):113–126.

Howard, M. F. and Poeppel, D. (2010). Discrimination of speech stimuli based on neuronal response phase patterns depends on acoustics but not comprehension. *Journal of Neurophysiology*, 104(5):2500–2511.

Luo, H. and Poeppel, D. (2007). Phase patterns of neuronal responses reliably discriminate speech in human auditory cortex. *Neuron*, 54(6):1001–1010.

Nourski, K. V., Reale, R. A., Oya, H., Kawasaki, H., Kovach, C. K., Chen, H., Matthew A. Howard, I., and Brugge, J. F. (2009). Temporal envelope of time-compressed speech represented in the human auditory cortex. *Journal of Neuroscience*, 29(49):15564–15574.