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Theta-Band Neural Oscillations Reflect Cognitive Control During Language Processing

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As we interpret language moment by moment, we often encounter conflicting cues in the input that create incompatible representations of sentence meaning, which must be promptly resolved. Although ample evidence suggests that cognitive control aids in the resolution of such conflict, the methods commonly used to assess cognitive control's involvement in language comprehension provide limited information about the time course of its engagement. Here, we show that neural oscillatory activity in the theta-band (~3–8 Hz), which is associated with cognitive control in nonlinguistic tasks like Stroop and Flanker, provides a real-time index of cognitive control during language processing. We conducted time-frequency analyses of four electroencephalogram data sets, and consistently observed that increased theta-band power was elicited by various kinds of linguistic conflict. Moreover, increases in the degree of conflict within a sentence produced greater increases in theta activity. These effects emerged as early as 300 ms from the onset of the initiating event, indicating rapid cognitive-control recruitment during sentence processing in response to conflicting representations. Crucially, the effect patterns could not be ascribed to processing difficulty that is not due to conflict (e.g., semantic implausibility was neither necessary nor sufficient to elicit theta activity). We suggest that neural oscillations in the theta-band offer a reliable way to test specific hypotheses about cognitive-control engagement during real-time language comprehension.

Public Significance Statement
The results reported in this work provide the clearest evidence available that theta-band oscillations index cognitive control demands during language comprehension, thus extending previous findings that theta-band activity is elicited by representational conflict in cognitive tasks like Flanker and Stroop. Our findings support the growing body of work indicating that cognitive control plays a core role in ordinary language comprehension and provide a novel application of an established electrophysiological measure to study the real-time dynamics of cognitive control operations during sentence processing. The theta effects observed in this work, which appeared rapidly upon encountering the linguistic conflict, corroborate psycholinguistic models predicting that conflict during comprehension must be resolved quickly for successful communication.

Keywords: cognitive control, language processing, electroencephalography, sentence comprehension, theta oscillations

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During language processing, readers and listeners must dynamically weigh multiple cues to interpretation to guide incremental parsing decisions. Sometimes, however, various cues point to different and incompatible representations of sentence meaning, forcing the comprehender to select a single best analysis from conflicting alternatives. For example, in a sentence like "This is the cat that the mouse chased," the syntactic structure dictates that the mouse is the chaser (the Agent) and the cat is the fleer (the Theme); but event plausibility supports the opposite role assignments (cats usually chase mice). Thus, the mouse-chasing-cat and cat-chasing-mouse interpretations both receive strong support from contradictory sources of evidence. Mounting data suggest that, in order to resolve such linguistic conflict, cognitive control aids in the regulation of comprehenders' language processing commitments to enable selection of one analysis over another (e.g., Hsu et al., 2021; January et al., 2009; Ness et al., 2023). Here, we test the hypothesis that neural oscillatory activity in the theta-band (3–8 Hz) provides a real-time index of cognitive-control engagement during sentence comprehension when such conflict arises, building on previous work (e.g., Rommers et al., 2017). We test this hypothesis in a comprehensive analysis of four different electroencephalogram (EEG) data sets, which had been previously collected and analyzed in terms of event-related potentials (ERPs) but not neural oscillations. Our findings demonstrate that theta-band power effects consistently track the presence and difficulty of linguistic conflict across a mix of sentence types that share the demand for cognitive control.

Cognitive Control During Language Processing

A growing body of work has shown that cognitive control plays an essential and pervasive role in language comprehension, by regulating information processing to support the selection of the most appropriate interpretation when linguistic input generates conflicting representations (Ness et al., 2023; Novick et al., 2005, 2010; Humphreys & Gennari, 2014). For instance, neuroimaging studies provide evidence that conflict during sentence processing activates the same prefrontal cortical regions as conflict in nonlinguistic tasks such as Flanker and Stroop, which suggests a common (domain-general) cognitive-control function (Hsu et al., 2017; January et al., 2009; Thothathiri et al., 2012; Ye & Zhou, 2009). Lesion studies find that damage to the same prefrontal areas results in patients' failure to resolve conflict across various nonlinguistic and linguistic tasks in a way that impedes comprehension, indicating that cognitive control is a necessary component to real-time interpretation procedures (e.g., Novick et al., 2009; Vuong & Martin, 2011). Some studies have also reported that, in healthy adults, individual differences in performance on standard measures of cognitive control correlate with performance on language processing tasks that create conflict between incompatible representations (e.g., Brothers et al., 2022; Brown-Schmidt, 2009; Nozari et al., 2016; Vuong & Martin, 2014). Moreover, multiweek training on a nonlinguistic cognitive control task leads to selective posttest improvement in the processing of sentences that contain conflicting cues to interpretation (Hussey et al., 2017; Novick et al., 2014), showing that increases in cognitive control can have ensuing effects on language comprehension. Finally, cross-task adaptation experiments have demonstrated that cognitive control can be modulated within healthy participants through performance on a canonical cognitive-control task (e.g., Stroop or Flanker), with direct impacts on subsequent sentence processing operations (Hsu et al., 2021; Hsu & Novick, 2016; Navarro-Torres et al., 2019; Ovans et al., 2022; Thothathiri et al., 2018). These effect patterns illustrate that an individual's state of cognitive control has a causal effect on their real-time parsing decisions (for a review, see Ness et al., 2023).

An important challenge for theories addressing the role of cognitive control in language processing is to unite a range of sentence processing phenomena by their common employment of cognitive control, while also specifying how cognitive control is distinct from other mechanisms. Everyday sentence processing presents readers and listeners with a variety of challenges to interpretation, including syntactically unexpected or ambiguous words, grammatically complex structures, inputs that require pragmatic inferences, and noisy environments. Because these various situations all impose measurable processing difficulty for comprehenders, it might be tempting to conclude that they all similarly engage cognitive control. Yet difficulty could arise for different reasons, invoking other domain-general mechanisms such as working memory or attention. Moreover, some linguistic processing challenges might be resolved through semantic or syntactic analysis without requiring domain-general mechanisms. If our psycholinguistic theories are unable to distinguish between situations that require cognitive control from those requiring other sorts of mechanisms, we risk the significant conceptual error of positing the same explanation for different phenomena. A successful theory of language comprehension requires a precise delineation of the processing challenges that consistently involve cognitive control and those that do not.

We have proposed that cognitive control is deployed during language comprehension specifically under conditions of conflict between strongly activated but incompatible representations of a sentence's meaning (Ness et al., 2023; Novick et al., 2005). The predictions of this proposal are illustrated by the sentence "The restaurant owner forgot which *waitress* the *customer* had *served* during dinner yesterday," which was investigated by Chow et al. (2016, and is Sentence 1.1 in Table 1 below). Here, two different interpretations are simultaneously supported: Upon encountering the verb "served", the syntactic cues in the sentence require that "customer" be assigned the agent role ("customer" is the syntactic subject of "served"), whereas world knowledge suggests that "waitress" should be assigned the Agent role (waitresses are likely to serve customers). The availability of two opposing interpretations in such role-reversal sentences gives rise to representational conflict. These and other situations that result in simultaneously active, incompatible representations are predicted to engender conflict, which recruits cognitive control.

Crucially, the model also predicts that sentences can be anomalous or difficult without involving representational conflict, as exemplified by "The restaurant owner forgot which teacher the child had *collected* during dinner yesterday". (Sentence 1.3 in Table 1). Here, the syntactic cues clearly indicate that "child" and "teacher" are Agent and Theme, respectively, of "collected", and this interpretation is semantically implausible (it is unusual for a child to collect a teacher). Unlike the reversible sentence above, however, the semantic cues do not support an alternative, conflicting analysis. The model predicts that this type of sentence will result in semantic processing difficulty *without* cognitive-control engagement.

Table 1
Example Sentences and Norming Values for Study 1 (Chow et al., 2016)

Condition	Sentence	CP	Pl
1.1. Role reversal	The restaurant owner forgot which waitress the customer had **served** during dinner yesterday.	CP: 0%	Pl: 23.8%
1.2. Control for role-reversal	The restaurant owner forgot which customer the waitress had **served** during dinner yesterday.	CP: 25%	Pl: 85.4%
1.3. No-conflict anomaly	The restaurant owner forgot which teacher the child had **collected** during dinner yesterday.	CP: 0%	Pl: 31.1%
1.4. Control for no-conflict anomaly	The restaurant owner forgot which insects the child had **collected** during dinner yesterday.	CP: 28%	Pl: 90.3%

Note. The critical word in each condition is marked in bold. CP = cloze probability (percentage of the target word in a sentence completion task); Pl = plausibility (percentage of "plausible" judgment in a plausibility judgment task).

The primary goal of our study is to test the model-derived predictions regarding cognitive-control engagement during real-time sentence comprehension. Specifically, we will test the hypothesis that processing challenges that engender conflict between incompatible representations will result in increased cognitive-control engagement. At the same time, we predict that challenging, yet nonconflict-inducing sentence processing scenarios will not engage cognitive control.

Theta-Band EEG Oscillations—A Potential Real-Time Marker of Cognitive Control

The present study measured scalp-recorded oscillatory neural activity in the theta-band (3–8 Hz) as an index of real-time cognitive-control engagement during language comprehension. Neural oscillations at multiple frequency bands (i.e., δ: 1–3 Hz; θ: 3–8 Hz; α: 8–12 Hz) are widely thought to support the dynamic formation of functional networks through short- and long-range communication between neural areas (Buzsáki & Draguhn, 2004; von Stein & Sarnthein, 2000). Neural oscillations, like event-related potentials, provide temporal resolution at a scale of tens of milliseconds, which enables sensitivity to the transient neurocognitive operations of real-time processing. Moreover, there is growing evidence that neural oscillations are sensitive to different processes than ERPs (e.g., M. C. Bastiaansen et al., 2008; M. Bastiaansen & Hagoort, 2015; Wang, Jensen, et al., 2012), even though they are extracted from the same EEG recordings, suggesting that they complement the existing findings so far from ERPs. We focused specifically on oscillations in the theta-band, because of a growing literature implicating theta-band activity in cognitive control, as summarized below.

Theta-Band Oscillations in Nonlinguistic Contexts

Several studies have demonstrated that theta-band oscillatory power increases under task conditions associated with cognitive-control engagement (e.g., Chevalier et al., 2021; Cohen & Cavanagh, 2011; Ergen et al., 2014; Haciahmet et al., 2023; Hanslmayr et al., 2008). For instance, Hanslmayr et al. (2008) showed that theta-band activity increased linearly with the degree of conflict in a Stroop trial (Incongruent > Neutral > Congruent) within 600 ms after conflict arises. Similarly, Cohen and Cavanagh (2011) demonstrated that theta-band activity correlates with the degree of conflict experienced in each trial in a Flanker task. The theta-band effects have generally been concentrated over frontal electrodes, and source localization analyses as well as convergent functional magnetic resonance imaging results have indicated that the generators of the theta-band activity are in brain regions associated with cognitive control, including the medial and lateral prefrontal cortex (for review, see Cavanagh & Frank, 2014). Together, the findings suggest that theta-band activity provides a real-time index of cognitive-control engagement, at least in nonlinguistic task performance.

Theta-Band EEG Oscillations During Sentence Processing

Theta-band effects have also been observed in studies of language processing, and several findings are compatible with an interpretation in terms of cognitive control (Kielar et al., 2015; Roehm et al., 2004, 2017). For instance, Rommers et al. (2017) found increased theta-band activity during the comprehension of sentences like "The children went outside to *look*," when a plausible but unexpected word ("look") appears in a context that generates an expectancy for another word (e.g., "play"); meanwhile, theta-band activity was not observed in low-constraint sentences that do not generate a strong prediction. This study concluded that theta-band activity could reflect cognitive control triggered by a discrepancy between predicted and received linguistic inputs, with control possibly contributing to adaptive learning from the prediction error that arises. This conclusion is similar to the hypothesis we test in the present study.

Most accounts of theta-power modulations during language processing, however, have not invoked cognitive control. Several researchers have concluded that theta-band effects reflect the difficulty of lexical retrieval (M. C. Bastiaansen et al., 2008; M. Bastiaansen & Hagoort, 2015; Hald et al., 2006). Lexical retrieval difficulty provides one possible explanation for findings that theta-band power increases in response to semantic anomalies, such as "The Dutch trains are *sour*" (M. Bastiaansen & Hagoort, 2015; Davidson & Indefrey, 2007; Hagoort et al., 2004; Kielar et al., 2015; Wang, Zhu, et al., 2012). In fact, Rommers et al. (2017) considered such an alternative account of the findings described above, suggesting that unpredicted but plausible words would require more lexical retrieval processing than predicted words.

It should be noted that lexical retrieval difficulty due to semantic anomaly does not provide a perfect explanation for theta-band effects during sentence processing. Semantic anomaly does not always elicit increased theta-band power (Penolazzi et al., 2009;

Wang, Jensen, et al., 2012), and theta-band power has been reported to increase for syntactic anomalies, such as subject–verb agreement violations (e.g., M. C. Bastiaansen et al., 2002; Kielar et al., 2015; Pérez et al., 2012), which may not impose demands on lexical retrieval. Furthermore, semantic and syntactic anomalies have sometimes been associated with additional patterns of oscillatory activity, specifically decreased power in the α or β bands (Davidson & Indefrey, 2007; Kielar et al., 2015; Pérez et al., 2012).

Other theta-band effects during language processing have been explained in terms of working memory (Bonhage et al., 2017; Meltzer et al., 2017; Meyer et al., 2015; Weiss et al., 2005; for a review, see Prystauka & Lewis, 2019). For instance, one study found that pronouns elicited greater theta-band power when they referred to an antecedent noun phrase that was embedded within a relative clause, compared to a nonembedded noun phrase in the preceding main clause (Meyer et al., 2015). This result was attributed to the difficulty of retrieving the referent from working memory, because the antecedent must be maintained across two clauses versus only one. Weiss et al. (2005) found that the processing of complex relative clauses increased the coherence between frontal and posterior electrodes specifically in the theta-band, which is also compatible with theta as an index of working memory demands. Furthermore, theta-band effects elicited by semantic anomalies, mentioned above, have sometimes been explained in terms of working memory, which may be necessary to integrate semantically implausible words (M. Bastiaansen & Hagoort, 2015; Hald et al., 2006; Kielar et al., 2015). Finally, increased theta-band power is widely observed in response to working memory demands in nonlinguistic tasks (e.g., Hsieh & Ranganath, 2014th, 2014; Jensen & Tesche, 2002; Sauseng et al., 2010; Zakrzewska & Brzezicka, 2014).

As with semantic anomalies, the explanation of language processing theta effects in terms of working memory is imperfect. Two studies found that the demands of understanding syntactically complex structures (e.g., relative clauses), which are widely assumed to be the paradigmatic case for working memory during sentence processing, modulated power in the α and β bands and did not affect theta-band activity (Meltzer & Braun, 2011; Meyer et al., 2013).

The Need for Greater Understanding of Theta-Band Activity During Language Processing

Overall, a growing body of work has observed modulations of theta-band oscillatory activity in contexts related to cognitive control, both during language processing and nonlinguistic task performance, suggesting that theta-band activity may provide an index of cognitive control engagement. However, theta-band effects are also observed in situations that are arguably unrelated to cognitive control, and some important contradictions and mixed results remain unexplained within the accumulated findings. Further empirical work is needed to build a comprehensive understanding of the functional underpinnings of theta-band oscillatory activity during language and cognition.

The Present Study

The present study systematically tested the hypothesis that representational conflict during language comprehension elicits increased oscillatory power in the theta-band. Using previously collected data from four EEG studies (Chow et al., 2016; Kim & Sikos, 2011; Ness & Meltzer-Asscher, 2018; Ovans et al., 2022), we tested this hypothesis in disparate types of language comprehension challenges, which typified different sources of representational conflict that occur during everyday language. In Study 1, we examined reversible sentences of the sort outlined above (Table 1, Sentence 1.1; Chow et al., 2016), which engender conflict between a syntactically licensed and a semantically plausible interpretation. In Study 2, we examined conflict between context-derived expectations and inputs that violate those expectations, exemplified by the sentence "Dan works as a cook, but he aspires to open his own *bakery*" (Ness & Meltzer-Asscher, 2018). Such sentences engender conflict between a strong prediction for *restaurant* and the bottom-up input *bakery*. In Studies 3 and 4, we again examined conflicts between strong syntactic and semantic cues, exemplified by the sentence fragment *The hearty meal would devour …*, which engenders conflict between a syntactically licensed interpretation (*meal* is the Agent of *devour*) and a semantically attractive but syntactically unlicensed interpretation (*meal* should be the Theme of *devour*; Kim & Sikos, 2011; Ovans et al., 2022). These four types of linguistic conflict are described in more detail in the sections below reporting each individual study.

Across our four studies, we also tested three subhypotheses, which expand on our general hypothesis that representational conflict during sentence processing elicits theta-band activity. The subhypotheses are as follows. Subhypothesis 1: In the absence of representational conflict, semantic implausibility is not, by itself, sufficient to elicit theta-band activity; Subhypothesis 2: Conflict can elicit theta-band activity in the absence of any semantic implausibility; Subhypothesis 3: Parametric manipulations of the degree of conflict lead to increases in theta-band activity. If our hypotheses are confirmed, the findings would establish theta-band power as a valuable new measure of cognitive-control engagement during language processing.

Our four studies are the first to directly test the hypothesis that representational conflict during sentence processing elicits increased theta-band power. Although we analyzed data from prior studies, these data sets were originally collected to test hypotheses about ERPs, specifically about the N400, P600, and post-N400 frontal positivity effects, and not about theta oscillations. We believe that ERPs and neural oscillations index different neurocognitive operations, and our predictions regarding the functional antecedents of theta oscillations are distinct from the predictions regarding ERPs. We elaborate on this point below by discussing each of our theta-band activity findings in relation to the original ERP results.

General Method—EEG Data Collection, Data Analysis, and Statistical Inferences

In each of our four studies, we analyzed EEG data that was collected while participants silently read sentences for comprehension, one word at a time from the center of a computer screen (Rapid Serial Visual Presentation [RSVP]). In all studies, one word within the stimulus sentences was the critical word, where the presence of representational conflict was manipulated, and our analyses focused on brain activity elicited by the critical word. In the section below, we describe the general methods for data formatting and preprocessing, time-frequency representation, and statistical inference, which we applied to all four data sets. Study-specific methodological details, which reflect differences among the studies with respect to experimental design and data acquisition systems, are reported later in the sections specific to each study.

Preprocessing

The raw EEG data from all four data sets was high-pass filtered at 0.1 Hz and rereferenced to the average of both mastoid electrodes. Eye-blink artifacts were identified and corrected using independent component analysis. Remaining artifacts were identified and rejected through visual inspection and automatic detection of major voltage movements.[1] The EEG time series was divided for analysis into epochs spanning 1.5 s prior to critical word onset to 2.0 s after critical word onset. Preprocessing was performed using functions in EEGLab (Delorme & Makeig, 2004).

Time-Frequency Representations

Time-frequency representations (TFRs) captured instantaneous power at each frequency, at each time point (as in Figures 1, 2, 3, 4, and 5). TFRs were created by convolving a complex Morlet wavelet with the preprocessed EEG time series data, using wavelet kernels at 30 log-spaced frequencies between 2 and 80 Hz (kernel width was five cycles at each frequency). The power at each time-frequency combination was calculated as the square of the corresponding wavelet coefficient. TFRs were computed using functions in the FieldTrip toolbox (Oostenveld et al., 2011). Descriptive power spectrum analyses and overall theta topography in each data set are provided in the Supplemental Materials. Note that although we computed TFRs that ranged from 2 to 80 Hz in the frequency dimension, our hypotheses specifically concerned theta-band activity (3–8 Hz), and our inferential statistical analyses focused on this band.

Statistical Analyses

We used a cluster-based permutation test programmed in Fieldtrip (Maris & Oostenveld, 2007) to evaluate support for our hypothesis that greater conflict would lead to increased theta-band power. Each test identified clusters of points in the observed time-frequency representation for which the difference in power between high- and low-conflict conditions was greater than expected by chance. A cluster's size was measured by identifying a set of adjacent (in time and frequency) points in the TFR for which the pointwise test for high conflict > low conflict was significant, and then summing the pointwise test statistics to yield an aggregate statistic for the whole cluster. This aggregate test statistic was then compared to a null hypothesis distribution, which was generated by creating 5,000 permutations of the original data set, where each permutation randomly reassigned condition labels within the data, and calculated the largest possible cluster of activity in each permutation. Each test produced a *p* value, which was calculated as the proportion of permutations that yielded a cluster larger than the cluster created from the observed data.

As our hypotheses were specifically about theta-band activity, we conducted a cluster-based permutation test on the TFRs spanning the frequency range 3–8 Hz and the time points 0–1,000 ms poststimulus-onset.[2] Analyses were performed on the average of TFRs computed for each of the 64 electrodes; each participant contributed one average TFR for each experimental condition. We additionally performed a more exploratory broadband cluster-based permutation test that spanned all frequencies between 2 and 30 Hz over all time points, in order to allow for effects outside the theta frequency band to emerge, even though we did not hypothesize any such effects. The broadband analyses produced no significant clusters in other frequency bands, but they did generally confirm the theta-band effects reported below. In what follows, we report the results of the narrow-band analyses, which identified clusters within the theta-band.

Transparency and Openness

We report all data exclusions, all manipulations, and all measures used in the studies. The data are available at https://osf.io/b43xc/?view_only=2100f776ac0a4def85db63b7c948bd44. The studies' designs and analyses were not preregistered.

Study 1

Study 1 tested the hypothesis that conflict between two thematic-role assignments elicits increased theta-band activity, by examining the role-reversal conflict depicted in Sentence 1.1 (see Table 1). As explained above, upon encountering the verb "served", event/world knowledge suggests that "the waitress" should be assigned the role of Agent, while the sentence structure points to the opposite role assignment ("customer" is the Agent and "waitress" is the Theme). This creates a conflict because both interpretations are simultaneously supported and the comprehender must select between them. We, therefore, hypothesized that cognitive-control engagement at the critical verb ("served") would increase theta-band activity compared to congruent sentences (e.g., "Which customer the waitress had *served*"; Sentence 1.2 in Table 1).

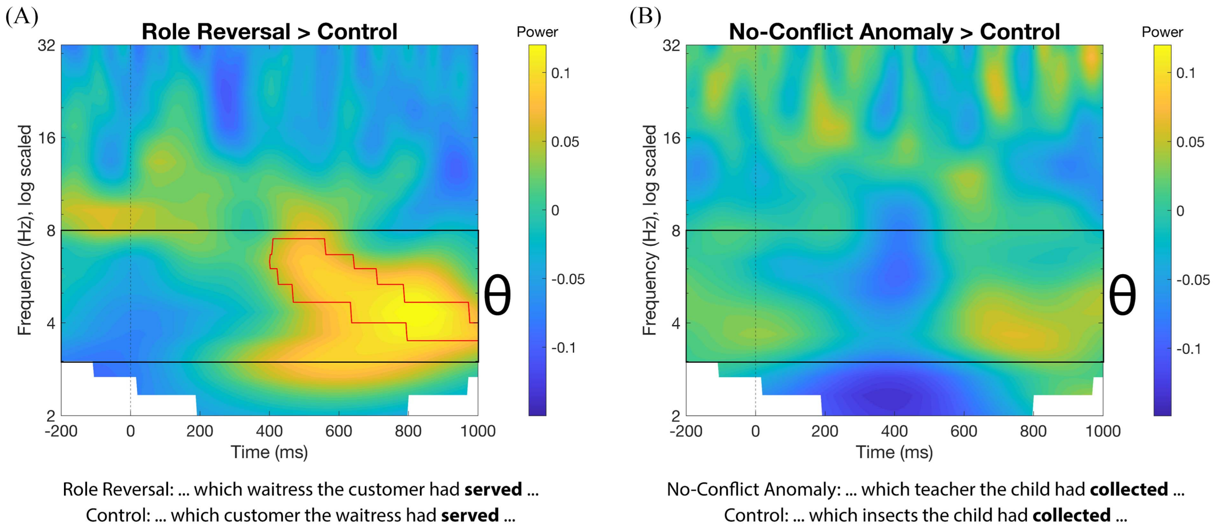
In addition, we examine another type of implausible sentence *that does not engender conflict*, for example, "Which teacher the child had *collected*" (Sentence 1.3 in Table 1). In these no-conflict anomalies (originally referred to as "Argument Substitution" by Chow et al., 2016), the critical verb (e.g., "collected") is implausible, but the sentences do not contain linguistic cues pointing to two conflicting interpretations. This allows us to address Subhypothesis 1, which is that in the absence of representational conflict, semantic implausibility will not elicit theta-band activity. This stems from our general hypothesis that theta-band activity specifically marks cognitive-control engagement. Thus, as opposed to role reversals, no-conflict anomalies are not expected to elicit increased theta-band activity compared to congruent sentences (Sentence 1.4 in Table 1).

[1] In Studies 1–3, trials were rejected if they contained voltage movements exceeding a threshold of 5 *SDs* from the epoch mean voltage, while in Study 4, the threshold was voltage movements exceeding 100 μV. Both thresholds are appropriate for artifact rejection. However, the difference between thresholds used in Studies 1–3 and 4 was unintentional and resulted from a miscommunication within our research team about which threshold to apply.

[2] Although some studies have defined the theta band more narrowly (e.g., 4–7 Hz), we examined a slightly wider band of frequencies in order to cover the full range of frequencies that have been characterized as theta activity across studies.

Figure 1

Difference in Oscillatory Power Between (A) Role-Reversal and Its Control Condition, and (B) No-Conflict Anomaly and Its Control Condition



Note. In both panels, the *x*-axis represents time (in milliseconds), with zero marking the onset of the critical word. The theta-band frequencies (~3–8 Hz) are delineated by the black box. The red outline marks the significant cluster for the effect of role-reversal relative to control sentences, determined by a cluster-based permutation test on all frequencies (2–30 Hz) and time points (0–1,000 ms), across all electrodes. See the online article for the color version of this figure.

Data Acquisition

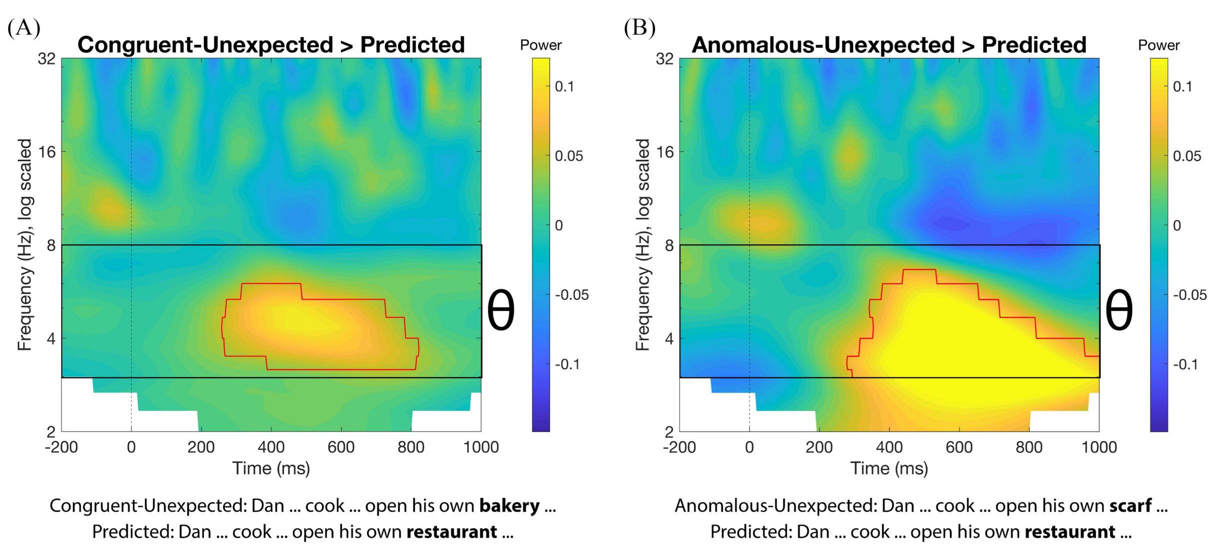
We analyzed data that was originally collected by Chow et al. (2016, Experiment 1). Continuous EEG was recorded at a 1,000 Hz sample rate with a Neuroscan Synamps EEG system from 29 Ag/AgCl scalp electrodes (10–20 configuration).

Materials, Procedure, and Participants

The stimulus materials consisted of 120 sentence pairs. Sixty sentence pairs contained a role-reversal sentence and its control (1.1 and 1.2 in Table 1, respectively), and 60 pairs contained a no-conflict anomalous sentence and its control (1.3 and 1.4 in Table 1,

Figure 2

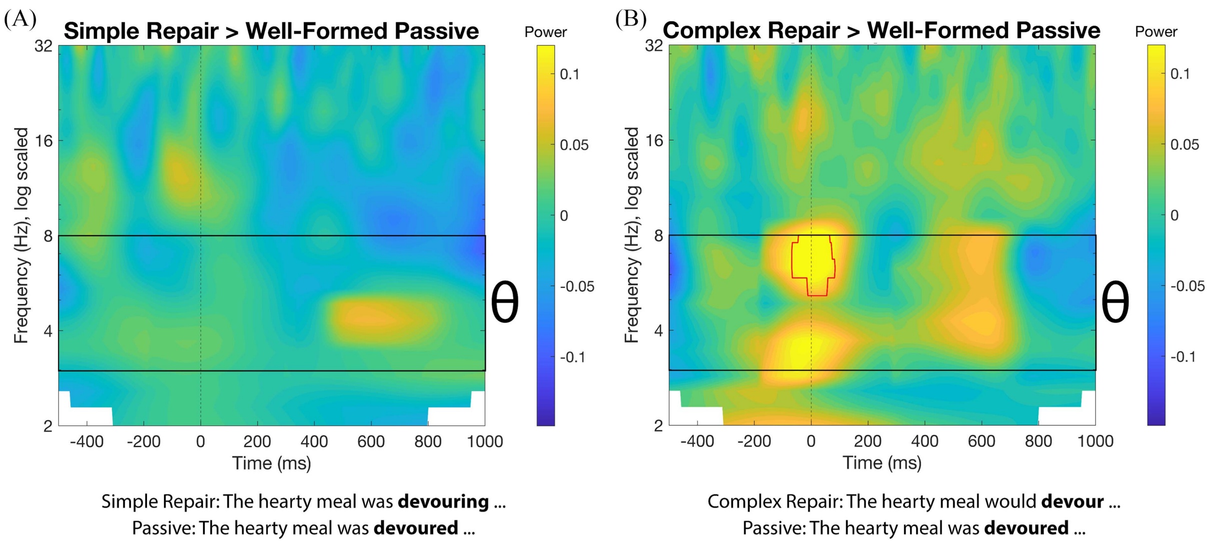
Difference in Oscillatory Power Between (A) Congruent-Unexpected and Predicted, (B) Anomalous-Unexpected and Predicted



Note. The *x*-axis represents time (in milliseconds) with zero marking the onset of the critical word. The theta-band frequencies (~3–8 Hz) are delineated by the black box. The red outline marks the significant cluster for the effect in each contrast, determined by a cluster-based permutation test on all frequencies (2–30 Hz) and time points (0–1,000 ms), across all electrodes. See the online article for the color version of this figure.

Figure 3

Difference in Oscillatory Power Between (A) Simple Repair and Well-Formed Passive, (B) Complex Repair and Well-Formed Passive



Note. The *x*-axis represents time (in milliseconds) with zero marking the onset of the verb. The theta-band frequencies (~3–8 Hz) are delineated by the black box. The red outline marks the significant cluster for the effect of complex repair relative to well-formed passive sentences, determined by a cluster-based permutation test on theta frequencies (3–8 Hz) and all time points (0–1,000 ms), across all electrodes. See the online article for the color version of this figure.

respectively). Both experimental sentence types potentially led to semantically implausible interpretations, as reflected in average cloze probability and plausibility judgments in each condition, which are reported in Table 1. Each participant saw one version of each sentence pair, resulting in 30 trials per condition. Sentences were administered in RSVP format (stimulus onset asynchrony [SOA] = 530 ms; interstimulus interval [ISI] = 230 ms). Following each sentence, participants indicated via button press whether the sentence was plausible. Participants were 24 native English speakers from the University of Maryland community.

Results

Differences in oscillatory power are shown across the time-frequency plane for role-reversal versus control (Figure 1A) and no-conflict anomalies versus control (Figure 1B); yellow indicates a positive increase in theta power, while blue indicates negative-going changes. role-reversal sentences appeared to elicit greater power than the control sentences in the theta frequency range (~3–8 Hz) in a latency window beginning ~400 ms from critical word onset spanning to the end of the epoch (Figure 1A). Confirming this observation, the permutation analysis identified a cluster of role-reversal > control differences in theta-band power that extended from 3.4 to 7.9 Hz and 400–1,000 ms after critical-verb onset (see Figure 1A; cluster-level $p = .009$). As can also be observed in Figure 1B, the no-conflict anomalies did not appear to increase theta-band power compared to their control sentences. No cluster of no-conflict anomaly > control differences was identified by the permutation test.

The topographic distribution of the theta-band effect is presented descriptively in Figure 6. The theta-band difference, calculated across a window spanning 400–1,000 ms from critical-verb onset was greatest over the left frontal and right posterior electrodes (Figure 6).

Discussion

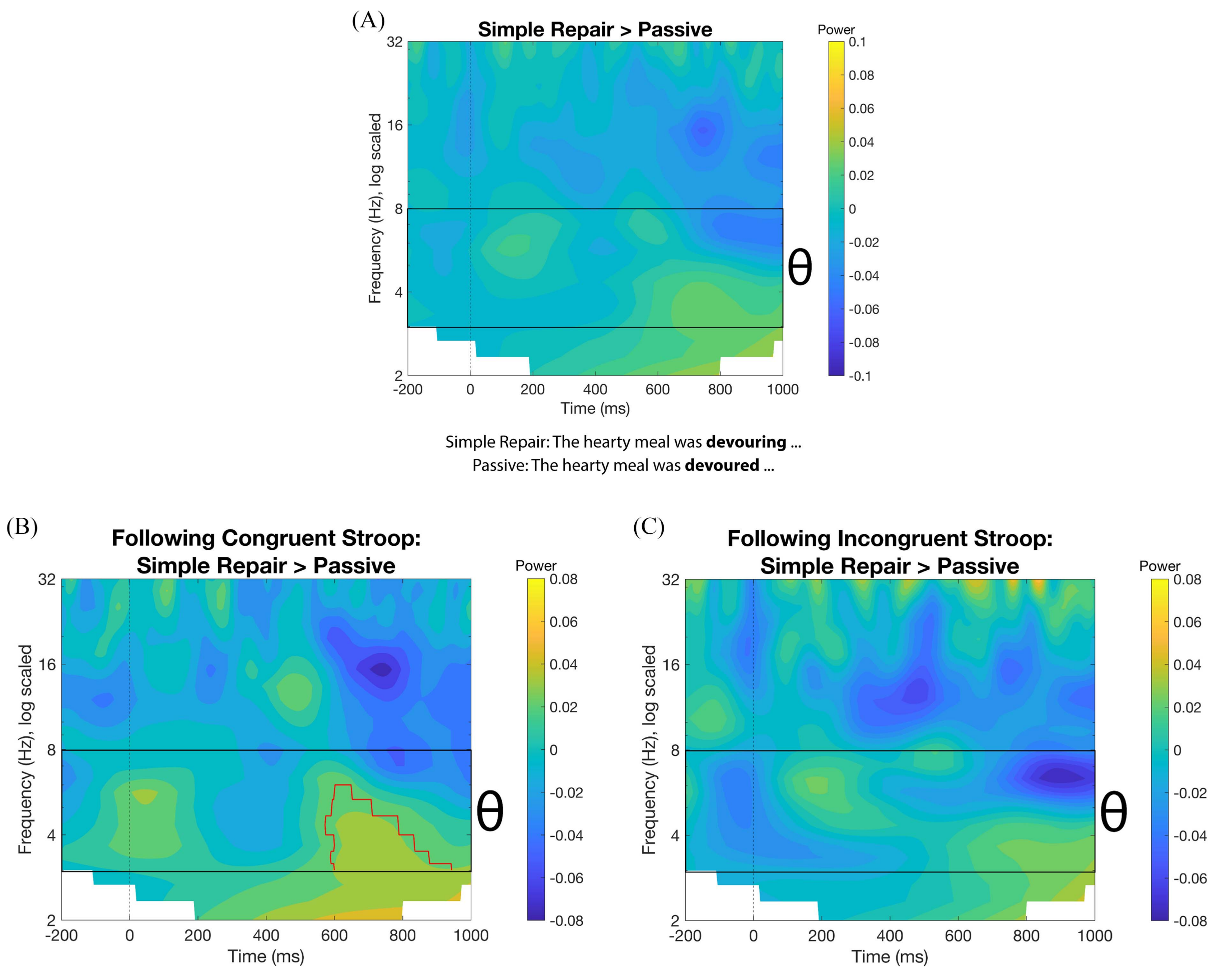
Role-Reversal conflict sentences (Sentence Type 1.1) elicited greater theta-band neural oscillatory activity than control sentences, but no-conflict anomalies (Sentence Type 1.3) did not. This effect pattern supports our general hypothesis that theta activity will increase in response to sentences that trigger conflict between two interpretations that each receive support from the linguistic input, as in our role-reversal sentences. Meanwhile, the no-conflict anomaly sentences, which were semantically implausible but did not engender conflict, did not increase theta-band activity. This pattern of effects provides support for our first subhypothesis: in the absence of representational conflict, semantic implausibility is not, by itself, sufficient to elicit theta-band activity. Overall, the results from Study 1 show a pattern in which representational conflict is the key antecedent condition for increased theta-band activity.

The theta effect began 400 ms after the critical-verb's onset, indicating rapid recruitment of cognitive control during real-time sentence processing. More specifically, the 400–1,000 ms window is commonly considered to reflect postretrieval, integrative processes (e.g., Brouwer et al., 2012; Delogu et al., 2019). The temporal profile of our theta-band effects is consistent with cognitive control engagement that occurs shortly after lexical retrieval of the verb.

The pattern of stimulus conditions that elicit theta-band effects in Study 1 dissociate from the conditions that elicit the ERP effects in the same data reported by Chow et al. (2016), which is consistent with the conclusion that the theta-band activity and the ERPs

Figure 4

Difference in Oscillatory Power Between (A) Simple Repair and Well-Formed Passive in All Trials, (B) Simple Repair and Well-Formed Passive Following Congruent Stroop, and (C) Simple Repair and Well-Formed Passive Following Incongruent Stroop

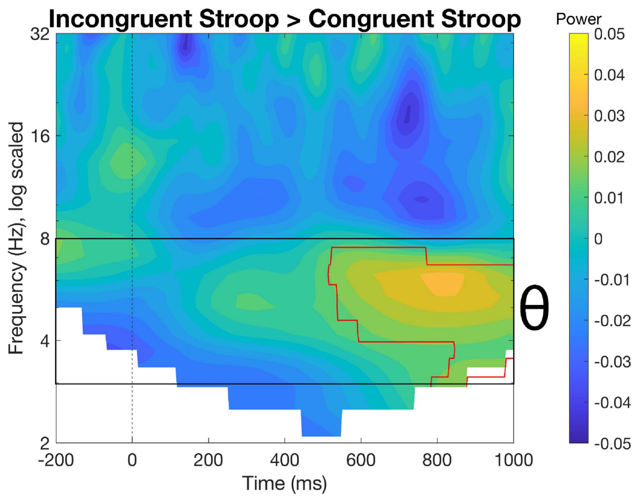


Note. The *x*-axis represents time (in milliseconds), with zero marking the onset of the critical word. The theta-band frequencies (~3–8 Hz) are delineated by the black box. The red outline marks the significant cluster for the effect of simple repair and well-formed passive following congruent Stroop, determined by a cluster-based permutation test on theta frequencies (3–8 Hz) and all time points (0–1,000 ms), across all electrodes. See the online article for the color version of this figure.

index distinct processes. While Chow et al. (2016) reported P600 ERP effects in both role reversals and no-conflict anomalies, our theta-band effect was specific to the former condition, suggesting a difference in the processes underlying the P600 ERP and the theta-band activity we have observed. Moreover, the absence of theta-band activity in the no-conflict anomaly condition also contrasts with Chow et al. (2016) observation of an N400 ERP effect in this condition. This dissociation is consistent with the conclusion that the theta-band activity in our study is not linked directly to semantic processing difficulty, which is a widely posited functional correlate of N400 effects.

Study 1 found that theta power increased when conflict arose between two interpretations that are both compatible with the linguistic input. However, the results allow for some potential variations of this conclusion. Because the role-reversal sentences can generate a semantically implausible outcome (e.g., it is unusual for a restaurant customer to serve a waitress), it is possible that semantic implausibility played *some* necessary role in eliciting the theta-band effects. Although semantic implausibility was not, by itself, sufficient to elicit theta-band effects—as evidenced by the no-conflict anomalous condition—it is conceivable that the theta-band effects in the role-reversal condition are due to the *combined* presence of representational conflict *and* the difficulty of semantically integrating implausible interpretations. In a second study that addressed this possibility, we examined conflicts that involved no semantic anomaly in order to test whether semantic anomaly is a necessary part of the antecedent conditions for theta-band effects.

Figure 5
Difference in Oscillatory Power Between Incongruent and Congruent Stroop



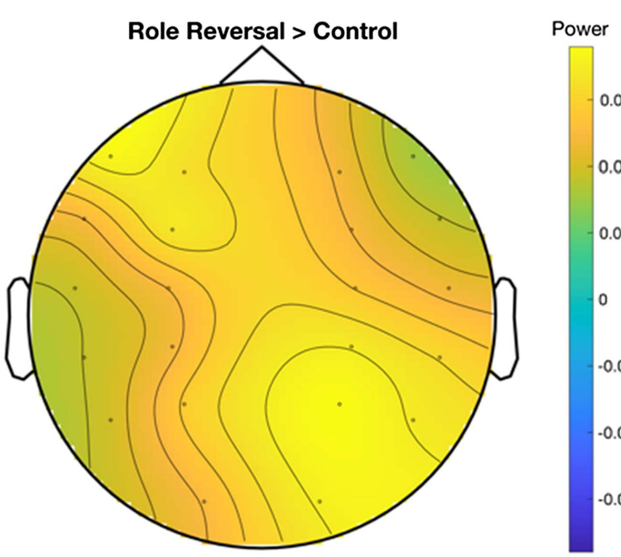
Note. The *x*-axis represents time (in milliseconds), with zero marking the onset of the critical word. The theta-band frequencies (~3–8 Hz) are delineated by the black box. The red outline marks the significant cluster for the effect of incongruent Stroop relative to congruent Stroop, determined by a cluster-based permutation test on all frequencies (2–30 Hz) and time points (0–1,000 ms), across all electrodes. See the online article for the color version of this figure.

Study 2

Study 2 investigated conflict between linguistic predictions and the bottom-up input (prediction violations). A previous study, reviewed in the Introduction, found that violations of predictions in strongly constraining sentences increased theta-band activity in a way that is consistent with cognitive-control operations (Rommers et al., 2017). However, other than this single study, the literature on theta effects in sentence processing has overwhelmingly focused on anomalous sentences (e.g., syntactic/semantic anomalies; see Introduction), reflecting a prevalent assumption that sentences must be abnormal in some way to elicit theta activity. In Study 2, we examined this issue by analyzing oscillatory EEG activity in high-constraint sentences, similar to Rommers et al. (2017), but with Hebrew sentences and participants. Participants read sentences like "Dan works as a cook, but he aspires to open his own *bakery*" (Table 2, Sentence 2.2; English translation). The initial portion of the sentence creates a strong prediction for the word "restaurant", which is violated by "bakery." We propose that incremental comprehension of such sentences creates a conflict between the strongly preactivated representation of the predicted word ("restaurant") and a lexical representation that is activated by the bottom-up input ("bakery"). We tested whether this conflict would result in increased theta-band activity, compared to no-conflict sentences like "Dan works as a cook, but he aspires to open his own *restaurant* " (Table 2, Sentence 2.1). Importantly, the conflict engendered by Sentence 2.2 does not involve semantic implausibility: Although the word "bakery" violates the prediction for "restaurant", it is plausible in its context. Whereas the theta-band effects in Study 1 might conceivably be due to the combined occurrence of representational conflict and semantic implausibility, the conflicts in Study 2 cannot be described in this way.

For comparison, we also examined sentences like "Dan works as a cook, but he aspires to open his own *scarf*" (Sentence 2.3), in which the same strong predictions were violated by a word that was flagrantly semantically anomalous ("scarf"); this is a condition not used by Rommers et al. (2017). This sentence type also engenders conflict between a preactivated prediction ("restaurant") and the bottom-up input ("scarf"). If implausibility is *necessary* for theta-band increases, then Sentence 2.3 but not 2.2 should elicit theta activity. We note that the presence of conflict in Sentence 2.3, as in Sentence 2.2, is due to the strength of the predictions afforded by the context (strong predictions of "restaurant" conflict with the bottom-up input).

Figure 6
Scalp Topography of the Role-Reversal > Control Difference in Theta-Band Power, Calculated Across a Time Window Spanning 400–1,000 ms From the Critical Verb Onset



Note. See the online article for the color version of this figure.

Data Acquisition

We analyzed data that were originally collected by Ness and Meltzer-Asscher (2018, Experiment 3). Continuous EEG was recorded at a 250 Hz sampling rate with a BrainVision actiCHamp EEG system from 34 Ag/AgCl electrodes (10–20 configuration).

Materials, Procedure, and Participants

The materials were 84 sets of Hebrew sentences, each of which consisted of three variations of the same high-constraint sentence, with a predicted critical word (e.g., "restaurant"), a congruent-unexpected critical word (e.g., "bakery"), or an anomalous-unexpected critical word (e.g., "scarf"). Example sentences, as well as average cloze probability in each condition, are provided in Table 2. The sentences were administered in RSVP format (SOA = 500 ms; ISI = 300 ms). Participants answered yes/no comprehension questions via button press after a third of the trials (randomly distributed). Each

Table 2
Example Sentences and Norming Values for Study 2 (Ness & Meltzer-Asscher, 2018)

Condition	Sentence	CP
2.1. Predicted	Dan works as a cook, but he aspires to open his own **restaurant** …	CP: 78.8%
2.2. Congruent-unexpected	Dan works as a cook, but he aspires to open his own **bakery** …	CP: 0.8%
2.3. Anomalous-unexpected	Dan works as a cook, but he aspires to open his own **scarf** …	CP: 0%

Note. The critical word in each condition is marked in bold. CP = cloze probability (percentage of the target word in a sentence completion task). The sentences were in Hebrew.

participant saw one version from each set, resulting in 28 trials per condition. Participants were 24 native Hebrew speakers from the Tel Aviv University community.

Results

Differences in oscillatory power are shown across the time-frequency plane for congruent-unexpected versus predicted (Figure 2A) and anomalous-unexpected versus predicted (Figure 2A). Both congruent-unexpected and anomalous-unexpected sentences appeared to elicit greater power than predicted sentences in the theta frequency range (~3–8 Hz) in a latency window starting at ~300 ms. This effect was greater and more prolonged in the anomalous-unexpected sentences. The cluster-based analysis identified a cluster of congruent-unexpected > predicted differences that extended from 3.3 to 6 Hz and 300–800 ms after critical-word onset (see Figure 2A; cluster-level $p = .004$), and a cluster of anomalous-unexpected > predicted differences that extended from 3 to 6.7 Hz and 300–1,000 ms after critical-word onset (see Figure 2B cluster-level $p < .001$).[3] A direct comparison between congruent-unexpected and anomalous-unexpected indicated significantly greater theta activity in anomalous-unexpected sentences (cluster-level $p < .002$).

The topographic distributions of the theta-band power effects in Study 2 are presented descriptively in Figure 7. The congruent-unexpected > predicted difference in theta-band power, calculated across a time window spanning 300–800 ms from critical-word onset, was maximal over left and right frontal electrodes (Figure 7A), while the anomalous-unexpected > predicted difference in theta-band power, calculated across a time window spanning 300–1,000 ms from critical-word onset, was maximal over right frontal electrodes (Figure 7B).

Discussion

Study 2 found that theta-band activity increased in response to conflict between a strong, context-driven prediction about linguistic input and prediction-violating linguistic input. These effects occurred both when the prediction-violating word was highly plausible (Sentence Type 2.2) or semantically anomalous (Sentence Type 2.3) given the context. The first theta effect, for plausible violations, conceptually replicates the earlier finding by Rommers et al. (2017), while the second theta effect, for implausible violations, extends that earlier study.

The result in the congruent-unexpected condition (Sentence Type 2.2) supports our Subhypothesis 2, by showing that semantic anomaly is not necessary for theta-band effects to occur; conflict, even when it involves a word that is highly plausible given its context, elicits robust theta-band activity. Study 1 was unable to test this idea, because it only involved conflicts generated by words that were implausible in their contexts.

Across Studies 1 and 2, we observed a notable distinction in theta effects between anomalous words appearing in low-constraint sentences (no-conflict anomalies; Study 1) versus in high-constraint sentences (anomalous-unexpected; Study 2), with only the latter eliciting a theta-power increase. This again is consistent with our general assumption that theta activity is not attributable to the difficulty in processing an anomaly: An increase in theta is observed only when the anomaly is accompanied by a representational conflict. The contrast between anomalies in high- and low-constraint contexts might be relevant to account for mixed findings in prior literature, a point we return to in the General Discussion.

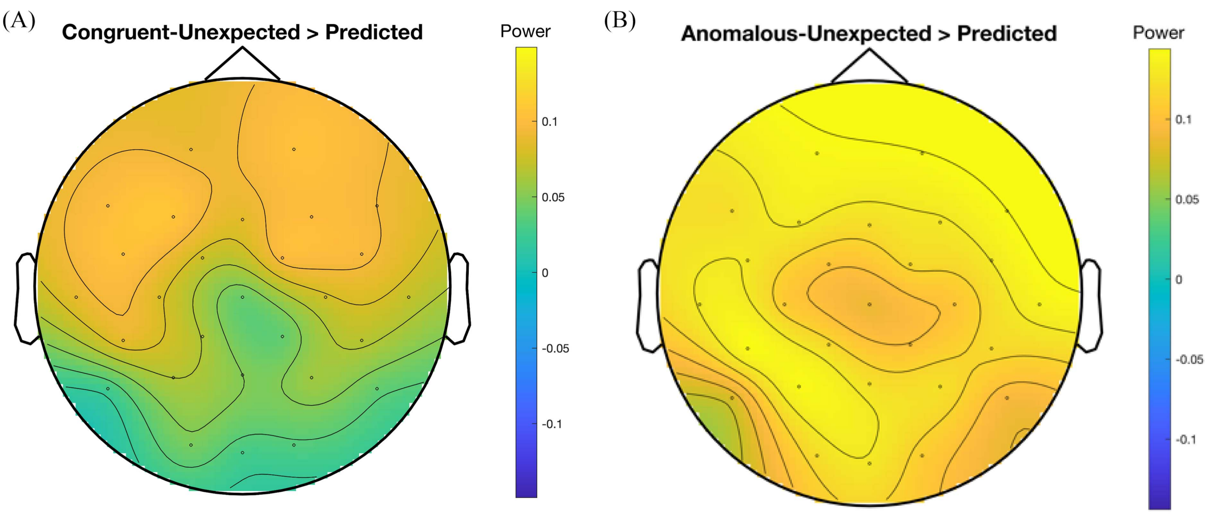
The stimulus conditions eliciting theta-band effects in Study 2, as in Study 1, dissociated from the conditions eliciting the ERP effects initially observed in the same data set. The original ERP analysis showed increased N400 amplitude in both unexpected conditions compared to predicted (Ness & Meltzer-Asscher, 2018). This was followed by an increased P600 (posterior positivity) in the anomalous-unexpected condition compared to predicted, but a frontal post-N400 positivity (f-PNP) in the congruent-unexpected condition. Thus, a theta effect in both unexpected conditions corroborates the conclusion from Study 1 that the theta effect is independent from the P600; that is, increases in theta power and in P600 amplitude do not have the same elicitation conditions. The results also indicate that theta power and the f-PNP have different elicitation and reflect different processes. Overall, our data suggest a functional distinction between theta activity and the ERP effects observed in the data, consistent with our hypothesis that theta-band activity marks conflict, which is not directly indexed by either of these ERP components.

In Study 2, we observed a pattern of larger theta-power effects in the anomalous-unexpected condition (Sentence 2.3) than in the congruent-unexpected condition (Sentence 2.2), which we did not explicitly hypothesize. We speculate that this pattern might have emerged because the linguistic conflict is more difficult to resolve in the anomalous-unexpected condition than in the congruent-unexpected condition. In congruent-unexpected sentences, the conflict between the prediction ("restaurant") and the bottom-up input ("bakery") can be resolved by committing to the word "bakery", which is incompatible with the predicted word but is both supported by the orthographic input and highly plausible in the sentence context. By

[3] In the broad-band analysis, this cluster spanned to frequencies below 3Hz.

Figure 7

Scalp Topographies of the Difference in Theta-Band Power for (A) Congruent-Unexpected > Predicted, Calculated Across a Time Window Spanning 300–800 ms From the Critical Word Onset; and (B) Anomalous-Unexpected > Predicted, Calculated Across a Time Window Spanning 300–1,000 ms From the Critical Word Onset



Note. See the online article for the color version of this figure.

contrast, in the anomalous-unexpected condition, resolving the conflict is more difficult. The word "scarf", for example, is supported by the bottom-up input but its semantic fit to the context is poor. It is therefore hard to integrate, which we suggest renders the decision of how to resolve the conflict more difficult, leading to larger theta effects.

Again, however, this explanation about the different degrees of conflict between the two conditions is speculative: First, the congruent-unexpected and anomalous-unexpected conditions differed not only in the degree of conflict, but also in plausibility, which can arguably introduce potential confounds. In addition, this is a post hoc explanation as we did not make any a priori hypotheses about the strength of theta effects in this study. The next study (Study 3) provides a more direct test of the hypothesis that parametric increases in conflict will lead to greater theta-band power effects. We compare theta activity in two sentence types that differed in the *degree* of conflict, but were otherwise closely matched in their syntactic and semantic properties.

Study 3

In Study 3, we examined brain responses to two similar types of conflict-engendering sentences, which differed by a small but important change in the ease with which the conflict could be resolved. Participants read sentences like "the hearty meal would *devour*" (Table 3, Sentence 3.3) and "the hearty meal was *devouring*" (Sentence 3.2; Kim & Sikos, 2011). In both of these sentences, the syntactic cues signal that the initial noun phrase *the hearty meal* should be the Agent of the verb "devour", while the semantic cues signal a Theme interpretation, as meals are highly likely to be devoured and unlikely to devour (Kim & Osterhout, 2005; Kim & Sikos, 2011; Ovans et al., 2022). The incompatibility of the syntactically and semantically supported interpretations engenders conflict.

We assume that Sentence 3.2 engenders *less* conflict than Sentence 3.3, because Sentence 3.2 can be rendered plausible by a single morphosyntactic edit (e.g., "devouring" → "devoured"), which resolves the conflict. Such an edit would be warranted, for instance, if the comprehender attributes the sentence's form to a morphosyntactic error by the producer (inferring that the intended message was "The hearty meal was devoured"; e.g., Gibson et al., 2013).

Meanwhile, the conflict in Sentence 3.3 is more difficult to resolve, because multiple morphosyntactic edits would be necessary to render the sentence plausible (e.g., "would devour" → "would *be* devour*ed*"). Given the number of edits required, a production error is an unlikely explanation for Sentence 3.3's form (Gibson et al., 2013), and the comprehender therefore faces an entrenched conflict between two competing representations, neither of which can be easily accommodated (meal-is-Theme requires the assumption of unlikely production errors and multiple edits, and meal-is-Agent is semantically implausible). Thus, Sentences 3.2 and 3.3 together offer a way to test how theta activity is affected by a parametric change in cognitive-control demands, using sentences that are otherwise highly similar in their lexical-semantic and syntactic content.

Table 3

Example Sentences for Study 3 (Kim & Sikos, 2011)

Condition	Sentence
3.1. Well-formed passive	The hearty meal was **devoured** …
3.2. Simple repair	The hearty meal was **devouring** …
3.3. Complex repair	The hearty meal would **devour** …

Note. The critical word in each condition is marked in bold.

Data Acquisition

We analyzed data that were originally collected by Kim and Sikos (2011). Continuous EEG was recorded at a 1,000 Hz sampling rate with a Neuroscan Synamps2 EEG system from 64 Ag/AgCl electrodes (extended 10–20 configuration).

Materials, Procedure, and Participants

The materials consisted of 96 sets, each of which contained three variations of the same sentence: simple repair (e.g., "The hearty meal was *devouring*"), complex repair ("The hearty meal would *devour*"), and well-formed passive ("The hearty meal was *devoured*"). Each participant saw one version of each sentence, resulting in 32 trials per condition. The sentences were administered in RSVP format with an SOA of 600 ms (ISI 500 ms). Following each sentence, participants indicated via button press whether the sentence was a normal sentence of English. We analyzed data from 39 native English-speaking participants from the University of Colorado Boulder community. The original study included an additional 16 participants; but their data were inaccessible for the current analysis due to storage device technical issues.

Results

Differences in oscillatory power are shown across the time-frequency plane for simple repair versus well-formed passive (Figure 3A) and complex repair versus well-formed passive (Figure 3B). The simple repair sentences appeared to elicit only weak theta-band activity at ~600 ms. The complex repair condition appeared to elicit two bursts of theta-band activity, relative to the well-formed passive condition, one occurring around the onset of the critical verb, and the other occurring ~600 ms after verb onset. Due to the early pattern of theta activity visible in the TFR, we extended the analysis window in this data set to begin 500 ms prior to the critical verb (to 1,000 ms after the onset of the critical verb). We discuss the reason for this early effect below.

The cluster-based permutation test identified one cluster of complex repair > well-formed passive differences that extended from 5.4 Hz to 8 Hz and from 70 ms prior to critical-verb onset to 90 ms after verb onset (see Figure 3B; cluster-level $p = .013$). No significant cluster was identified at the later latency (at ~600 ms). No simple repair > well-formed passive difference was identified by the cluster-based permutation test. A direct comparison between complex repair and simple repair conditions confirmed that theta activity was greater in the complex repair condition (cluster-level $p = .032$).

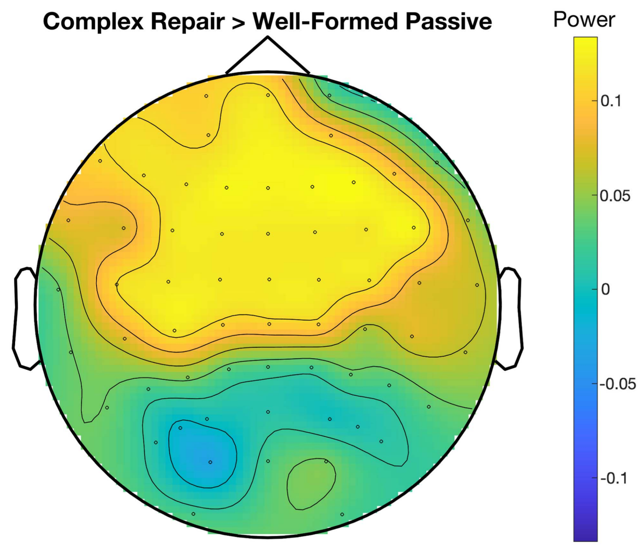
The topographic distributions of the differences in theta-band power between the complex repair and the passive control sentences are presented descriptively in Figure 8. The theta-band power difference, calculated across a time window spanning from 150 ms prior to the critical-verb onset to 150 ms after critical-verb onset, was greatest over frontal electrodes (Figure 8).

Discussion

Complex repair sentences (Sentence Type 3.3) elicited increased theta power compared to well-formed passive sentences (Sentence Type 3.1) and also compared to simple repair sentences (Sentence Type 3.2). This pattern of effects supports our general hypothesis that

Figure 8

Scalp Topography of the Complex Repair > Well-Formed Passive Difference in Theta-Band Power, Calculated Across a Time Window Spanning From 150 ms Prior to the Critical-Verb Onset to 150 ms After Critical-Verb Onset



Note. See the online article for the color version of this figure.

representational conflict during sentence comprehension generates increased theta-band power in the EEG. The increased theta-band power in the complex repair compared to the simple repair condition supports Subhypothesis 3: Parametric manipulations of the degree of conflict lead to increases in theta-band activity. The simple repair sentences did not increase theta-band power, compared to well-formed passive sentences.

The absence of increased theta-band activity for the simple repair condition compared to the well-formed passive condition is noteworthy. A moderate increase in theta-band activity was visible in the TFR at ~500–700 ms (Figure 3A), but it was not statistically significant in our cluster-based permutation test. Although we predicted less theta-band activity in the simple repair than in the complex repair condition, we nevertheless predicted *some* theta-band activity in the simple repair sentences, due to the conflict we believe to be present in this condition. The lack of an effect in the simple repair condition therefore fails to support our general hypothesis. We propose a speculative explanation for this absent effect: Because the conflict engendered by the simple effect items is easily resolved, as we discussed above, these sentences may not always require significant increases in cognitive-control engagement. That is, simple repair sentences engender only mild conflict and therefore elicit only small increases in cognitive control, which can be difficult to measure in the form of theta-band effects. This revised version of our hypothesis is partially tested in the following study (Study 4).

A second noteworthy aspect of our results is that the theta-band effect in the complex repair condition coincided with the onset of the critical verb ("devour"), which was considerably earlier than the theta effects in Studies 1 and 2 (~300–1,000 ms after critical-word onset). Our explanation of this early latency effect is that it reflects participants' responses to the word *preceding* the critical verb ("would"), because participants have learned that this precritical word predicts the conflict in the sentence. In this study's stimulus materials, the auxiliary verb "would" was a perfect cue (100% probability in the experiment) that the next word would be an anomalous, untensed verb (e.g., "devour"); both the well-formed passive and the simple repair anomaly conditions were always preceded instead by "was." This distributional property of the stimuli allows participants to learn to respond anticipatorily to the conflict in the complex repair sentences upon encountering the precritical verb "would." A theta-band burst 600 ms after the onset of "would" coincides with the onset of the critical verb, which explains the effect's latency. Visual inspection of the TFR suggested an additional, later theta effect that was more similar to those in Studies 1 and 2 (around 600 ms after the critical-verb onset; Figure 3B), but this activity was not statistically significant in our cluster-based permutation test. This may reflect trials in which conflict-processing persists into the following word, or cases where anticipatory commitments did not occur, although anticipation was not directly tested in the present study.

As in Studies 1 and 2, the theta-band oscillatory effects in Study 3 dissociated from the pattern of ERP effects observed in the same EEG data set, consistent with the conclusion that the theta-band activity and the ERPs reflect distinct processes. The original ERP analysis showed a larger P600 effect in the simple repair than in the complex repair condition (Kim & Sikos, 2011). Thus, the P600 effects were larger exactly when theta-band power effects were smaller. Our conclusion is that these opposite-going theta-band power and P600 effects index independent and complementary neural responses to the same functional conditions. The larger P600 effect in the simple repair condition was attributed to the fact that these sentences can be rendered plausible with a single morphosyntactic edit ("devouring" → "devoured"), while the complex repair condition cannot (Kim & Sikos, 2011). The morphosyntactic properties of the simple repair sentences make it likely that comprehenders will mentally repair them, which is reflected in larger P600 effects; that is, the larger P600 effect reflects a larger proportion of trials in which a repair operation takes place. Meanwhile, because the complex repair sentences are less likely to be repaired, the conflict between the syntactic and semantic cues is difficult to resolve, which is what leads to increased cognitive-control engagement and hence greater theta-band activity.

We have so far provided no evidence for our speculation above that the simple repair sentences' failure to elicit theta effects (i.e., the null effect in the simple repair > well-formed passive contrast) reflects the ease with which these sentences are repaired and a resulting modest demand for cognitive control. In a fourth study, we examined whether simple repair sentences would trigger greater cognitive-control engagement when participants are in a *state of low cognitive control* as they began processing the sentences. Such a state should necessitate *upregulation* of cognitive control upon encountering the conflict during the sentences themselves, measurable by increased theta activity. Since Study 3 did not vary or evaluate individuals' level of cognitive control before simple repair sentences, it is possible that any observable theta effects were diluted due to natural fluctuations in participants' cognitive-control states throughout the experimental context. In the next study, Study 4, we tested this revised version of our hypothesis that assumes that simple repair sentences engender only mild conflict.

Study 4

In Study 4, we tested whether simple repair sentences, which failed to elicit theta-band effects in Study 3, would do so if participants were in a state of low cognitive control as they began processing the sentences. Study 4 experimentally manipulated the state of cognitive control *within individuals* before they encountered sentences. Participants in the experiment alternated between reading sentences and performing the Stroop task (trials from both tasks were pseudorandomly interleaved). Incongruent Stroop trials upregulated cognitive control, whereas congruent Stroop trials did not. We then measured how the processing of each sentence was affected by the level of cognitive control induced by a preceding Stroop trial. Previous work has shown that such manipulations of an individual's cognitive-control state are effective for observing changes in language processing operations when representational conflict occurs (Ovans et al., 2022; see also Hsu et al., 2021; Hsu & Novick, 2016; Thothathiri et al., 2018).

We predicted that the mild conflict engendered by simple repair sentences (Table 4, Example 4.2) would elicit measurable theta-power increases compared to well-formed passive sentences *following congruent Stroop trials*, which placed participants in a low cognitive-control state before reading. Conversely, we predicted that simple repair sentences would elicit *smaller* (or even no) theta-power increases *following incongruent Stroop trials*, which placed participants in an elevated cognitive-control state before reading, decreasing the need for additional control engagement.

Data Acquisition

We analyzed data that were originally collected by Ovans et al. (2022). Continuous EEG was recorded at a 1,000 Hz sampling rate with a Neuroscan Synamps2 EEG system from 64 Ag/AgCl electrodes (extended 10–20 configuration).

Materials, Procedure, and Participants

The stimulus materials were 120 sentence pairs, each of which consisted of two variants of the same sentence: simple repair (e.g., "The hearty meal was devouring") and well-formed passive (e.g., "The hearty meal was devoured"). Each participant saw one version from each pair. Each sentence type was preceded by a congruent Stroop item in half of the trials and an incongruent Stroop item in the other half, resulting in 30 trials per condition (four conditions, crossing two Stroop trial types and two sentence trial types). The sentences were presented in RSVP format (SOA = 500 ms; ISI = 117 ms). Following each sentence, participants indicated via button press whether the sentence was "normal".

Table 4
Example Sentences for Study 4 (Ovans et al., 2022)

Condition	Sentence
4.1. Well-formed passive	The hearty meal was **devoured** …
4.2. Simple repair	The hearty meal was **devouring** …

Note. The critical word in each condition is marked in bold. In Study 4, incongruent or congruent Stroop items preceded well-formed passive and simple repair sentences to manipulate cognitive-control engagement prior to reading (see text; see also Ovans et al., 2022 for details).

In Stroop trials, participants indicated the font color of the printed word stimulus via a button press. Participants saw an extra 120 Stroop trials and 240 filler sentences to create additional sequence pairs so that participants could not predict whether the next trial would be a Stroop or sentence item (Stroop-to-Stroop, Stroop-to-Sentence, Sentence-to-Stroop, and Sentence-to-Sentence). Participants were 61 native English-speaking participants from the University of Colorado Boulder community.

Results

Sentence Trials

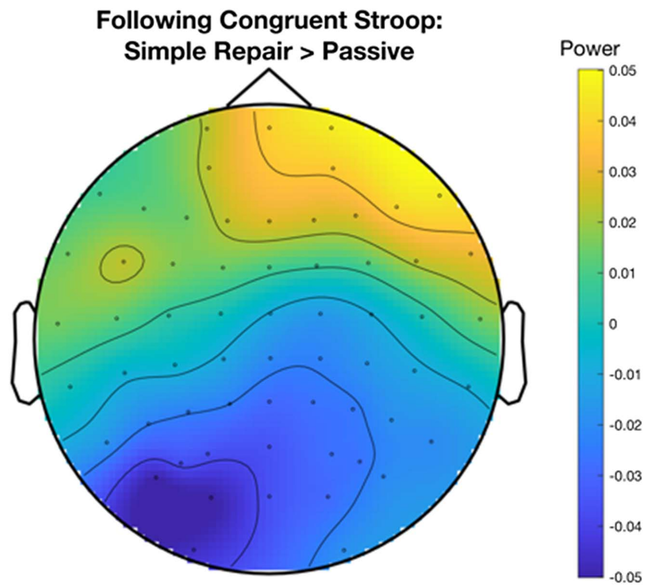
Differences in oscillatory power are shown across the time-frequency plane for simple repair versus well-formed passive in all trials (Figure 4A); in trials following congruent Stroop items (Figure 4B); and in trials following incongruent Stroop items (Figure 4C). An increase in theta power for simple repair over well-formed passive sentences was visible following congruent Stroop trials (Figure 4B), but not following incongruent Stroop trials (Figure 4C), or in all trials collapsed across preceding Stroop type (Figure 4A).

For sentence trials following congruent Stroop trials, the theta-focused cluster-based permutation analysis identified a cluster of simple repair > well-formed passive differences, which extended from 3 to 5.7 Hz and 600–1,000 ms after critical-verb onset (see Figure 4B, cluster-level $p = .05$). No cluster of simple repair > well-formed passive differences was identified by the permutation tests for trials following incongruent Stroop items or for all trials collapsed across preceding Stroop type.

The topographic distribution of the difference in theta-band power between simple repair and well-formed passive conditions is presented descriptively in Figure 9. The theta-band power difference, calculated across a time window spanning 600–1,000 ms from critical-verb onset, was greatest over the right frontal electrodes.

Figure 9

Scalp Topography of the Simple Repair > Well-Formed Passive Difference in Theta-Band Power on Trials Following Congruent Stroop, Calculated Across a Time Window Spanning 600–1,000 ms From the Critical-Verb Onset



Note. See the online article for the color version of this figure.

Stroop Trials

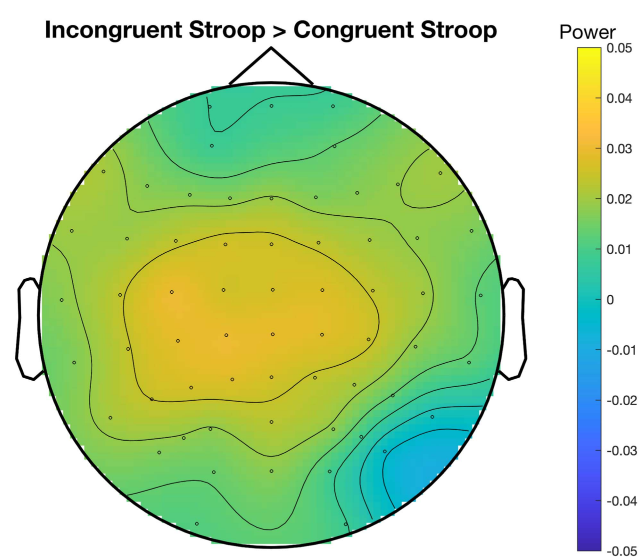
Differences in oscillatory power are shown across the time-frequency plane for incongruent versus congruent Stroop trials (Figure 5). Incongruent Stroop trials appeared to elicit more theta activity than congruent Stroop. Cluster-based analyses identified a cluster of incongruent > congruent differences that extended from 3 to 7.8 Hz and 500–1,000 ms after the stimulus onset (see Figure 5; cluster-level $p < .001$). The topography of this effect is presented in Figure 10.

Discussion

In Study 4, we assumed that our simple repair sentences involved only mild conflict and were easily repairable due to semantic cues that strongly supported a Theme interpretation of the subject noun (i.e., "meal" as the Theme, not the Agent, of the verb "devour"). By manipulating readers' state of cognitive control before processing the sentences, we tested the hypothesis that measurable cognitive-control engagement to resolve the conflict would occur only if participants were in a low state of control before reading. We found that theta power increased in the simple repair sentences relative to the well-formed passive sentences, but specifically after congruent Stroop trials, when cognitive control status was relatively downregulated before participants began reading. The simple repair sentences did not elicit increased theta-band activity following incongruent Stroop trials, when cognitive control was already in an upregulated state before reading. We conclude from this pattern of effects that when cognitive control is in a low state of activation, the conflict engendered by simple repair sentences requires increased

Figure 10

Scalp Topography of the Incongruent Stroop > Congruent Stroop Difference in Theta-Band Power, Calculated Across a Time Window Spanning 500–1,000 ms From Stimuli Onset



Note. See the online article for the color version of this figure.

cognitive control, in order to help resolve the conflict. Meanwhile, cognitive-control recruitment in response to (mild) conflict is not necessary when cognitive control is already engaged.

The finding in Study 4 is compatible with our speculative conclusions about Study 3, in which simple repair sentences failed to elicit significant theta effects. We attributed this pattern to the ease with which simple repair sentences can be mentally edited to accommodate a plausible interpretation. We assume that these sentences engender only a mild degree of conflict, which is easily resolved, and therefore may not often elicit significant theta-band activity. In Study 4, we carefully manipulated the state of cognitive control using Stroop. These mild conflicts required significant cognitive-control engagement only when the system was in a state of low activity (following congruent Stroop) as the sentence began.

An additional result in Study 4 was the confirmation that the conflict-engendering incongruent Stroop trials also elicited increases in theta-band power compared to congruent Stroop trials. This corroborates prior findings that the conflict in the Stroop task modulates neural oscillatory activity in the theta-band (Cavanagh & Frank, 2014; Hanslmayr et al., 2008) and is therefore consistent with our assertion that Stroop trial-type successfully affected the state of cognitive control, which in turn affected sentence processing operations. The incongruent > congruent Stroop differences in theta-band power were maximal over frontal and central electrodes with a slightly left-lateralized pattern. We speculate that the left lateralization reflects activity in the motor cortex of the left hemisphere, as pressing buttons for the Stroop task requires response control, and most of our participants are right-handed. The grand-averaged theta activity for all Stroop trials is mid-frontal (see Supplemental Materials, Figure 2).

As in Studies 1, 2, and 3, Study 4 showed that the pattern of theta-band effects is distinct from the ERP effects in the same data set. The original ERP analysis found that the state of cognitive control prior to the sentence modulated the P600 effect: There was a larger P600 effect for simple repair sentences at the verb, following *incongruent* Stroop compared to congruent Stroop trials (Ovans et al., 2022). This effect is in the opposite direction of the theta-band effects in the current analyses, which shows an increase in theta activity for sentences following *congruent* Stroop trials. The ERP pattern is consistent with our view that the P600 does not directly index cognitive control (unlike our assertion that theta does), but instead a syntactic editing operation ("devouring" → "devoured") that is *regulated by* cognitive control. When cognitive control is upregulated following incongruent Stroop, it is sustained into the following sentence, allowing comprehenders to more strongly commit to the plausible meal-as-Theme interpretation and initiate repair operations, yielding larger P600s (Ovans et al., 2022; for a review, see Ness et al., 2023).

General Discussion

In this work, we tested the hypothesis that neural oscillatory activity in the theta frequency band marks the engagement of cognitive control during sentence processing in response to representational conflict. We tested this hypothesis by conducting time-frequency analyses of four EEG data sets from previously published studies that measured ERPs during sentence processing. Across all four studies, which involved a variety of stimulus types and experimental contexts, linguistic conflict led to increased theta-band power, while other possible explanations of theta-band activity, such as semantic anomaly, were unable to predict the pattern of effects with any consistency.

Thematic Role Conflict

In Study 1, we found that conflict between two thematic-role assignments, which were both supported by the linguistic input (role reversals, e.g., Sentence 1.1), elicited increased theta-band power relative to their control sentences. Meanwhile, structurally similar sentences that contained a semantically implausible critical verb but did not engender conflict (no-conflict anomaly; Sentence 1.3) failed to elicit theta power increases. This pattern of results suggests that theta-band activity is an index of cognitive-control engagement.

Conflict Between a Lexical Prediction and the Bottom-Up Input

In Study 2, we generalized the findings from Study 1 to a different type of conflict, which arose from the disconfirmation of a strong prediction (Sentence 2.2). Theta power increased when a highly constraining context (that generates a strong prediction for a specific word) was followed by an unpredicted but plausible word. We attribute this theta effect to the conflict between a preactivated representation of the predicted word and the unexpected word that appeared instead, which received bottom-up support.

Our findings in Study 2 conceptually replicate an earlier study by Rommers et al. (2017), which also observed theta power increases in response to plausible violations of strong predictions but used English sentences, while ours were in Hebrew. As we do here, Rommers et al. (2017) interpreted their theta-band effects in terms of cognitive-control engagement.

One important aspect of the findings in Study 2 is that clear theta-band effects occur in sentences that contain no flagrant violation of linguistic constraints. Linguistic knowledge violations are often used in psycholinguistic experiments but can sometimes lead to theoretical questions about whether they have elicited responses that are not a normal part of language processing. Crucially, our experimental sentences in Study 2 are not contrived in this way; yet they still generate representational conflict that engages cognitive control, suggesting that conflict and the need for control during language comprehension may be somewhat commonplace (Ness et al., 2023).

Degrees of Conflict

In Study 3, we again observed, as in Study 1, that conflict between thematic-role assignments elicited theta-band activity, and furthermore found that parametric increases in the degree of conflict led to significantly larger theta-band effects (Sentence 3.2 vs. 3.3). We manipulated the degree of conflict in terms of the ease with which the conflict could be resolved by positing an error by the producer. Theta activity was robust in response to conflict that was difficult to resolve (Sentence 3.3), when arriving at a semantically plausible interpretation requires the assumption of an improbable production error (e.g., a producer mistakenly uttered "would devour" when "would *be* devour*ed*" was intended). In comparison, theta activity was not significantly increased when comprehenders can easily resolve a conflict by arriving at a semantically plausible interpretation that requires an assumption of a highly probable production error (e.g., a producer mistakenly uttered "devouring" when "devoured" was intended; Sentence 3.2).

The Engagement Status of Cognitive Control During Language Processing

In Study 4, we examined how the brain's response to linguistic conflict was impacted by an individual's *state* of cognitive control. Theta power increased in response to sentences that engendered a minor and easily resolvable conflict, but specifically when cognitive control was placed beforehand in a low state of engagement (following a congruent Stroop trial). In this situation, linguistic conflict required an increase of cognitive control, which was measured in the form of theta power. When cognitive control was placed in an upregulated state beforehand (following an incongruent Stroop trial), less recruitment of cognitive control was needed for the processing of a linguistic conflict. In this condition, no theta power increases were observed in response to linguistic conflict. This adds to the mounting body of research showing that the relative state of cognitive-control engagement has a direct impact on sentence processing and comprehension (e.g., Hsu et al., 2021; Hsu & Novick, 2016; Ovans et al., 2022; Thothathiri et al., 2018; see Ness et al., 2023, for a computationally plausible model that accounts for such effects).

Functional Distinction Between Theta Effects and ERP Effects

Our theoretical account of the theta-band oscillatory effects in four studies, in terms of representational conflict, differs from the accounts provided by the original studies for the ERP effects that were observed in the same data—N400, P600, and anterior positivities (Chow et al., 2016; Kim & Sikos, 2011; Ness & Meltzer-Asscher, 2018; Ovans et al., 2022). It is important to note that these diverging theoretical conclusions do not amount to incompatible explanations of the same phenomenon. Instead, the theta-band effects and ERP effects index different cognitive operations and therefore require distinct accounts (M. Bastiaansen & Hagoort, 2015; Hagoort et al., 2004; Hald et al., 2006). Across our four studies, the experimental conditions that systematically increased theta-band power did not systematically modulate any of the three key ERP effects in the same way (see Discussion sections within each Study for details on the differing ERP and theta patterns). Moreover, the theta-band oscillations generally differed from the ERPs in terms of latencies and scalp distributions. The distinctiveness of the conditions leading to theta-band oscillations and ERP effects is consistent with the conclusion that theta-band oscillations and ERPs reflect distinct neural *and functional* processes, which can be measured from the same EEG recording. In our view, this functional divergence of neural oscillations and ERPs highlights the value of measuring all of these different features of the EEG as part of a multidimensional characterization of brain activity during sentence processing.

Our finding that theta-band effects are distinct from classic language-related ERP effects in terms of their neurocognitive underpinnings does not imply a complete disconnection between neural oscillatory and ERP effects. The relationship between the neurocognitive processes measured by neural oscillations and ERPs is currently a matter of considerable uncertainty in cognitive neuroscience, which should be addressed by direct investigation in future studies. It is plausible that measures of theta-band activity different from those used here might more directly align with ERPs. One potential avenue for investigation involves separating neural oscillatory activity into two components: (a) evoked power, which quantifies the oscillatory energy of the event-related potential and reflects only activity that is phased-locked to the stimulus onset; and (b) induced power, which is not phase-locked with the stimulus and is calculated by subtracting evoked from total power (for reference, see David et al., 2006). Although total theta power, which we measured here, dissociates quite clearly from the language processing N400, P600, and anterior positivity ERPs, it is possible that some aspect of neural oscillatory activity aligns quite directly with one or more of these ERPs.

Alternative Accounts of Theta-Band Effects During Sentence Processing

Our account in terms of cognitive-control engagement also contrasts with some previous functional explanations of theta-band activity during sentence processing—in terms of the difficulty of lexical retrieval (M. Bastiaansen & Hagoort, 2015; Hald et al., 2006) or working memory processing (Bonhage et al., 2017; Meltzer et al., 2017; Meyer et al., 2015). In the following sections, we consider how these different explanations of theta-band activity during sentence processing might or might not be connected to our own account.

The Relation Between Theta-Band Activity and Lexical Integration

Several studies have proposed that theta power during language comprehension reflects the difficulty of lexical integration in response to semantically anomalous words (M. Bastiaansen & Hagoort, 2015; Hald et al., 2006). The key motivation for such accounts is their ability to explain findings that theta power is greater for semantically implausible than plausible words (M. Bastiaansen & Hagoort, 2015; Davidson & Indefrey, 2007; Hagoort et al., 2004; Wang, Zhu, & Bastiaansen, 2012), although this pattern has not always been reported (Penolazzi et al., 2009; Wang, Jensen, et al., 2012).

Across our four studies, however, semantic implausibility failed to systematically predict increased theta-band power. When critical words were semantically implausible but did not engender representational conflict, no theta-power effects occurred, as in Study 1 (e.g., "The restaurant owner forgot which teacher the child had *collected*"). Meanwhile, when critical words were plausible but engendered conflict, theta-power effects were observed, as in Study 2 (e.g., "Dan works as a cook, but he aspires to open his own *bakery*"). And for the semantically implausible sentences in Study 3 ("The hearty meal was *devouring*" and "The hearty meal would *devour*"), semantic implausibility alone did not guarantee theta effects; robust representational conflict was necessary. Thus, an account of theta-band effects focused on lexical integration difficulty due to implausibility fails to explain our data.

In view of our findings, we suggest that some previously reported theta-band effects in response to semantic anomalies might reflect cognitive control, which responds to conflict between the bottom-up linguistic input and strong predictions generated by the sentence context, as highlighted in Study 2. In fact, cognitive control has been considered before as an explanation for theta band increases to anomalies (Roehm et al., 2004; Rommers et al., 2017), along with other explanations that do not directly reflect lexical integration, such as prediction error (Hald et al., 2006; Rommers et al., 2017), or working memory (Hald et al., 2006; Kielar et al., 2015). Hald et al. (2006) observed a distinction between theta increases at temporal channels, which seem consistent with lexical retrieval, and frontally concentrated theta effects, which may be more related to executive processes. Although we do not wish to conclude that theta power is unrelated to lexical integration difficulty, the pattern of theta-power effects in our four studies is predicted by representational conflict and not by implausibility.

Working Memory Accounts of Theta-Band Activity

Working memory demands do not explain the pattern of theta-band effects observed here. The critical stimuli in our four studies were selected because they engendered representational conflict *without* imposing increased demands on working memory. Our stimuli did not contain long-distance syntactic dependencies, which are widely thought to engage working memory within psycholinguistics because portions of the input must be maintained for extended periods of time or in the face of interference before the dependency can be resolved (e.g., Caplan & Waters, 1999; Gibson, 2000; Lewis et al., 2006; Van Dyke & McElree, 2006). Our study also did not involve an overt requirement to retain information in memory, as is common in tasks that are designed to test the effects of working memory demands. Under these conditions, without obvious working memory demands, we still consistently observed theta-band effects in each of the experimental contrasts across studies.

We suggest that some theta-band effects during language processing that were associated with working memory in previous studies might be compatible instead with a conflict-processing account of the sort we propose here. Meyer et al. (2015) observed theta effects at pronouns inside sentences containing complex, relative clause modified noun phrases. Theta power was greater when the pronoun referred to a noun that was embedded inside the relative clause, versus the head noun of the noun phrase. This finding can potentially be explained in terms of *retrieval* from working memory, which is more difficult when the antecedent sits inside an embedded clause. We suggest that these theta-band effects might actually stem from representational conflict between the main and embedded nouns, both of which are candidate antecedents for the pronoun.

In fact, other forms of evidence relating theta-band activity to working memory activity *in the service of language processing* are relatively weak. As mentioned in the Introduction, several studies that examined the cost of processing long-distance dependencies within syntactically complex structures have observed effects in the α ($\sim$8–12 Hz) and β ($\sim$13–30 Hz) bands, and not the theta band (Meltzer & Braun, 2011; Meyer et al., 2013). Thus, theta-band power does not increase under the conditions that psycholinguists have most often associated with working memory demands during sentence comprehension. Two other studies reported increased theta-band power when participants maintained lists of unrelated words in memory, compared to retaining the words from coherent sentences (Bonhage et al., 2017; Meltzer et al., 2017). These theta effects do seem related to retention demands in working memory, but those retention demands do not seem critical to sentence processing. The effect pattern indicates that retention demands are *minimized* during sentence processing, compared to remembering word lists, reflected in lower levels of theta power, presumably because syntactic and semantic information in sentences facilitates memory by chunking words into meaningful units (Bonhage et al., 2017).

We do not suggest here that working memory plays no role in language processing. Rather, our main conclusion is that the specific language processing challenges we have examined here, across four studies, involve cognitive control, rather than working memory, and are reflected in increased theta-band power. Moreover, some language processing operations that may be conceptualized in terms of working memory retrieval, such as retrieving the antecedent for a pronoun, might be better understood in terms of cognitive control rather than working memory because of conflict between potential referents; alternatively, perhaps such conflicts reflect the *role of cognitive control in* working memory. Further research is needed to identify specific language processing operations that call on working memory resources separately from cognitive control, and whether those demands are reflected in theta-band activity.

The Topography of Theta Effects in Response to Linguistic Conflict

The conflict-related theta effects in our four studies were concentrated over frontal electrodes, which is consistent with neural generators in the prefrontal cortex. However, the detailed scalp topographies of the theta effects in the four studies were not identical; individual effect patterns variously contained activity over left, right, and midline frontal electrodes, and also left and right posterior channels. This topographic variability suggests some differences in the specific anatomical regions contributing to the effects. Although the scalp topography of our effects is not a key aspect of our conclusions, and although EEG data can provide only coarse-grained information about anatomical generators, we will offer brief, speculative comments on the topographic variability we observed.

One possible explanation for the differences in scalp topographies among our studies is that the different types of conflicts they examined require the coordination of different types of information (see Hald et al., 2006 for similar conclusions about variability in frontal theta-band topographies). For instance, a conflict between a predicted word and a contradictory input may primarily involve lexical representations, while a role-reversal conflict involves syntactic and semantic cues. In general, we assume that cognitive control is accomplished by networks of brain regions, which consist of multiple hubs in prefrontal cortex and "content-specific" areas in the posterior cortex; the frontal hubs assemble with the posterior regions in different configurations depending on the particular type of conflict involved (Hsu et al., 2017; Ness et al., 2023; see also Cavanagh & Frank, 2014). If cognitive control operates over a range of content-specific representations across the four studies we reported here, then this would naturally engage distinct (though overlapping) networks of brain areas, with different topographies in scalp-measured brain activity.

Some previous studies of cognitive control in simple nonlinguistic tasks like Stroop have produced patterns of theta activity that are more focally centered than our own effects on midline frontal electrodes (e.g., Eisma et al., 2021), and such focally midline frontal topographies have sometimes been attributed to specific medial prefrontal structures such as the anterior cingulate (for reference, see Cavanagh & Frank, 2014). However, cognitive-control effects may not always manifest in such focal patterns. In our Study 4, Stroop conflict elicited a broad, frontal-central topographic pattern of theta effects, rather a highly focal pattern, and similar patterns have been observed by others (e.g., Eschmann et al., 2018).

We cannot draw stronger conclusions regarding the specific variations in topography observed here or in previous research until future work is conducted, which should carefully manipulate the specific sorts of representations that generate conflict and examine how different types of conflict impact the topographic pattern of theta activity.

Conclusions and Future Directions

We found that linguistic conflict during sentence comprehension leads to increased neural oscillatory activity in the theta frequency band. Across four studies, conflict provided a consistent explanation of this activity, while other conceivable explanations, such as lexical integration difficulty and working memory demands, did not. Our inference is that theta-band oscillatory EEG activity provides an index of cognitive-control engagement during language processing.

Theta-band EEG activity provides an index of cognitive control with high temporal precision during language processing. In general, theta effects arose ∼400 ms from the onset of the critical words and persisted onward, suggesting that conflict resolution mechanisms engage rapidly, around the later portions of a time window that is widely associated with lexical retrieval within the psycholinguistic literature. This suggests that conflict occurs already at the level of lexical retrieval. Given the temporally dynamic nature of conflict effects on theta-band oscillations, the measure provides a potentially valuable index of real-time processing dynamics of linguistic conflict during sentence processing.

The finding reported here, that theta-band activity indexes cognitive-control engagement with high temporal resolution, opens the door to asking numerous important currently outstanding questions in future research. First, based on the timing of theta-band effects, one can deduce the stages of processing or levels of representation at which a conflict arises, or what processing stages are a prerequisite for conflict detection. Second, one can ask how long cognitive control remains engaged once triggered; one might also test whether control engages proactively when a conflict is likely but not yet evidenced. Finally, it may be possible to ask how cognitive-control engagement interacts with individual differences. Namely, the time-course information that theta provides could enable inquiries into whether individuals vary in the extent to which they can recruit cognitive control, how quickly they engage it, and how fast it decays within a person. Such measures would further clarify how cognitive control has a rapid and consequential impact on real-time language comprehension.

Constraints on Generality

The primary aim of our study is to characterize patterns of neurocognitive functioning typical of human beings. In order to achieve this aim, we have investigated neurophysiological recordings from healthy, college-aged participants. This population is often studied in cognitive neuroscience research due to their typical cognitive functioning and minimal confounding factors. The population allows for a clear examination of the neural mechanisms underlying cognitive control during language processing. The findings reported in this article are based on samples from student populations at three universities (University of Colorado Boulder, University of Maryland College Park, and Tel Aviv University). The data were collected prior to the initiation of this study.

Our findings are most likely to generalize to individuals who share the demographic and cognitive characteristics of our study population. There may be limitations in the generalizability of our findings to other populations, such as older adults, children and adolescents, or individuals with neurological or psychiatric conditions. Future research should aim to replicate these findings in diverse populations to determine the extent to which they generalize beyond the current sample.

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