Oscillatory dynamics of complex dependency processing reveal unique roles for attention and working memory mechanisms

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Domain general cognitive processes, such as working memory (WM), play critical roles in sentence comprehension, but much uncertainty remains over the precise nature of these roles. Here we examined the neural oscillatory dynamics of a well-known processing asymmetry between object-extracted (ORC) and subject-extracted (SRC) relative clauses to provide new insight into the engagement of working memory and attention during complex dependency processing. Previous research evaluating these sentence types have mainly focused on minimally dimensional measures of processing difficulty, such as reading time and ERP. Neural oscillatory dynamics, on the other hand, provide a higher dimensional space to evaluate processing differences between these conditions which might be lost when averaging over multiple frequencies, locations, and time points such as in ERP analyses. Furthermore, neural oscillations have previously been uniquely linked to specific domain general cognitive processes, such as working memory recall and attention focus. Thus, we attempt to use these measures to evaluate two major theorized sources of relative clause processing discrepancies, working memory and frequency/expectation based accounts.

1. The lawyer that the$_{\mathbf{C}}$ judge$_{\mathbf{A}}$ disliked was$_{\mathbf{B}}$ fired for corruption. **ORC, more demanding**
2. The lawyer that disliked$_{\mathbf{C}}$ the judge$_{\mathbf{A}}$ was$_{\mathbf{B}}$ fired for corruption. **SRC, less demanding**

Sentence processing theories that ascribe WM demands to the processing discrepancy between relative clause types have hypothesized that: **A**) increased interference demands from unresolved dependencies[1] due to the shared thematic role of agent between the main noun phrase and the embedded noun phrase, and **B**) increased integration costs at the main verb[2]. An increase in WM interference would be most apparent when comparing activity at the embedded noun-phrasesA across sentences, the point at which the maintenance of two separate agents begins, and which would only occur for ORC sentences. Integration cost demands, on the other hand, would be most evident at the onset of the main verb phrase$_{B}$ as at this point agent/patient nouns need to be recalled from WM. Theories that propose frequency-based expectation violations underlie the processing asymmetry hypothesize that, since SRCs are more common than ORCs in English, ORCs will be more surprising, and differences in processing difficulties should be apparent at the word immediately following the complementizer *that* **(C).** It is unclear what underlying cognitive cost expectation violations would incur – so we evaluated an index of attention as well as WM.

We evaluated mid-frontal theta (4-7Hz) power and occipital alpha (8-12Hz) power in scalp recorded EEG collected while 205 participants read relative clause containing sentences within the context of a large-scale study designed to measure multiple facets of the neural dynamics of sentence processing. **We assumed increases in mid-frontal theta power would reflect increases in working memory recall[3,4] and event-related de-synchronization of occipital alpha power would reflect increases in sustained attention[4,5].**

We used the Morelet wavelet transform[6] to create time-frequency representations of and determined individual theta and alpha power by identifying peak power spectra from a set of non-complex sentences presented during the experiment (see figure captions for additional description). Mid-frontal theta power increased for ORC sentences, mainly at the onset of the main verb phrase, and to a lesser extent within the embedded noun phrase (Fig1A). Additionally, alpha power decreased throughout the relative clause, resolving at the main verb phrase (Fig1B). Notably, this decrease reflects a lack of alpha synchrony during ORCs. **Overall, the lack of alpha synchronization we find in ORCs is consistent with ORCs requiring greater attentional demand. Furthermore, the results in the theta band provide support for a theory of increased integration (working memory recall demands) on the verb (B).**

REF: [1] Van Dyke & Lewis (2003) *JML*. **[2]** Gibson (2000) *Image, Language Brain* **[3]** Hsieh & Ragnanath (2015) *Neuroimage* **[4]** Klimesch (1999) *Brain Research Reviews* **[5]** Clayton, Yeung, Kadosh (2015) *TiCS* **[6]** Torrence & Compo (1998) *Bulletin of the American Metroligcal Society*

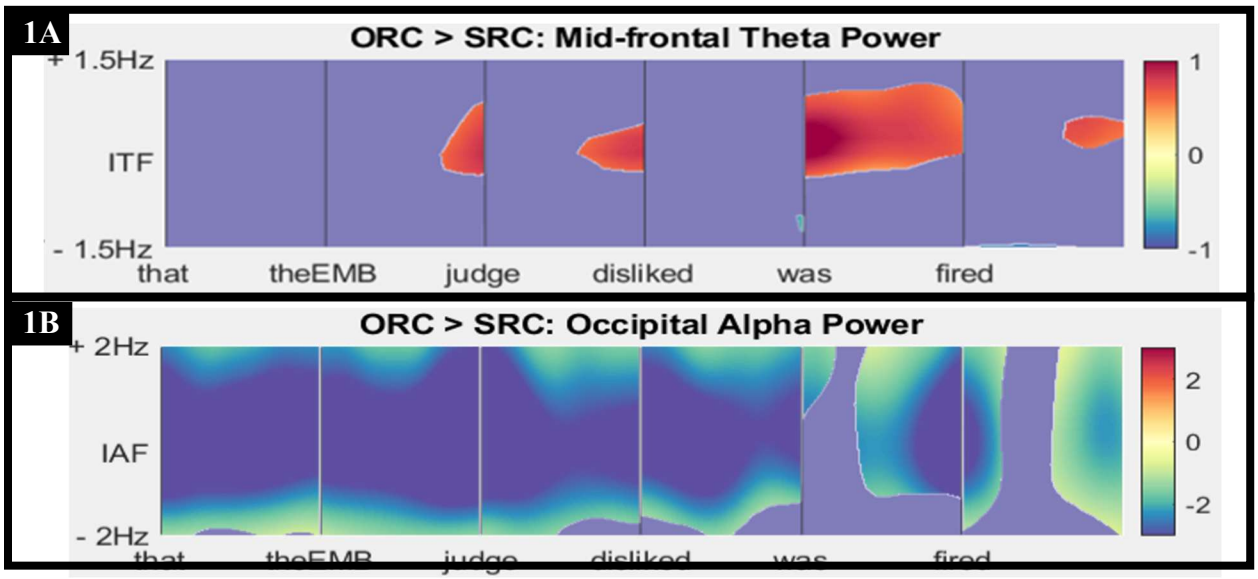

Figure 1: Power Contrast maps (ORC > SRC) Mid-frontal Theta (A) and Occipital Alpha (B) Both figures above represent power contrasts (more red, higher synchronization; more blue, higher desynchronization) between object-relative containing (ORC) and subject-relative containing (SRC) sentences, word by word. Word category was controlled for with the resulting contrast maps presented in ORC word ordering. Purple coloring represents time x frequency combinations did not have a significantly non-zero ORC > SRC contrast (FDR corrected). Individual theta frequency **(ITF, 1A)** was determined by a local spectra maximum between 4-7Hz with a +/- 1.5 Hz bandwidth. Individual alpha frequency **(IAF, 1B)** determined by a local spectra maximum between 8-12Hz with a +/- 2 Hz bandwidth. Mid-frontal theta synchronization was greater for ORC containing sentences **(A)**, largest at the main verb and present to a lesser extent on the offset of the embedded noun phrase. Occipital alpha desynchronization was greater for ORC containing sentences **(B)**, throughout the course of a relative clause. **Individual condition plots (Figure 2)** show that the mid-frontal theta synchronization effect **(1A)** was due in part to an increase in mid-frontal theta desynchronization for the main-verb during SRC containing sentences. Furthermore, the occipital alpha desynchronization displayed in the contrast TFR **(1B)** is due to a lack of alpha synchrony for ORC containing sentences. Taken together, these results suggest that working memory recall is taxed during the integration of information at the main verb of a sentence (theta synchronization), while attention is more focused during ORC processing overall.

Figure 2: Individual condition TFRs