Published in final edited form as:

Brain Lang. 2013 December ; 127(3): . doi:10.1016/j.bandl.2013.09.003.

Gamma- and theta-band synchronization during semantic priming reflect local and long-range lexical-semantic networks

Monika S. Mellem^{a,*}, Rhonda B. Friedman^a, and Andrei V. Medvedev^a

^aDepartment of Neurology, Georgetown University Medical Center, 4000 Reservoir Road NW, Washington, DC, 20007, USA

Abstract

Anterior and posterior brain areas are involved in the storage and retrieval of semantic representations, but it is not known how these areas dynamically interact during semantic processing. We hypothesized that long-range theta-band coherence would reflect coupling of these areas and examined the oscillatory dynamics of lexical-semantic processing using a semantic priming paradigm with a delayed letter-search task while recording subjects' EEG. Time-frequency analysis revealed facilitation of semantic processing for Related compared to Unrelated conditions, which resulted in a reduced N400 and reduced gamma power from 150-450 ms. Moreover, we observed greater anterior-posterior theta coherence for Unrelated compared to Related conditions over the time windows 150-425 ms and 600-900 ms. We suggest that while gamma power reflects activation of local functional networks supporting semantic representations, theta coherence indicates dynamic coupling of anterior and posterior areas for retrieval and post-retrieval processing and possibly an interaction between semantic relatedness and working memory.

Keywords

dynamic connectivity; coherence; electroencephalography; language; oscillatory dynamics

1. Introduction

In order to understand and interact with the world around us, our brains must store information about all of the objects, concepts, and beings we encounter. These so-called "semantic representations" are essential to our lives, as evidenced by the severe disability caused by disorders that degrade these representations or impair access to them (e.g., Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Rogers & Friedman, 2008). As such, much effort has appropriately been put towards investigating how the brain stores semantic representations and how we access the correct representation in a given situation from among the many competing ones. Lexical-semantics, the study of meaning as denoted by words (as opposed to pictures or symbols), has been used as a convenient way to probe semantic representations in the brain. Evidence suggests that there is a widespread network

© 2013 Elsevier Inc. All rights reserved.

*Correspondence: Monika S. Mellem, Georgetown University Medical Center, 4000 Reservoir Rd., NW, Building D, Room 207, Washington, DC, 20007, USA, Phone: (202) 687-2687, Fax: (202) 687-7378, monikamellem@gmail.com.

Conflict of Interest: None declared.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

of areas responsible for storage and retrieval of semantic representations divided grossly into posterior and anterior regions, respectively (for reviews, see Binder, Desai, Graves, & Conant, 2009; Bookheimer, 2002; Lau, Phillips, & Poeppel, 2008). It is thought that parts of the temporal and parietal lobes are heteromodal cortex mainly involved in the storage of these representations while the left inferior frontal gyrus (LIFG) is involved in top-down retrieval and manipulation of semantic information. Evidence from tracing indicates that these anterior and posterior areas are anatomically connected (Petrides & Pandya, 2009), while fMRI BOLD correlations suggest they are also functionally connected (Bokde, Tagamets, Friedman, & Horwitz, 2001; Xiang, Fonteijn, Norris, & Hagoort, 2010). But how these areas are dynamically recruited or can interact during retrieval of these semantic representations is not yet known.

Evidence from other disciplines suggests that anterior-posterior theta (4-7 Hz) coherence may be a basis for functional coupling between frontal and posterior areas during cognitive operations (Sarnthein, Petsche, Rappelsberger, Shaw, & von Stein, 1998; Sauseng et al., 2005; Summerfield & Mangels, 2005). Coherent oscillations are thought to be a mechanism to dynamically link functional networks throughout the brain because they enable temporal synchronization of neuronal groups (e.g., Buzsaki, 2006; Varela, Lachaux, Rodriguez, & Martinerie, 2001). More specifically, the communication through coherence (CTC) hypothesis states that coherence reflects long-range synchronization between distant neuronal groups and enables communication between these distant brain areas (Fries, 2005). This is in contrast to spectral power which likely reflects local synchronization within a brain area. Thus the local synchronization as measured by power analysis is thought to reflect local networks, while the long-range synchronization measured by coherence analysis indicates the formation of functional long-range networks. Based on the CTC hypothesis and evidence for the role of theta coherence, we hypothesized that long-range theta synchronization is the basis of dynamic anterior-posterior communication during retrieval of semantic representations, and this should be observable through differences in theta coherence reflecting differences in semantic processing.

Previous studies examining oscillatory synchronization during semantic paradigms have mainly examined spectral power rather than coherence and have demonstrated relationships between theta and gamma (>30 Hz) power and lexical-semantic retrieval. Theta power changes have been seen during the comparison of open class words (greater semantic content) and closed class words (less semantic content) in sentences (Bastiaansen, van der Linden, ter Keurs, Dijkstra, & Hagoort, 2005) and the comparison of nouns with different semantic features (primarily visual v. auditory) over occipital and temporal cortices (Bastiaansen, Oostenveld, Jensen, & Hagoort, 2008). Additionally, differences in gamma power for nouns v. verbs reflected differences in semantic associations (visual v. motor) (Pulvermüller, Lutzenberger, & Preissl, 1999). An intracerebral EEG study found increases in gamma power in the pars triangularis for a semantic v. phonological judgment task (Mainy, Jung, Baci, Kahane, Schoendorff, et al., 2008). As a fast rhythm, the gamma oscillation is well suited to cognitive and language processing because of its ability to quickly form transient networks. It has been proposed that faster rhythms like gamma are also well suited to the scale of local synchronization (mm-cm) while lower frequencies are better suited to long-range interactions since they typically synchronize more slowly (Von Stein & Sarnthein, 2000). Indeed, gamma power changes have been reported for other fast language processes such as word production (Crone, Hao, Hart, Boatman, Lesser, et al., 2001), semantic violation in sentences (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Hald, Bastiaansen, & Hagoort, 2006; Penolazzi, Angrilli, & Job, 2009), and word repetition priming (Matsumoto & Iidaka, 2008).

Evidence for long-range lexical-semantic networks using coherence analysis is more limited. Weiss and Mueller (2003) reported greater coherence at 30 Hz for semantically-congruent words in a sentence than for semantically-incongruent words but only for a single pair of channels, Pz-P4 in the 10-20 EEG electrode system. These channels are less than 10 cm apart, and therefore their coherence may be due to volume conduction and not two discrete neuronal populations participating in a large-scale semantic network (see Nunez & Srinivasan, 2006, for a discussion of volume conduction effects on coherence). A recent MEG study found coherence differences centered at 8 Hz and 333 ms for semantically primed words compared with unprimed words between left superior temporal cortex and right temporal cortex structures (Kujala, Vartiainen, Laaksonen, & Salmelin, 2011). While these studies provide evidence for coherence as a viable method for investigating long-range synchronization during semantic paradigms, neither study addresses the potential mechanism of interaction in the anterior-posterior semantic retrieval network.

In this study we used a semantic priming paradigm to investigate this anterior-posterior semantic retrieval network and, more generally, the roles of local and long-range synchronization during semantic processing. When a target word is preceded by a semantically-related prime word, the amount of processing required to retrieve that subsequent target word is reduced (i.e., “elm” facilitates retrieval of “maple”) compared to an unrelated prime word. This prime word is thought to partially activate related words through automatic spreading activation (ASA) hence lowering the threshold required for selection of the correct target word (Posner & Snyder, 1975). The effect of semantic priming is apparent through several measures including a decrease in reaction time and in the electrophysiological signal (as typically measured by the N400 ERP component) (see Kutas & Federmeier 2011, for a review). In this study, we expect to see the effects of semantic priming reflected in decreased gamma power for related compared to unrelated target words. Additionally, when the target word is not preceded by a related prime, fMRI studies have shown that the LIFG is recruited, presumably as an aid to retrieval (Badre et al., 2005; Gold et al., 2006). Thus greater anterior-posterior theta coherence for unrelated target words would reflect the need for additional frontally-mediated cognitive processing than would be necessary when a semantically-related prime precedes the target. Therefore our study addressed the roles of both local and long-range synchronization in establishing local and long-range functional networks for lexical-semantic retrieval.

2. Materials and Methods

2.1 Subjects

Twenty-two healthy volunteers participated in the experiment and received monetary compensation for their participation. The data of one subject had to be excluded from group analysis due to excessive noise. Thus analysis was carried out for the remaining 21 subjects (age 18-30, 8 males). All were native English speakers without a history of neurological or psychiatric problems or learning disabilities. All were currently pursuing a university education or had completed an undergraduate degree. Three subjects reported being left-handed while the remaining reported being right-handed. All gave informed consent (approved by the Georgetown Medical Center IRB) before starting the experiment.

2.2 Stimuli

We used 200 semantically-related word pairs taken from published experiments (Anaki & Henik, 2003; Avons, Russo, Cinel, Verolini, Glynn, et al., 2009; Hutchinson, 2002; Rogers & Friedman, 2008; Slowiaczek, 1994; Stolz & Besner, 1998). In the pair, the prime word, e.g. “elm”, was followed by a related target word, e.g. “maple.” These words were then scrambled to form an additional 200 unrelated word pairs which were examined to ensure no

new related pairs were formed. This allowed matching across all lexical variables when comparing Related and Unrelated target words. Half of the Unrelated pairs were shown at a short ISI and half at a long ISI with the pairs corresponding to each ISI counterbalanced across subjects. The same method was used on the Related pairs. Only long ISI pairs are examined here, and only nouns were used as stimuli.

2.3 Design and procedure

Subjects were asked to silently read the stimuli presented on the computer monitor in front of them while performing a delayed letter-search task (Kutas & Hillyard, 1989). In this task subjects made speeded responses identifying whether a certain letter, presented after the word pair, had been in either of the preceding words. On half of all trials, the letter was present (requiring a “yes” response); across those trials, 51% of the letters appeared in the prime and 49% appeared in the target. With this task the decision and response came well after the semantic priming occurred and did not interfere with the semantic neural response. Subjects were asked to minimize any movements and eyeblinking while words were on the screen. Stimuli were presented on the monitor in black Arial font against a gray background. The words subtended a horizontal visual angle of at most 5.6° (for an 11-letter word), and the letters appearing after the words subtended at most 0.9°. Subjects viewed 200 trials which each consisted of a fixation cross (1800 ms), prime word (150 ms), blank screen (850 ms), target word (150 ms), blank screen (1150 ms), letter (250 ms), and fixation cross (until subject responded) (see Figure 1A). Reaction time (RT) was measured from the onset of the letter until the button-pressing response. An additional 200 trials with a short ISI for the prime word (150 ms prime and 100 ms blank following prime) were also viewed but their data are not presented here. The order of Related and Unrelated targets was counterbalanced across subjects. Not including a short practice session of 12 trials at the beginning of the experiment, there were 4 blocks of stimuli less than 10 minutes each with subject-determined breaks in between. The total time for the session including setup was under 1.25 hours for each subject. After the recording session, subjects were debriefed. When asked if they noticed anything about the stimuli, all reported that some stimuli seemed to be related while others were not related. This helped us confirm that they were semantically processing the words.

2.4 EEG recording and preprocessing

EEG was continuously recorded using a 128-electrode EEG system (Electrical Geodesics Inc., Eugene, OR) sampling at 200Hz. Electrode locations are shown in Supplementary Figure 1. During the recording, impedances were kept below 70k Ω , all channels were referenced to the vertex, and a bandpass hardware filter (0.1-100Hz) was applied. The following preprocessing steps were performed offline: data were bandpass (0.3-100Hz) and notch (60Hz) filtered to remove low frequency and line noise; data were segmented into trials from -1000ms to 2000 ms around target stimuli; ocular artifacts were corrected (Gratton, Coles, & Donchin, 1983); data from all channels were re-referenced to the average reference (Bertrand, Perrin, & Pernier, 1985); and the average baseline 200 ms before the target stimulus presentation was subtracted from trials. Trials with artifacts larger than $\pm 100\mu\text{V}$ were removed before analysis. On average, the same percentage of trials (13.8%) were removed from both Unrelated and Related conditions from each subject's data.

2.5 Time-frequency analysis

Event-related changes in EEG power and coherence were examined by computing time-frequency representations (TFR) of the single word trial data using the multi-taper approach described by Mitra and Pesaran (1999). The open source Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) and in-house Matlab code were used for these calculations. Because we computed the TFRs of the single trials before averaging, our

analysis reflects both evoked and induced EEG activity, i.e., oscillatory activity that is both phase-locked and non-phase-locked to the stimuli, and the analysis utilized both real and imaginary components of the frequency response. Both evoked and induced rhythms have been found to be critical to semantic processing (Bastiaansen, van der Linden, ter Keurs, Dijkstra, & Hagoort, 2005; Bastiaansen, Oostenveld, Jensen, & Hagoort, 2008; Mainy, Jung, Baciú, Kahane, Schoendorff, et al., 2008; Pulvermüller, Lutzenberger, & Preissl, 1999), but for our study we did not initially have a theoretical motive for separating their analysis. A preliminary analysis of evoked-only gamma power did not yield significant effects, thus we have decided to examine evoked and induced information together to avoid theoretical complications of examining induced-only activity (evoked and induced activity may not combine linearly). Also these types of rhythms reflect complementary underlying dynamics. This is because evoked activity is caused by the event (stimulus) while induced is related to background activity that has been modulated by the event. Events affect both types of activity, so it is worth examining the total activity. Also evoked activity tends to appear earlier and is more related to 'primary' (i.e., sensory) processing while induced activity develops later and involves 'secondary' (i.e., higher order or integrative) processing. Usually earlier components are also present in the ERP while later components can be averaged out and therefore be missing from the ERP because of their greater jitter relative to the stimulus onset. This consideration also does not support teasing them apart because both may be important for the task. In order to optimize the trade-off between time- and frequency resolution, TFRs were constructed in two different, partially overlapping, frequency ranges. In the low-frequency range (2–30 Hz), 400 ms Hanning windows were used to compute power and coherence changes in frequency steps of 1 Hz and time steps of 10 ms. Regarding temporal resolution, any given time-point in the resulting TFR is a weighted average of the time-points ranging from 200 ms before to 200 ms after this time point, and this gives a frequency resolution of $1/0.4 = 2.5$ Hz. In the high-frequency range (25–100 Hz), 400 ms discrete prolate spheroidal sequence windows (multitapers) were used to compute power and coherence changes in 2.5-Hz frequency steps and 10 ms time steps with 5-Hz frequency smoothing. These calculations were performed starting 500 ms before the word appeared on the screen to 1500 ms after the word onset.

Coherence between electrodes has been used extensively as a measure of long-distance synchrony (e.g., Summerfield & Mangels, 2005; Weiss & Mueller, 2003). While power is calculated from the auto-spectrum of a single channel, coherence utilizes the normalized squared cross-spectrum between pairs of channels to quantify the stability of phase difference between the signals (see Nunez & Srinivasan, 2006, for relevant mathematical equations). Coherence is high if the signals are synchronized, i.e., the relative phase difference is stable across trials. If the event-related coherence is greater than baseline, the TFR displays coherence increases. While there are some limitations in the interpretation of coherence between nearby electrodes, it is well-accepted to perform coherence between electrodes to investigate large-scale network dynamics (for a review, see Varela, Lachaux, Rodriguez, & Martinerie, 2001). Unlike measures that only take the phase into account, coherence computes the consistent synchronization based on both amplitude and phase and may thus be more robust against noise and spurious phase-locking. Since coherence is then normalized by the power at each electrode, power in theory should not contribute to the level of coherence. We calculated TFRs of coherence using the same parameters as above. We tested a selection of 32 electrodes spread across the scalp as seed channels with 12 of those channels clustered over left frontal areas. For each seed channel, 127 coherence TFRs were calculated (one for each pair of channels).

The TFRs of target word trials were averaged separately for Related and Unrelated conditions. The power and coherence changes were then expressed as percent increases or decreases relative to a baseline of -50 ms to 50 ms around the target stimulus. Our main

results did not depend on the choice of baseline as -200ms to -100ms was also tested as a baseline and presented similar results. A peri-stimulus baseline minimizes overlap with the semantic processing of the prime and is thus preferred.

2.6 Statistical analysis

For behavioral data, we performed a single t-test between grand-averaged RT for Unrelated v. Related conditions. Similarly, a t-test was used to assess the amplitude difference between the two conditions at the spatiotemporal peak of the N400 ERP component.

To evaluate statistical differences between conditions for TFRs, we used a nonparametric statistical method with False Discovery Rate (FDR) correction. This method is optimal when there is no a priori knowledge of the spatiotemporal locus of the effect. In undertaking the large number of comparisons to find a possible effect, we would run into a multiple-comparisons problem and would not be able to control the Type 1 error rate. The FDR correction with the nonparametric statistical method can control this error rate (Genovese, Lazar, & Nichols, 2002).

The nonparametric analysis is fully explained by Maris and Oostenveld (2007). Essentially, a simple dependent-samples t-test was performed on the observed data for each time-frequency-channel data point. Next, a null distribution which assumes no difference between conditions was created. This distribution is obtained by 1000 times randomly assigning the conditions in subjects and calculating the t-statistic for each randomization. Finally, we compared the t-statistics of the observed data to the nonparametric null distribution and calculated the proportion of t-statistics larger or smaller than the observed ones. These p-values were then thresholded using the FDR algorithm to ensure that the expected proportion of falsely rejected hypotheses was less than 5%. This allowed us to control the Type 1 error rate.

We examined the difference Unrelated-Related for both power and coherence data (please note that with EEG data, this subtraction allows us to examine both Unrelated > Related and Related > Unrelated contrasts which appear as positive and negative differences, respectively). We performed the nonparametric analysis with FDR thresholding on all pairs of time-frequency-electrode data points; this was done separately on lower frequencies (4-30 Hz) and higher frequencies (25-60 Hz). Thus the significant effects reported below span the theta, alpha, and beta bands (4-30 Hz) or the gamma band (30-60 Hz). Effects less than 165 ms long (the average minimum time to complete a full theta cycle) or spanning less than 3 adjacent channels were not considered as they were likely to be false positives and therefore not robust effects.

3. Results

3.1 Behavioral Results

We found that behavioral responses were significantly faster for the Related compared to the Unrelated condition (Unrelated RT = 779 ms; Related RT = 760 ms; one-tailed, paired t-test: $p=0.03$) as measured from the onset of the letter. This effect has been shown repeatedly with the lexical decision task; to our knowledge, this is the first report of a RT difference using the delayed letter-search task. Average accuracy on the task was 93% with all subjects performing at greater than 80% accuracy. No difference in accuracy was seen between conditions based on relatedness (Unrelated correct = 93.7%; Related correct = 92.7%; two-tailed, paired t-test: $p=0.22$). But there is a significant difference in accuracy based on which word the letter appeared in (in prime only = 84%; in target only = 91%; in both = 98%; in neither = 97%; one way ANOVA: $p<0.001$) indicating that the task is hardest when the letter is only in the prime word.

3.2 ERP Results

We first confirmed the neural effect of semantic priming by examining the N400 ERP component. Grand-averaged ERPs for Unrelated and Related conditions are presented in Figure 1B. The difference between the N400 amplitudes can be seen between approximately 275–500 ms. This N400 effect (greater negative deflection for the Unrelated than the Related condition) is significant as tested near its spatiotemporal peak at electrode 62 between 350–450 ms (one-tailed, paired t-test: $p=0.02$). Additionally, the topography of the difference between conditions has the typical broad negative distribution centered at parietal electrodes (Figure 1B). The positivity over the left frontal electrodes results from a greater positive waveform for the Unrelated than the Related condition and hence is likely the opposite end of the effective dipole causing the N400. This frontal effect is often too sparsely sampled by EEG systems with fewer electrodes on the forehead and cheek and therefore is not commonly observed or reported. Additionally, while the $1\mu\text{V}$ effect size may seem smaller than is normally reported, it is mainly a consequence of using the vertex as the reference and subsequently re-referencing to the average reference and does not reflect a lack of semantic processing (for similar effects, see Hill, Strube, Roesch-Ely, & Weisbrod, 2002; Hill, Ott, & Weisbrod, 2005). Thus the N400 priming effect helped us confirm that semantic processing took place.

3.3 EEG Power Results

Significance testing over the 4–60 Hz range on the contrast Unrelated- revealed one significant power effect in the gamma band in the hypothesized direction (Unrelated > Related), and two significant effects in the opposite direction (Related > Unrelated) which we call “reverse effects”. The gamma-band effect in the expected direction can be seen in Figure 2. Gamma power decreased for the Related compared to the Unrelated condition in the window 45–50Hz, 150–450 ms. The significant portion of this difference is shown in the masked difference TFR and masked topography plot. The main difference is centered over six right parietal electrodes near the peak of the N400 effect. There was also a significant difference at a single left frontal electrode (ch. 32), though isolated single channel effects are less robust. Results in the gamma band are susceptible to miniature saccadic artifacts (Yuval-Greenberg, Tomer, Keren, Nelken, & Deouell, 2008), thus we checked if our results fit the characteristics of this saccadic gamma response (30–90 Hz, 200–300ms, largest at electrodes near the orbits for average re-referenced data) and for saccadic spike potentials themselves. These additional examinations appear in more detail in the supplementary section (see Supplementary Figures 2, 3, & 4), but overall our gamma result does not appear to fit these criteria. Thus it is still most likely that this gamma effect is due to semantic processing and not a saccadic artifact.

The two reverse effects were in the gamma and alpha bands. The reverse gamma effect (Figure 3) resulted from greater power for the Related than the Unrelated condition. This effect spanned a later time (300–800 ms) and lower frequency (35–40Hz) window and was centered more posteriorly than the positive gamma effect. The significant difference is shown in the masked graphs. The reverse alpha effect is shown in Figure 4. As decreases in the alpha power are thought to reflect active processing (Klimesch, Sauseng, & Hanslmayr, 2007), the greater power decreases for Related than Unrelated in our study reflect more task-related activity for Related than Unrelated (thus a “reverse” effect compared to the typical direction of the priming effect). This difference occurs between 600–1000 ms and 8–12Hz over left frontal electrodes. The significant difference can be seen in the masked graphs. No other robust significant differences in power were observed. Specifically, while theta power changes have been related to lexical-semantic processing (Roehm, Bornkessel, & Schleusewsky, 2007; Bastiaansen, van der Linden, ter Keurs, Dijkstra, & Hagoort, 2005), we observed no robust difference in theta power here. The theta power increases relative to

baseline that were observed for both Related and Unrelated conditions in Figure 4 did not differ between conditions. Also, we observed a short (<100ms) significant difference in theta power increases (Unrelated>Related) in right frontal electrodes (not pictured), but the brevity of this effect did not fit our reporting criteria to avoid false negatives.

3.4 EEG Coherence Results

Of the 32 seed channels tested, we only found five with robust significantly-different coherence changes. These differences were only in the theta band. We observed significantly greater theta coherence for Unrelated>Related in two time windows, 150-425 ms and 600-900 ms. These coherence differences resulted from increased theta coherence relative to baseline for the Unrelated condition but no coherence increases relative to baseline in the Related condition (see the effect in an example seed channel, Channel 34, in Figure 5A). The earlier theta effect appeared in three adjacent seed channels (of the 32 tested seed channels) over the left frontal cortex and displayed significant coherence with several adjacent posterior channels (Figure 5B showing topography of coherence changes for seed channels 32, 127, and 128). The later theta effect appeared in four adjacent seed channels over the left frontal cortex. Each seed channel displayed significant coherence with a large number of adjacent posterior electrodes (Figure 5C showing topography of coherence changes for seed channels 32, 33, 34, 128). Each topographical map represents significant coherence changes from baseline across the scalp as calculated from the noted seed channel (indicated with the red star). As the channels with significant coherence are greater than 10cm apart, we think it is unlikely that coherence is due to volume conduction (see Nunez & Srinivasan, 2006, for a discussion of volume conduction effects on coherence). Notably, we did not observe significant coherence differences for the channels which are right homologues to the left channels with significant coherence. We also did not observe significant coherence differences in other frequency bands that fit our criteria to eliminate false positives. Specifically, a beta effect may fit with another report of beta coherence differences during priming (Ghuman, Bar, Dobbins, & Schnyer, 2008), but it was not robust enough for us to consider it a real effect (see Supplementary Figure 5). We also confirmed that the observed theta coherence increases were independent of theta power increases (see Supplementary Figure 6). Please see the Supplementary Data for a discussion regarding the sufficiency of coherence alone to form a functional network.

4. Discussion

In this study, we examined whether theta coherence might be the mechanism by which a dynamic anterior-posterior network retrieves semantic representations. Additionally, we investigated if gamma power was involved in forming local functional networks for the activation of lexical-semantic representations. Subjects engaged in a semantic priming paradigm, and their neural responses to the Unrelated and Related word pairs were compared. We first confirmed the effect of semantic priming on the neural response by examining the N400 ERP component. Then we analyzed the time-frequency responses. The results for power and coherence analyses are discussed below.

4.1 Local Synchronization

We hypothesized that decreases in gamma power would reflect facilitation of lexical-semantic processing for Related words compared with Unrelated words during single word reading. Our analysis of power changes did reveal this gamma effect (Unrelated > Related) between 45-50 Hz and 150-450 ms. Additionally there were two effects in the reverse direction (Related > Unrelated) in the gamma and alpha bands; while their interpretation is less clear, they do not reflect facilitation of semantic retrieval.

The early gamma effect is in the same direction as the classic reaction time and N400 effects (Unrelated > Related). Thus, we believe that the gamma power increase relative to baseline between 45-50 Hz and 150-450 ms at the parietal electrodes in both conditions reflects the activation of local functional networks involved in the lexical-semantic representation. More specifically, the smaller gamma power increase in the Related condition may signify less gross activation or, in other words, more focused activation due to the priming of a related semantic representation and the automatic spreading activation (ASA) which accompanies priming. The gamma power difference at the single left frontal electrode may reflect local networks in left frontal areas thought to be involved in top-down semantic processing. Gamma frequencies are thought to transiently bind together cell assemblies (Buzsaki & Draguhn, 2004; Engel, Fries, & Singer, 2001; Harris, Csicsvari, Hirase, Dragoi, & Buzsaki, 2003) and work on a more local scale (Von Stein & Sarnthein, 2000); thus, they are a likely mechanism for dynamically forming local networks involved in semantic processing.

Gamma has been previously observed during studies involving lexical-semantic processing. Studies of single word reading found differences in gamma power modulation based on the semantic features of the word or semantic demands of a task (Mainy, Jung, Baciú, Kahane, Schoendorff, et al., 2008; Pulvermüller, Lutzenberger, & Preissl, 1999). Pulvermüller et al. report that gamma power between 25-35 Hz and 500-800 ms was greater for verbs than for nouns at electrodes over motor cortex and greater for nouns than verbs over occipital cortex. This dissociation by ROI reflects the primarily motor and visual properties of verbs and nouns, respectively. Subjects performed an indirect task of lexical decision which indicates gamma power can be modulated even when not directly relevant to the task. While we observed a gamma effect that also reflected greater power for the condition requiring more semantic processing, our effect was in a different part of the gamma band (45-50 Hz) and in an earlier time window (150-450 ms). Thus, the difference between the timing, frequency, and location of the two results may be related to different networks being engaged at different times and reflected in different parts of the gamma band. Using intracerebral EEG, Mainy et al. observed greater gamma power across 40-150 Hz and peaking at 400ms in the left pars triangularis while subjects performed a semantic categorization task compared to either a phonological rhyming task or a visual task. Intracerebral EEG has several advantages over scalp EEG including reduced volume conduction and better localization ability, but the electrodes are necessarily confined to very local areas. EEG at the scalp usually reflects averaging over larger cortical areas and thus provides a more global measure of activity. So the gamma power increases that we observed likely reflect involvement of a lexical-semantic network even beyond the pars triangularis. Although these studies used different types of tasks, one more indirectly probing lexical-semantics and the other directly so, the differences in gamma reactivity during semantic processing do not seem to be determined solely by the type of task in the same manner as previously found during repetition priming (Gruber & Müller, 2006). Several studies have also found greater gamma power increases for semantically-congruent words in sentences than for semantically-incongruent words when subject read for comprehension (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Hald, Bastiaansen, & Hagoort, 2006; Penolazzi, Angrilli, & Job, 2009). These gamma increases are interpreted as reflecting semantic unification, since there are no increases when an incongruent word cannot be integrated properly within the context of a sentence. On the whole, activity in networks relevant to semantic retrieval and unification seem to be reflected in the gamma band.

While our early gamma effect may reflect local networks involved in the activation of stored lexical-semantic representations, we also observed two later effects in the gamma- and alpha-bands (between 300-800 ms and 600-1000 ms, respectively) for which the interpretation is less clear. Since the direction of these effects was opposite to the early gamma effect, it is unlikely that they reflect facilitation of semantic retrieval processes. One

possible interpretation is that they reflect attentional processing. Alpha power decreases are often correlated with increases in attention (see Klimesch, 1999, for a review) especially those in the lower alpha band (8-10 Hz). These decreases are also generally topographically widespread over the entire scalp. Our data appear to be centered on the lower half of the alpha band and are also topographically widespread for both Related and Unrelated conditions (not pictured) though the significant difference between conditions is frontal. Gamma power increases have also been observed during increases in attention (see Jensen, Kaiser, & Lachaux, 2007, for a review). It is possible that subjects increased their attention towards Related target words; they were unaware ahead of time that there would be semantically-related pairs, and the observed relationships may have peaked their interest and attention. As subjects noticed the relatedness of some pairs, they may also have been performing an implicit semantic relatedness judgment. The semantic judgment task has previously been correlated with topographically widespread alpha power decreases (Klimesch, Doppelmayr, Pachinger, & Russegger, 1997). It is possible that this judgment was made only for the related pairs as the unrelated pairs would not encourage a judgment without an explicit judgment task; this may explain the differential response in alpha power decreases. These interpretations are speculative though, and further research could help clarify our results.

4.2 Long-range Synchronization

Our coherence analysis revealed significantly greater theta coherence for Unrelated than Related conditions between left anterior channels and bilateral posterior channels. We did not observe robust significant coherence differences in other frequency bands nor, notably, between other pairs of channels. This specific topographical pattern of left anterior to posterior coherence suggests that coupling may be occurring between left frontal and posterior areas during semantic processing. Examining our results in the context of the fMRI literature may help us to better understand this possible interpretation.

When the target word is not preceded by a related prime, fMRI studies have shown that the left inferior frontal gyrus (LIFG) is recruited in addition to posterior cortex, typically interpreted as frontally-mediated retrieval of semantics (Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Gold, Balota, Jones, Powell, Smith, & Andersen, 2006; Wagner, Paré-Blagoev, Clark, & Poldrack, 2001). Additionally, fMRI connectivity analysis has demonstrated that these areas are functionally connected albeit on a slow scale (Bokde, Tagamets, Friedman, & Horwitz, 2001; Xiang, Fonteijn, Norris, & Hagoort, 2010). But a possible method of real-time communication between these areas is not known. This study investigated whether anterior-posterior coherence might reflect the dynamic communication between these areas. Indeed we observed significantly greater anterior-posterior theta coherence for the Unrelated condition compared with Related condition between 150-425 ms and 600-900 ms. Also, the topography of left anterior to posterior coherence is likely reflecting phase synchronization between those left anterior and posterior areas seen in the fMRI BOLD studies of semantic priming. While it is reasonable to suggest that phase synchronization is occurring between these areas, scalp EEG analysis is limited in localizing this coherence to specific brain areas, and this suggestion would benefit from specific testing in future studies. Since gamma power has been correlated with BOLD activity (e.g., Goense & Logothetis, 2008; Schölvinck, Maier, Ye, Duyn, & Leopold, 2010), the gamma difference we observe at the single left frontal channel may reflect differences in LIFG activity observed in these previous neuroimaging studies. But presence of gamma power in a single channel is not very robust. Moreover, neither gamma power nor BOLD levels can speak to dynamic coupling between LIFG and posterior storage areas, the theta coherence analysis helps elucidate this mechanism.

What might be the nature of the semantic process that theta coherence is reflecting? Our semantic priming paradigm with a delayed letter search task has been repeatedly used to assess semantic priming (e.g., Kutas & Hillyard, 1989; Kutas, 1993; Lau, Almeida, Hines, & Poeppel, 2009), but it has not often been acknowledged that the working memory component may be interacting with the semantic processing in this paradigm. Thus we may interpret the theta coherence effect as reflecting only differences in semantic retrieval processing or both retrieval differences and working memory differences. We present both options below.

Within the context of the fMRI literature and the role of left frontal areas for top-down assistance of semantic processing, we may interpret theta coupling as possibly being top-down (although note that coherence is not a measure of directionality). In this case, theta coherence could reflect a controlled retrieval mechanism to provide assistance when retrieval is more difficult (Badre, et al., 2005; Wagner, et al., 2001). Additionally, LIFG may assist in efficient retrieval during these more difficult situations but may not be essential to retrieval as temporary lesions to the LIFG through transcranial magnetic stimulation slows reaction time but does not impede accuracy for semantic tasks (Devlin, Matthews, & Rushworth, 2003). This proposal of additional assistance is also in line with evidence that prefrontal regions are recruited when strong associations between stimuli are lacking (Miller & Cohen, 2001). Namely, a strong association between prime and target may provide sufficient ASA for the target to be retrieved without top-down assistance, but a weak or non-existent association may not provide sufficient automatic activation for the most efficient retrieval of the target. In this case a top-down process provides a facilitating or bias signal to more efficiently retrieve the meaning of the target word than through ASA alone. As we observe greater theta coherence for the Unrelated condition than the Related condition and imaging studies have shown greater LIFG and posterior cortex activation in the Unrelated than the Related condition (Badre et al., 2005; Gold et al., 2006; Wagner et al., 2001), we suggest that theta coherence reflects greater anterior-posterior communication between these areas when they are active and are providing top-down retrieval assistance during the Unrelated condition. While there is no doubt that semantic processing occurs in this paradigm (based on the N400 and RT effects), one might wonder how much top-down processing could be occurring without the use of an explicitly semantic task. Gold et al. (2006) seem to address this, as they use a lexical decision task during semantic priming and still observe LIFG activation. Thus a task involving semantic demands may not be necessary to engage frontally-mediated or top-down mechanisms. Additionally, N400 effects during semantic priming (see Kutas & Federmeier, 2011, for a review) suggest that retrieval takes place between about 200-600ms post-stimulus. Since the earlier coherence effect of 150-425ms occurs largely within this window, it is likely that this earlier effect reflects semantic retrieval processing.

The later 600-900ms window of coherence may reflect another aspect of semantic processing, semantic selection, and/or working memory differences between conditions. Selection of the correct representation from multiple possibilities involves LIFG inhibiting incorrect representations in posterior cortex following retrieval processing (Badre et al., 2005; Gold et al., 2006). An electrophysiological index called the post-N400 positivity (PNP) which occurs between 600-900ms in left frontal electrodes has previously been proposed to reflect semantic selection (Van Petten & Luka, 2006; for a review, see Van Petten & Luka, 2012). But ERPs cannot speak to coupling of brain areas, so the later theta coherence may additionally support communication between LIFG and posterior areas for semantic selection. A downside to this interpretation is that it is not completely clear why the Related condition would engage selection processing to a lesser degree than the Unrelated condition especially if coherence differences originate from less theta coherence

for the Related target than the Related prime (versus the same amount of coherence for Unrelated primes and targets).

Another possible interpretation of the later theta coherence results comes from the addition of a working memory task to the semantic priming paradigm, so these results may also reflect semantic influence on working memory processing. As subjects performed the letter search task after the presentation of the prime and target, they had to hold the two words in mind for successful task completion. Related words are likely easier to hold in mind than unrelated words, and this may ease the working memory requirements. This interaction of working memory processing on semantic relatedness has been previously investigated using EEG. Cameron et al. (2005) had subjects read three words and then perform either a delayed semantic relatedness judgment for a fourth word (semantic priming + working memory condition) or a delayed control task on the fourth word that did not require holding the first three words in mind (semantic priming + no working memory condition). Notably the fourth word was either related or unrelated to the third word thus providing the semantic relatedness contrast. The ERP results show a larger N400 effect when the task requires retention of the words as opposed to when retention is not necessary. Thus they saw that working memory interacts with long-term memory processing of the semantic representation, and an interaction between semantic relatedness and the type of task was significant in the 660-900ms interval. Based on this timing, it is possible that in our study the later theta coherence effect of 600-900ms reflects both semantic relatedness and working memory effects, but the earlier coherence effect between 150-425ms occurs before working memory is fully engaged and likely only reflects semantic retrieval processing. Increases in anterior-posterior theta coherence have also previously been observed under greater working memory demands although these studies did not have a semantic component (Sarnthein, Petsche, Rappelsberger, Shaw, & von Stein, 1998; Sauseng, Klimesch, Schabus, & Doppelmayr, 2005). Sarnthein et al. (1998) saw greater theta coherence during the retention of visual stimuli than during the perception of these stimuli, while Sauseng et al. (2005) observed increased theta coherence with increased central executive processing of stimuli held in visuospatial working memory. But this is the first proposal that anterior-posterior theta coherence can reflect both working memory and semantic processing demands. As the effects likely interact from 600-900ms post-target, greater theta coherence in this window for Unrelated than Related trials may reflect a combination of increased semantic selection processing and increased working memory demands. This proposal could be tested with a study which separately modulates semantic relatedness and working memory processing as done by Cameron et al. (2005). This dual role for theta coherence during both semantic retrieval and working memory processing may at first seem to present a contradiction, but closer consideration helps to resolve it. As the frequency of synchronization is likely dictated by the distance and transmission speed between brain areas (Von Stein & Sarnthein, 2000), coupling in a lower frequency like the theta band is a good candidate for communication between frontal and posterior storage areas whether those areas support semantic processing or working memory.

While a prevalent view of coherence is that it serves as a mechanism for large-scale integration and communication (Engel, Fries, & Singer, 2001; Fries, 2005), the field still lacks a clear understanding of the effects of priming on coherence and how the effects relate to these large-scale functions. It is possible that different effects of priming on coherence reflect different top-down facilitation mechanisms. Two recent studies have found coherence increases and power or ERP decreases after priming. Ghuman et al. (Ghuman, Bar, Dobbins, & Schnyer, 2008) observed increased fronto-temporal beta coherence after repetition priming between 200-300 ms, while Kujala et al. (Kujala, Vartiainen, Laaksonen, & Salmelin, 2011) found bilateral temporal alpha coherence increases after semantic priming centered at 333 ms. It was suggested that increased coherence after priming may reflect

more effective information transfer between areas while simultaneous decreases in power indicate less reliance on local processing; furthermore, this phenomenon could be a mechanism for facilitating behavioral responses through a supportive or repetitive context (Ghuman et al., 2008). This supportive context may allow subjects to make predictions and expect a set of stimuli, and this top-down prediction facilitates retrieval. We also observed some increases in anterior-posterior beta coherence after priming although this effect was not very strong and thus is not reported as a main result (see Supplementary Data). While these beta coherence increases are in line with the findings of Ghuman et al. and may reflect facilitation through prediction, the main result of our study was decreased theta coherence after priming. The differences in the frequency of these effects and the direction of the effects suggests that we may be observing evidence for a different type of top-down retrieval mechanism. We proposed above that this top-down retrieval mechanism is seen when contextual support for retrieval is low. This mechanism would allow efficient processing of stimuli even without context akin to the proposal of object-based top-down assistance for retrieval (Fenske, Aminoff, Gronau, & Bar, 2006). In this proposal, simplified information is extracted from early visual analysis and used by the PFC to restrict the set of possible representations for the object in conditions without context; thus the PFC can still efficiently assist in retrieving the correct representation. This top-down mechanism exists alongside another where context is used to make predictions which facilitate retrieval of representations in conditions with context. While it is an open question which information may be used by the PFC to restrict the set of semantic representations in the Unrelated condition, it is possible that theta coherence may reflect a similar top-down mechanism to assist in the retrieval during this condition as opposed to beta coherence which may reflect a top-down mechanism to facilitate retrieval through prediction or expectancy. Ghuman et al. and Kujala et al. did not report the theta coherence effects as their windows of analysis were more limited. Ghuman and colleagues did not examine theta frequencies while Kujala and colleagues did not examine theta responses after 650 ms nor from left frontal seed channels, and therefore those analyses may have missed the theta effects we observed. Nevertheless, our own and previous studies suggest that coherence, depending on the frequency band, can serve as a mechanism for both facilitation through top-down prediction as well as top-down retrieval during more difficult retrieval conditions.

4.3 Conclusions

Our results indicate that oscillatory synchronization serves as a mechanism to assemble both local and long-range networks for semantic retrieval. Initially, parietal gamma-band synchronization may reflect the activation of local functional networks of semantic representations while anterior-posterior theta coherence may enable frontally-mediated retrieval of these representations when they are not related to the previous word. This is followed by later theta-band coherence which possibly reflects semantic relatedness effects on working memory. Taken with previous neuroimaging results, we have a fuller picture of the mechanisms of semantic processing – it likely involves not only recruitment of anterior and posterior brain areas but also theta phase synchronization between these areas. The semantic system is widespread and operates in diverse ways. Further work could help clarify how oscillatory synchronization might be the mechanism for local and long-range functional connectivity for other aspects of semantic processing, and moreover, for language networks in general.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This work was supported by the National Institutes of Health (F31DC010545 to M.S.M, partly by R01DC010780 and R01DC007169 to R.B.F, and partly by R21RR025786 to A.V.M). We would like to thank Peter Turkeltaub and our anonymous reviewers for their thoughtful comments on this manuscript.

References

- Anaki D, Henik A. Is there a “strength effect” in automatic semantic priming? *Memory & Cognition*. 2003; 31(2):262–272. [PubMed: 12749468]
- Avons SE, Russo R, Cinel C, Verolini V, Glynn K, McDonald R, Cameron M. Associative and repetition priming with the repeated masked prime technique: no priming found. *Memory & Cognition*. 2009; 37(1):100–114. [PubMed: 19103980]
- Badre D, Poldrack RA, Paré-Blagoev EJ, Insler RZ, Wagner AD. Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron*. 2005; 47(6):907–918. [PubMed: 16157284]
- Bastiaansen MCM, Oostenveld R, Jensen O, Hagoort P. I see what you mean: theta power increases are involved in the retrieval of lexical semantic information. *Brain & Language*. 2008; 106(1):15–28. [PubMed: 18262262]
- Bastiaansen MCM, van der Linden M, ter Keurs M, Dijkstra T, Hagoort P. Theta responses are involved in lexical-semantic retrieval during language processing. *Journal of Cognitive Neuroscience*. 2005; 17(3):530–541. [PubMed: 15814011]
- Bertrand O, Perrin F, Pernier J. A theoretical justification of the average reference in topographic evoked potential studies. *Electroencephalography and Clinical Neurophysiology*. 1985; 62(6):462–464. [PubMed: 2415344]
- Binder JR, Desai RH, Graves WW, Conant LL. Where is the semantic system? a critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*. 2009; 19(12):2767–2796. [PubMed: 19329570]
- Bokde ALW, Tagamets MA, Friedman RB, Horwitz B. Functional interactions of the inferior frontal cortex during the processing of words and word-like stimuli. *Neuron*. 2001; 30(2):609–617. [PubMed: 11395018]
- Bookheimer S. Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Review of Neuroscience*. 2002; 25:151–188.
- Buzsáki, G. *Rhythms of the brain*. New York (NY): Oxford University Press; 2006.
- Buzsáki G, Draguhn A. Neuronal Oscillations in Cortical Networks. *Science*. 2004; 304(5679):1926–1929. [PubMed: 15218136]
- Cameron KA, Haarmann HJ, Grafman J, Ruchkin DS. Long-term memory is the representational basis for semantic verbal short-term memory. *Psychophysiology*. 2005; 42(6):643–653. [PubMed: 16364060]
- Crone NE, Hao L, Hart J, Boatman D, Lesser RP, Irizarry R, Gordon B. Electrographic gamma activity during word production in spoken and sign language. *Neurology*. 2001; 57(11):2045–2053. [PubMed: 11739824]
- Damasio H, Tranel D, Grabowski T, Adolphs R, Damasio A. Neural systems behind word and concept retrieval. *Cognition*. 2004; 92(1-2):179–229. [PubMed: 15037130]
- Devlin JT, Matthews PM, Rushworth MFS. Semantic processing in the left inferior prefrontal cortex: a combined functional magnetic resonance imaging and transcranial magnetic stimulation study. *Journal of Cognitive Neuroscience*. 2003; 15(1):71–84. [PubMed: 12590844]
- Engel AK, Fries P, Singer W. Dynamic predictions: Oscillations and synchrony in top-down processing. *Nature Reviews Neuroscience*. 2001; 2(10):704–716. 4.
- Fenske MJ, Aminoff E, Gronau N, Bar M. Top-down facilitation of visual object recognition: object-based and context-based contributions. *Progress in Brain Research*. 2006; 155(B):3–21. [PubMed: 17027376]
- Franklin MS, Dien J, Neely JH, Huber E, Waterson LD. Semantic priming modulates the N400, N300, and N400RP. *Clinical Neurophysiology*. 2007; 118(5):1053–1068. [PubMed: 17336145]

- Fries P. A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. *Trends in Cognitive Science*. 2005; 9(10):474–480.
- Frith CD, Friston KJ, Liddle PF, Frackowiak RS. A PET study of word finding. *Neuropsychologia*. 1991; 29(12):1137–1148. [PubMed: 1791928]
- Genovese CR, Lazar NA, Nichols T. Thresholding of statistical maps in functional neuroimaging using the false discovery rate. *Neuroimage*. 2002; 15(4):870–878. [PubMed: 11906227]
- Ghuman AS, Bar M, Dobbins IG, Schnyer DM. The effects of priming on frontal-temporal communication. *Proceedings of the National Academy of Science USA*. 2008; 105:8405–8409.
- Goense JBM, Logothetis NK. Neurophysiology of the BOLD fMRI signal in awake monkeys. *Current Biology*. 2008; 18(9):631–640. [PubMed: 18439825]
- Gold BT, Balota DA, Jones SJ, Powell DK, Smith CD, Andersen AH. Dissociation of automatic and strategic lexical-semantics: functional magnetic resonance imaging evidence for differing roles of multiple frontotemporal regions. *Journal of Neuroscience*. 2006; 26(24):6523–6532. [PubMed: 16775140]
- Gratton G, Coles MG, Donchin E. A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*. 1983; 55(4):468–484. [PubMed: 6187540]
- Gruber T, Müller MM. Oscillatory brain activity in the human EEG during indirect and direct memory tasks. *Brain Research*. 2006; 1097(1):194–204. [PubMed: 16729980]
- Hagoort P, Hald L, Bastiaansen M, Petersson KM. Integration of Word Meaning and World Knowledge in Language Comprehension. *Science*. 2004; 304(5669):438–441. [PubMed: 15031438]
- Hald LA, Bastiaansen MCM, Hagoort P. EEG theta and gamma responses to semantic violations in online sentence processing. *Brain & Language*. 2006; 96(1):90–105. [PubMed: 16083953]
- Hassler U, Trujillo Barreto N, Gruber T. Induced gamma band responses in human EEG after the control of miniature saccadic artifacts. *Neuroimage*. 2011; 57(4):1411–1421. [PubMed: 21645624]
- Harris KD, Csicsvari J, Hirase H, Dragoi G, Buzsaki G. Organization of cell assemblies in the hippocampus. *Nature*. 2003; 424(6948):552–556. [PubMed: 12891358]
- Hill H, Ott F, Weisbrod M. SOA-dependent N400 and P300 semantic priming effects using pseudoword primes and a delayed lexical decision. *International Journal of Psychophysiology*. 2005; 56(3):209–221. [PubMed: 15866325]
- Hill H, Strube M, Roesch-Ely D, Weisbrod M. Automatic vs. controlled processes in semantic priming--differentiation by event-related potentials. *International Journal of Psychophysiology*. 2002; 44(3):197–218. [PubMed: 12031295]
- Holcomb P. Automatic and attentional processing – an event-related brain potential analysis of semantic priming. *Brain & Language*. 1988; 3(1):66–85. [PubMed: 3179703]
- Hutchinson KA. The effect of asymmetrical association on positive and negative semantic priming. *Memory & Cognition*. 2002; 30(8):1263–1276. [PubMed: 12661857]
- Jensen O, Kaiser J, Lachaux JP. Human gamma-frequency oscillations associated with attention and memory. *Trends in Neuroscience*. 2007; 30(7):317–324.
- Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Research Reviews*. 1999; 29(2-3):169–195. [PubMed: 10209231]
- Klimesch W, Doppelmayr M, Pachinger T, Russegger H. Event-related desynchronization in the alpha band and the processing of semantic information. *Cognitive Brain Research*. 1997; 6(2):83–94. [PubMed: 9450602]
- Klimesch W, Sauseng P, Hanslmayr S. EEG alpha oscillations: the inhibition-timing hypothesis. *Brain Research Reviews*. 2007; 53(1):63–88. [PubMed: 16887192]
- Kujala J, Vartiainen J, Laaksonen H, Salmelin R. Neural interactions at the core of phonological and semantic priming of written words. *Cerebral Cortex*. 2011; 22(10):2305–2312. [PubMed: 22056541]
- Kutas M. In the company of other words – Electrophysiological evidence for single-word and sentence context effects. *Language & Cognitive Processes*. 1993; 8(4):533–572.
- Kutas M, Federmeier KD. Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Reviews of Psychology*. 2011; 62(1):621–647.

- Kutas M, Hillyard SA. An electrophysiological probe of incidental semantic association. *Journal of Cognitive Neuroscience*. 1989; 1(1):38–49. [PubMed: 23968409]
- Lau E, Almeida D, Hines PC, Poeppel D. A lexical basis for N400 context effects: Evidence from MEG. *Brain and Language*. 2009; 111(3):161–172. [PubMed: 19815267]
- Lau EF, Phillips C, Poeppel D. A cortical network for semantics: (de)constructing the N400. *Nature Reviews Neuroscience*. 2008; 9(12):920–933.
- Mainy N, Jung J, Baciú M, Kahane P, Schoendorff B, Minotti L, Hoffmann D, Bertrand O, Lachaux J. Cortical dynamics of word recognition. *Human Brain Mapping*. 2008; 29(11):1215–1230. [PubMed: 17712785]
- Maris E, Oostenveld R. Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*. 2007; 164(1):177–190. [PubMed: 17517438]
- Matsumoto A, Iidaka T. Gamma band synchronization and the formation of representations in visual word processing: evidence from repetition and homophone priming. *Journal of Cognitive Neuroscience*. 2008; 20(11):2088–2096. [PubMed: 18416680]
- McNamara, T. *Semantic priming: Perspectives from memory and word recognition*. New York: Psychology Press; 2005.
- Miller EK, Cohen JD. An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*. 2001; 24:167(1)
- Neely JH. Semantic priming and retrieval from lexical memory: role of inhibitionless spreading activation and limited-capacity attention. *Journal of Experimental Psychology: General*. 1977; 106:226–254.
- Nunez, PL.; Srinivasan, R. *Electric fields of the brain: the neurophysics of EEG*. New York: Oxford University Press; 2006.
- Oostenveld R, Fries P, Maris E, Schoffelen JM. FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence & Neuroscience*. 2011; 2011:1–9. [PubMed: 21837235]
- Penolazzi B, Angrilli A, Job R. Gamma EEG activity induced by semantic violation during sentence reading. *Neuroscience Letters*. 2009; 465(1):74–78. [PubMed: 19723559]
- Petrides M, Pandya DN. Distinct parietal and temporal pathways to the homologues of Broca's area in the monkey. *PLoS Biology*. 2009; 7(8):e1000170. [PubMed: 19668354]
- Posner, MI.; Snyder, CRR. Facilitation and inhibition in the processing of signals. In: Rabbitt, P.; Dornic, S., editors. *Attention and performance*. New York: Academic Press; 1975. p. 669–682.
- Pulvermüller F, Lutzenberger W, Preissl H. Nouns and verbs in the intact brain: evidence from event-related potentials and high-frequency cortical responses. *Cerebral Cortex*. 1999; 9(5):497–506. [PubMed: 10450894]
- Roehm D, Bornkessel I, Schlesewsky M. The internal structure of the N400: frequency characteristics of a language related ERP component. *Chaos and Complexity Letters*. 2007; 2(2/3):365–395.
- Rogers SL, Friedman RB. The underlying mechanisms of semantic memory loss in Alzheimer's disease and semantic dementia. *Neuropsychologia*. 2008; 46:12–21. [PubMed: 17897685]
- Sarnthein J, Petsche H, Rappelsberger P, Shaw GL, von Stein A. Synchronization between prefrontal and posterior association cortex during human working memory. *Proceedings of the National Academy of Science USA*. 1998; 95(12):7092–7096.
- Sauseng P, Klimesch W, Schabus M, Doppelmayr M. Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *International Journal of Psychophysiology*. 2005; 57(2):97–103. [PubMed: 15967528]
- Schölvinck ML, Maier A, Ye FQ, Duyn JH, Leopold DA. Neural basis of global resting-state fMRI activity. *Proceedings of the National Academy of Science USA*. 2010; 107:10238(22):10243.
- Slowiack LM. Semantic priming in a single-word shadowing task. *American Journal of Psychology*. 1994; 107(2):245–260.
- Stolz JA, Besner D. Levels of representation in visual word recognition: a dissociation between morphological and semantic processing. *Journal of Experimental Psychology: Human Perception & Performance*. 1998; 24(6):1642–1655. [PubMed: 9861715]

- Summerfield C, Mangels JA. Coherent theta-band EEG activity predicts item-context binding during encoding. *Neuroimage*. 2005; 24(3):692–703. [PubMed: 15652304]
- Swick D, Kutas M, Knight RT. Prefrontal lesions eliminate the LPC but do not affect the N400 during sentence reading. *Journal of Cognitive Neuroscience Supplement*. 1998; 29
- Van Petten C, Luka BJ. Neural localization of semantic context effects in electromagnetic and hemodynamic studies. *Brain & Language*. 2006; 97(3):279–293. [PubMed: 16343606]
- Van Petten C, Luka BJ. Prediction during language comprehension: Benefits, costs, and ERP components. *International Journal of Psychophysiology*. 2012; 83(2):176–190. [PubMed: 22019481]
- Varela F, Lachaux JP, Rodriguez E, Martinerie J. The brainweb: phase synchronization and large-scale integration. *Nature Reviews Neuroscience*. 2001; 2(4):229–239.
- von Stein A, Sarnthein J. Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology*. 2000; 38(3):301–313. [PubMed: 11102669]
- Xiang HD, Fonteijn HM, Norris DG, Hagoort P. Topographical functional connectivity pattern in the perisylvian language networks. *Cerebral Cortex*. 2010; 20(3):549–560. [PubMed: 19546155]
- Wagner AD, Paré-Blagoev EJ, Clark J, Poldrack RA. Recovering meaning: left prefrontal cortex guides controlled semantic retrieval. *Neuron*. 2001; 31(2):329–338. [PubMed: 11502262]
- Weiss S, Mueller HM. The contribution of EEG coherence to the investigation of language. *Brain & Language*. 2003; 85(2):325–343. [PubMed: 12735948]
- Yuval-Greenberg S, Tomer O, Keren AS, Nelken I, Deouell LY. Transient induced gamma-band response in EEG as a manifestation of miniature saccades. *Neuron*. 2008; 58(3):429–441. [PubMed: 18466752]

Highlights

- Oscillatory mechanisms of local and long-range semantic networks were investigated.
- Gamma power increases indicated activation of local semantic networks.
- Theta coherence reflected dynamic coupling of anterior and posterior networks.
- Theta coherence may be a dynamic mechanism for top-down semantic processing.

Figure 1. Semantic priming task and N400 ERP effect

A) Subjects viewed prime-target pairs that were either semantically unrelated or related. They were then asked to identify if the given letter had appeared in either word. Please see the Methods section for a complete explanation of the paradigm. B) Grand-averaged ERP waveforms of Unrelated (dotted) and Related (solid) conditions at electrode 62 (electrode Pz in the 10-20 system). Note the N400 effect between 275 and 500 ms as delineated by the vertical gray lines. The topography of the difference wave shows the typical broad scalp distribution of the N400 effect centered over parietal electrodes between 350-450 ms. $t=0$ corresponds to the onset of the target words.

Figure 2. Gamma power effect

TFRs showing significantly greater gamma power increases for the Unrelated than Related condition averaged over the six right parietal electrodes (78, 79, 84, 85, 86, 91) where the effect is maximal. The unthresholded difference between conditions is plotted as well as the topography of that difference. Those channels used for the TFRs are marked with small black stars on the topographical map. The statistically thresholded difference (masked) and corresponding masked topography (i.e., only differences with $p < 0.05$ appear in colors other than green) are also plotted. The topography map also shows a significant difference at a single left frontal channel (32). Plots are shown as relative change compared to baseline. $t=0$ corresponds to the onset of the target words.

Figure 3. Late gamma power effect

TFRs showing reverse gamma-band effect averaged over 4 posterior electrodes (62, 72, 74, 75) where the effect is maximal. The displays follow the organization explained in Figure 2.

Figure 4. Late alpha power effect

TFRs showing the lower-band activity averaged over the 8 left frontal electrodes (32, 38, 39, 43, 44, 49, 127, 128) where an alpha effect is maximal. The displays follow the organization explained in Figure 2.

A. Coherence TFRs, Seed Channel 34

B. Summary of Early Theta Coherence

C. Summary of Late Theta Coherence

Figure 5. Theta coherence effects

A) Example of coherence at a single seed channel, Channel 34. TFRs showing theta-band coherence over three posterior electrodes (73, 81, 88) from seed channel 34 (red star in topographs). TFRs show a coherence increase for the Unrelated condition but not the Related condition. The displays follow the organization explained in Figure 2. B) Summary of coherence in the early time window. Topographies showing significantly greater coherence increases for Unrelated than Related between 150-425 ms for three adjacent left frontal seed channels. The red star indicates the placement of the seed channel for each topography plot. The unique time window chosen for each topography plot reflects the extent of the significant effect for that seed channel. Plots display the statistically thresholded difference and are shown as a relative change compared to baseline. C) Summary of coherence in the later time window. Topographies showing significantly greater coherence increases for Unrelated than Related between 600-900 ms for four adjacent left frontal seed channels. The displays follow the organization explained in part B.