EEG Evidence of Hierarchical Structure Building in Sentence Processing

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Traditional approaches to demonstrate structure building with EEG required a comparison between a grammatical and an ungrammatical structure. As such, the evidence for structure building, from these studies, can only be interpreted as a difference between the two, rather than showing how grammatical structures are processed by themselves. Novel approaches demonstrate hierarchical structure building with grammatical sentences only [1]. For example, given a sentence [big plans bring hope], the frequency-tracking approach can provide evidence that the component frequencies corresponding to the syllable, phrase, and sentence level have higher intensities than other frequencies. However, of the three linguistically meaningful levels (syllable, phrase, and sentence), the sentence level frequency is the most convincing. All other frequencies can be explained as something other than a response to that linguistic structure. In this example from Fig. 1A, the frequency response to phrases (which are double the frequency of the sentences) can be understood as a harmonic to the sentence level response [2]. This is because there is a symmetry between the phrase level structure in terms of number of syllables (2 and 2). Also, the frequency response to syllables can be interpreted as auditory responses, as well as harmonics from lower frequencies.

In our view, for this method of frequency tracking of grammatical structure to be useful to the understanding of hierarchical structure building, a number of requirements need to be met. First, harmonics to higher level structures cannot be equated to responses to lower-level structures. Secondly, the responses showing structure building should reflect parsing, rather than part of speech of the component words [2].

We conducted an experiment testing Mandarin-speaking adult participants, which examined the hypothesis that component frequencies from structures can be used to demonstrate hierarchical structure building and reflect parsing results. We constructed two types of sentences, for which words have the same length and part of speech at the same locations, but will be parsed into different structures. Sentences in both conditions have the [N_3 V_2 N_2 Adv_3] structure where the numbers indicate the number of syllables for that word, but they would be parsed into different structures (e.g., buyers think pianos nice-sounding, Fig 1B; pianists play pianos nice-sounding, Fig 1C), as a function of the verb type (ECM, transitive). The ECM verb constructs a main clause followed by another clause (so the two clauses are 5+5), but the transitive verb does not construct such symmetries in terms of syllable numbers and structure (Fig 1). Given all lengths of syllables to be 250ms, the ECM structure included two structures with 5 syllables each (corresponding to 0.8Hz), and the transitive structure does not include this frequency component. We used the same way as [1] to construct our EEG experiment, where each epoch included 10 sentences of the same structure without silences between the sentences. Twelve epochs were in a block, and each participant listened to 16 blocks of sentences (8 block per condition). To analyze the results, we averaged the signals from different conditions in the time domain, before the ITC was computed.

Results from 24 adult participants support the notion that the EEG frequency components reflect parsed structures, as the frequency corresponding to the clauses (0.8Hz) had higher inter trial phase coherence (ITC) values, but all other linguistically meaningful frequencies were comparable between the conditions (Fig 2).

In conclusion, the steady-state EEG methodology can detect linguistic constituencies above and beyond the level of words and reflect the results of parsing. When the constituency is correctly sized, this method shows that there are robust responses to phrases and larger constituents, and alternatives such as identifying part of speech of words cannot explain these results.

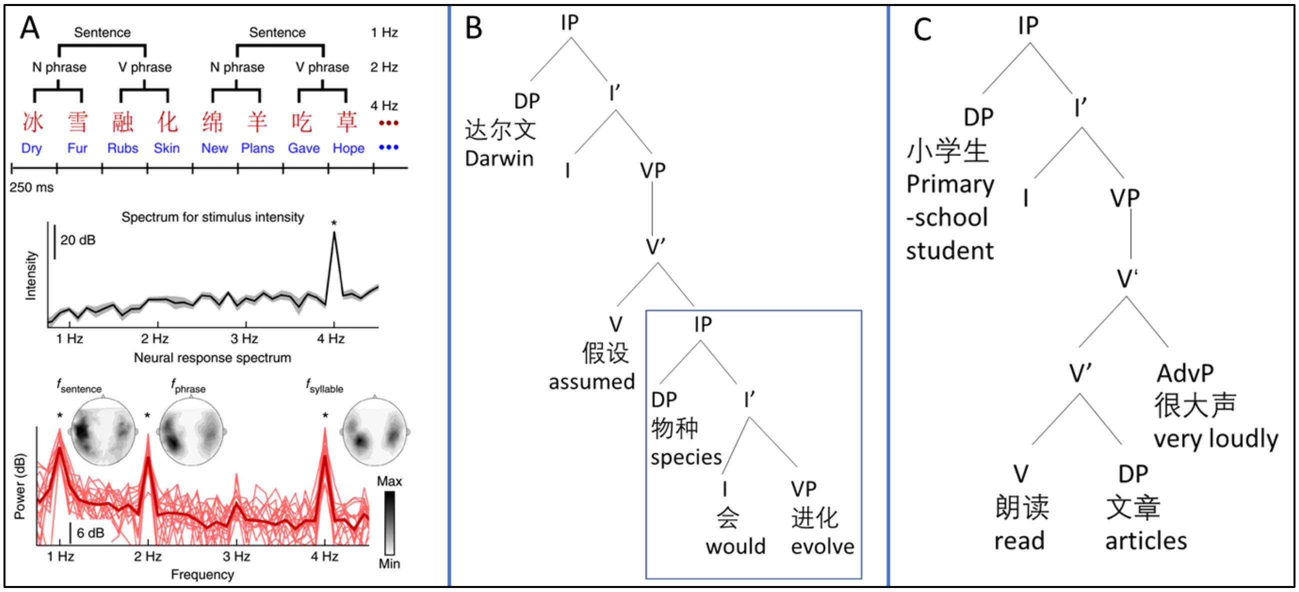

Fig 1. Illustrations of the stimuli in different experiment. A) Figure from [2], where the structure of the simple sentence type [Adj N V N] is shown. B) Structure of the ECM sentences in our experiment C) Structure of the transitive (TrV) sentences in our experiment.

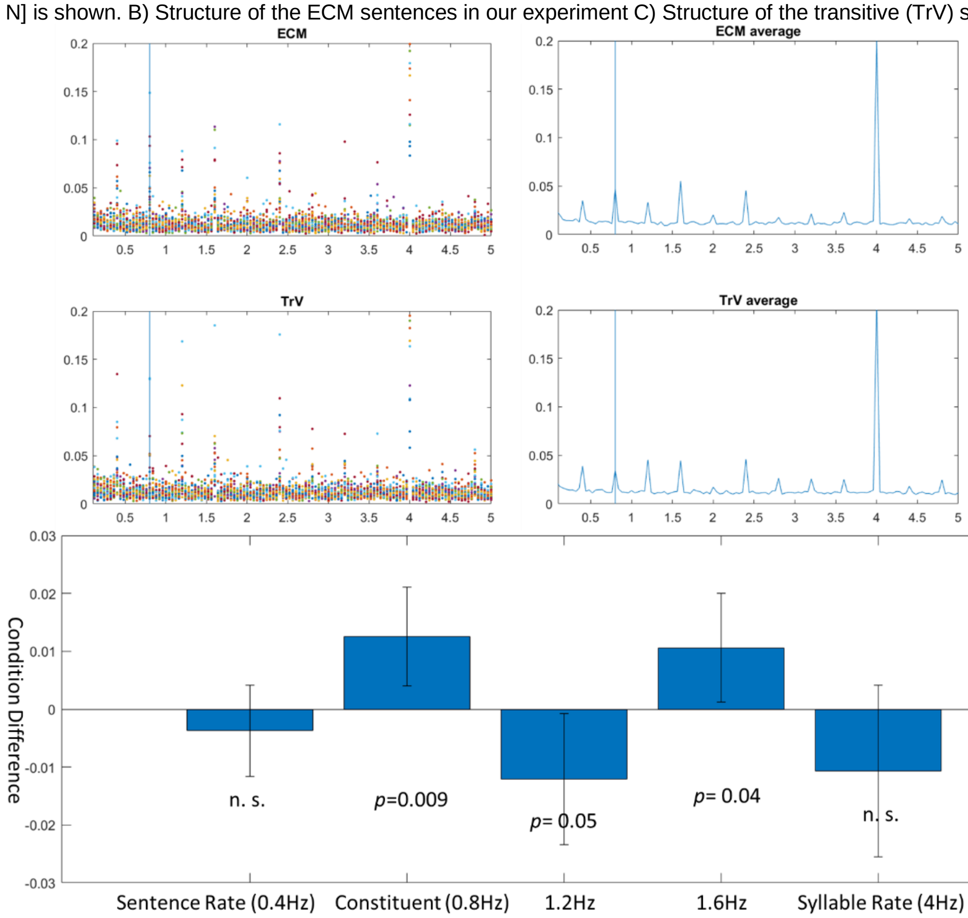

Fig 2. Results from the experiment. On the top, ITC values from individual participants (left) and averages for all participants in the condition (right). The x-axis represents different frequencies; the y-axis represents ITC values. On the bottom, bar plots of the condition difference, at the rates multiple to the sentence rate.

References. [1] Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, *207*(4427), 203-205. [2] Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2016). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature neuroscience, 19(*1), 158-164.