Investigating Neural Sensitivity To Hierarchical Structure in Linguistic and Musical Stimuli in Humans And Rats

Language is a uniquely human cognitive ability with highly complex hierarchical structure [1]: morphemes combine into words, words combine into phrases, and phrases combine into sentences. No other animal has a communicative system rivaling human language in its complexity [2]. The hierarchical structure present in language arises due to the dependencies between linguistic units at different levels of language organization. There exists a diversity of dependency types corresponding to different types of hierarchical structure, from local phonological dependencies in which properties of a linguistic unit predict properties of an adjacent unit, to a number of syntactic non-local dependency types in which properties of a linguistic unit affect properties of non-adjacent linguistic units that could be arbitrarily far removed in terms of the linear sequential distance [3]. The hallmark of language is its use of complex, non-local dependencies that cannot be learned via associative learning mechanisms [3,4].

Seminal debates in theoretical, psycho- and neuro-linguistics concern the question of whether language uses a unique and language-specific hierarchical building operation (or set of operations) independent of semantic processing, such as Merge in the Minimalist Program [5], or whether it recruits cognitive machinery from other domains for hierarchical structure processing. The answer to this question has important consequences for understanding the nature of the human-specific faculty of language. An emerging body of research suggests that certain changes in oscillatory behavior that track hierarchical linguistic structure are "footprints" of these operations, whatever their nature is [6]. For example, when a string of one syllable nonsense words without syntactic organization is presented to subjects at a 4-Hz rate, it elicits an increase in power in the MEG response at the word presentation rate (4 Hz). However, when the words are organized into two word phrases (e.g. "[blue sky]", "[chop wood]"), it elicits an increase in MEG power at 4-Hz and at 2-Hz, i.e. the phrase presentation rate. And, when the phrases are organized into sentences (e.g. "[[tall girls] [chop wood]]"), it elicits increases in power at the word rate (4-Hz), the phrase rate (2-Hz), and an additional increase in power at 1-Hz, i.e. the sentence presentation rate. By contrast, when the subjects do not understand the experimental language, the same stimuli elicit a power increase only at 4-Hz (the word presentation rate) [7]. Further work has shown that this change in neural activity can be detected using EEG [8] and that a relatively short 40 minute exposure session to nonword sequences following rules of an artificial grammar leads to detectable entrainment of cortical activity to the structure of that artificial grammar [9]. Investigations of these neural behaviors could have important consequences for understanding the human language faculty. However, several open issues remain, including the following two questions:

(Q1) To what extent are neurobiological processes observed in these studies human- and language-specific? Do they use cognitive machinery present in other species or other cognitive domains?

(Q2) Does the processing of more complex non-local dependencies rely on the same processes?

We have investigated those questions in two implicit artificial grammar learning experiments with humans and rats. In the experiments, the subjects were exposed to sequences of stimuli generated using artificial grammars (AGs) with different types of dependencies (Fig. 1). The type of stimuli - nonsense words or musical tones - were manipulated to address Q1 in Experiment 1, and the complexity of the dependencies used in the AG were manipulated to address Q2 in Experiment 2. Behavioral and neural

(EEG in humans, EEG and LFP in rats) responses were collected to assess whether all types of structures are tracked by oscillatory brain activity, for both stimulus types.

The collected data is currently being analyzed for the evidence of presence of neural entrainment to the hierarchical structure in the subjects' brain activity. Specifically, we are investigating whether human EEG and rat LFP data exhibit (i) increase in power at harmonics of stimulus presentation rate, which could arise due to non-local dependencies lasting (whole number) multiples of stimulus duration [7-9], and (ii) changes in beta (15-35Hz) and gamma (30-80Hz) frequency range power at dependency closing elements in the sequence (e.g. A2, B2 and C2 in Fig 2C and 2D), as it has been linked to syntactic binding processes [6, 10]. In the presentation, the results of these investigations will be discussed in the context of the human-specific faculty of language and the question of what might make humans uniquely able to learn, produce and comprehend complex hierarchical structure.

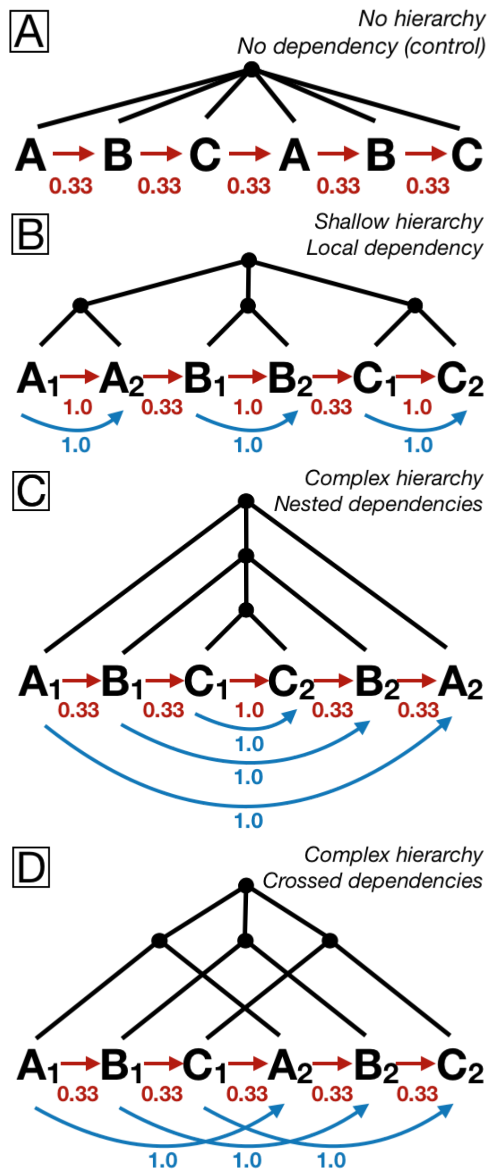

Figure 1. An example of a six element sequence with its associated tree/graph structure in different conditions in experiment 1 and 2. Capital letters denote categories of stimuli, the same capital letters with different indices denote elements with dependencies between them; red arrows and numbers below them represent the sequential transitional probability of the category after the arrow following the category before the arrow; blue arrows represent non-local dependencies between elements of the sequence.

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