Cognitive control supports recovery from misanalysis: Evidence from neural oscillations

Valerie Langlois[1], Madeleine Wade[1], Angela Montiel[1], Tal Ness[2], Jared Novick[2], & Albert Kim[1]
[1]University of Colorado Boulder, [2]University of Maryland

There is growing evidence that cognitive control plays an important role in real-time sentence processing[1-3]. However, there is also a lack of consensus across the field about which specific sorts of language processing challenges do or do not engage cognitive control. Here we tested the hypothesis that cognitive control is engaged specifically when comprehenders must resolve representational conflict between multiple interpretations. We evaluated our hypothesis by testing whether cognitive control would be engaged in response to garden-path errors during sentence reading, in which comprehenders must resolve conflict between an initial but incorrect interpretation and an alternative, grammatically licensed interpretation. Crucially, we also predicted that semantic and syntactic anomalies, which are difficult to process but do not engender representational conflict, would not engage cognitive control. As a dependent measure of real time cognitive control engagement during sentence processing, we used neural oscillatory activity in the theta-band (3-8 Hz), which has previously shown sensitivity to tasks like Stroop[4].

Thirty participants read ambiguous and unambiguous English sentences (Table 1.1) in the RSVP format while EEG was recorded. Ambiguous sentences were initially compatible with a reflexive or transitive parse at the main verb (Anna dressed herself *or* Anna dressed the baby). Comprehenders tend to commit early to the transitive parse, which becomes incompatible with the input beginning at 'baby' or 'spit'[5,6]. To successfully understand the sentence, comprehenders must resolve representational conflict between the initial but incorrect transitive parse and grammatically licensed reflexive parse. We hypothesized that this conflict engages cognitive control, leading to an increase in theta-band activity. Consistent with this prediction, ambiguous sentences elicited increased theta-band power ~500 ms after 'baby', relative to the unambiguous control sentences (cluster-based permutation test[7] p=.02, Fig.1a). The ambiguous garden path sentences also elicited a classic P600 ERP effect at 'baby' and 'spit', relative to the same words within unambiguous control sentences (p=.05; p<.01; Fig.1c).

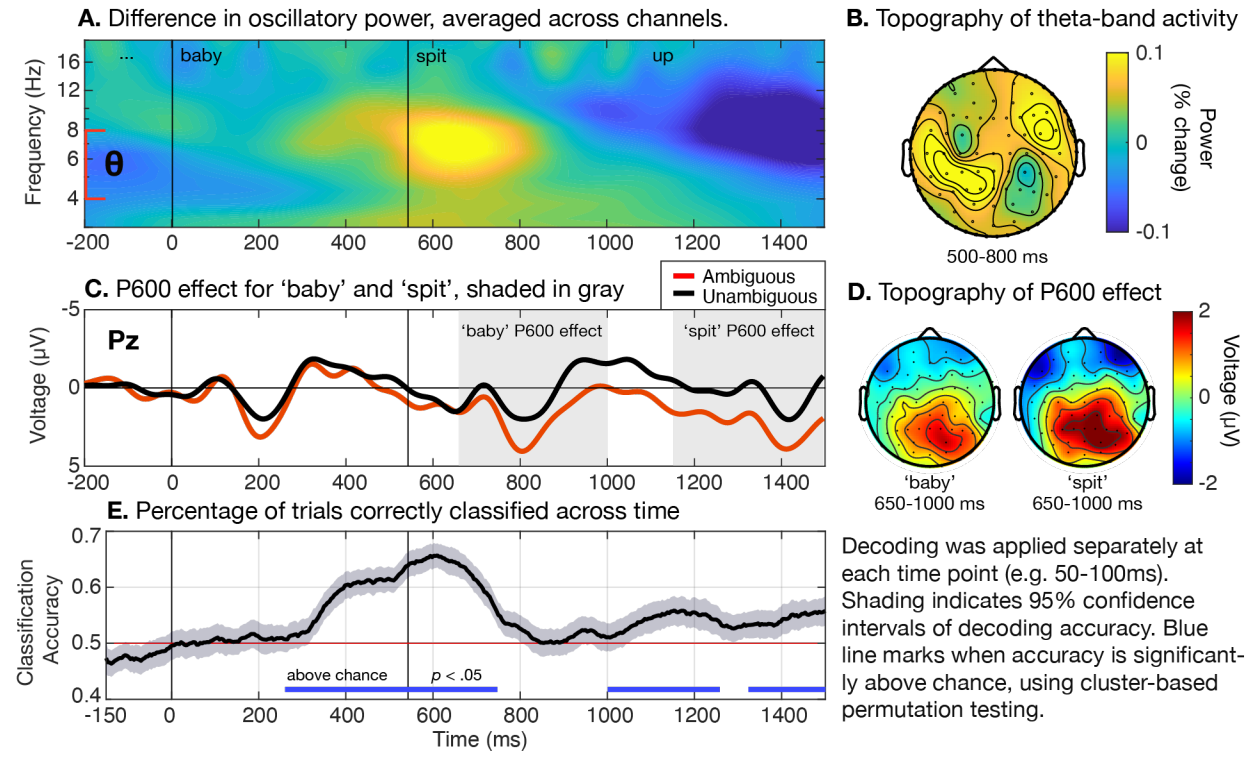
The same participants read 90 sentences that were either syntactically anomalous, semantically anomalous, or well-formed (Table 1.2). The anomalies engender semantic and syntactic processing difficulty which makes them challenging, but lack representational conflict. As predicted, the anomalous verbs elicited no increased theta-band power, relative to well-formed verbs (Fig.2&3). Meanwhile, the anomalies did elicit N400 and P600 effects in the ERP, indicating that the anomalies did impose semantic and syntactic processing difficulty.

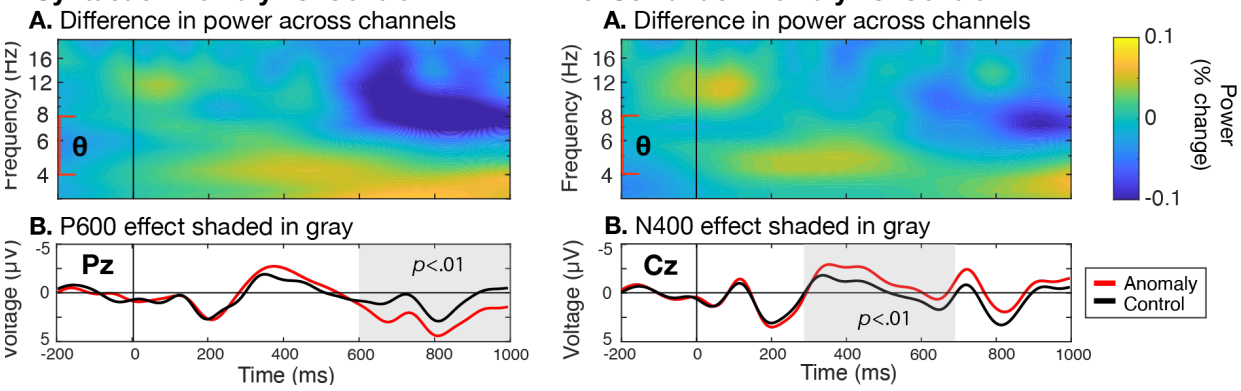
We further assessed whether theta activity reflects processes that support recovery from misinterpretation, by asking whether we could decode comprehension accuracy from trial-level theta activity. We trained a linear classifier to separate trial-level patterns of brain activity corresponding to correctly or incorrectly understood sentences. Trials were labeled based on responses to post-sentence questions like "Did Anna dress herself?" A YES response indicated correct reanalysis (Anna dressed herself), while a NO response indicated a failure to revise the incorrect garden path interpretation (Anna dressed the baby). We trained the classifier on separate 50 ms windows of EEG activity, beginning at 150 ms before the onset of 'baby' and continuing in 4 ms increments up to 1500 ms. Activity in each window was represented as a vector of mean theta power values at each of the 64 channels. Classifier decoding accuracy was above chance from 250-750 ms after the onset of baby (p<.01), and peaked at ~65% around 600 ms, which coincided with the latency of the significant group-level ambiguity effect (Fig.1e).

Our findings provide new evidence that cognitive control is engaged in real-time to support recovery from misanalysis during sentence processing. Theta-band activity provides a selective index of cognitive control engagement, which occurs in response to representational conflict during sentence processing but not during other difficult processing scenarios which lack conflict. Theta-band activity is a promising tool for future investigation of the real-time dynamics of cognitive control engagement during sentence processing.

Table 1. Example sentences with critical words in bold. Each sentence type had N=30

	Sentence Type	Sentence	Prediction
1a	Garden-Path Ambiguous:	While Anna dressed the **baby spit** up in the crib.	↑ theta
b	Unambiguous:	While Anna dressed, the **baby spit** up in the crib.	
2a	Syntactic Anomaly:	The chicks always **chirps** until the father brings food.	no theta change
b	Semantic Anomaly:	The chicks always **staple** until the father brings food.	
c	Control:	The chicks always **chirp** until the father brings food.	





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