Neural Interactions at the Core of Phonological and Semantic Priming of Written Words

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Word processing is often probed with experiments where a target word is primed by preceding semantically or phonologically related words. Behaviorally, priming results in faster reaction times, interpreted as increased efficiency of cognitive processing. At the neural level, priming reduces the level of neural activation, but the actual neural mechanisms that could account for the increased efficiency have remained unclear. We examined whether enhanced information transfer among functionally relevant brain areas could provide such a mechanism. Neural activity was tracked with magnetoencephalography while subjects read lists of semantically or phonologically related words. Increased priming resulted in reduced cortical activation. In contrast, coherence between brain regions was simultaneously enhanced. Furthermore, while the reduced level of activation was detected in the same area and time window (superior temporal cortex [STC] at 250–650 ms) for both phonological and semantic priming, the spatiospectral connectivity patterns appeared distinct for the 2 processes. Causal interactions further indicated a driving role for the left STC in phonological processing. Our results highlight coherence as a neural mechanism of priming and dissociate semantic and phonological processing via their distinct connectivity profiles.

Keywords: connectivity, Granger causality, language, magnetoencephalography, reading

Introduction

In neuroimaging, numerous studies have addressed the neural correlates of phonological and semantic processing in reading (reviewed, e.g., in Jobard et al. 2003; Salmelin and Kujala 2006). Electroencephalography (EEG) and magnetoencephalography (MEG) find a sustained evoked activation of the middle superior temporal cortex (STC) at 200–800 ms after the word onset, whose strength is decreased when the word is preceded (primed) by a semantically or phonologically related context set by isolated words or sentences (e.g., Nobre and McCarthy 1994; Simos et al. 1997; Helenius et al. 1998). Functional magnetic resonance imaging (fMRI) findings have suggested involvement of distinct spatial structures in phonological and semantic processing (Jobard et al. 2003), but they too have shown decreased blood oxygen level–dependent (BOLD) signal for primed words in frontal, parietal, and temporal cortices (Rossell et al. 2003; Kircher et al. 2009). Behaviorally, phonological and semantic priming result in faster reaction times, for example, in lexicality decisions, interpreted as increased efficiency of cognitive processing (Rossell et al. 2003). In the behavioral context, a partial activation of the target representation by the prime has been thought to reduce the processing demands for the target (Posner and Snyder 1975a, 1975b; Brunel et al. 2009). The diminished neuroimaging signals for the target may thus be viewed as the neural reflection of such a reduced need for stimulus analysis. However, the actual neural mechanisms that could serve to reduce the processing demands in local neuronal assemblies and support an increased efficiency of cognitive processing by priming have remained unclear.

Based on transcranial magnetic stimulation findings, it has been proposed that the more efficient processing via preactivation could result from temporal alignment of neural activity in local neuronal assemblies and synchronization of activity in neuronal networks (Mottaghy et al. 2006). Indeed, one could hypothesize that in priming the reduced local processing demands would result from more efficient information transfer within neuronal networks. In this framework, the diminished activation levels, observed as reductions of both MEG/EEG evoked responses and BOLD fMRI signal, would be an epiphenomenon that follows this enhancement. In particular, this type of mechanism could be envisioned for complex cognitive processes, such as reading, that are thought to be mapped at the level of multifocal neural systems rather than specific anatomical sites (Mesulam 1990). Furthermore, the communication within such distributed systems could be achieved via coherent oscillations, which have been proposed to enable effective transmission between neuronal groups by simultaneously opening their communication windows for both input and output (Fries 2005).

In the present study, we hypothesized that priming would lead to increased interareal synchronization, while neural activation levels, as measured with evoked responses, show the usual reduction from one word (prime) to the next (target). We applied data-driven interaction analysis on an MEG data set where visually presented lists of 4 words were related either semantically or phonologically. Previously conducted analysis of the evoked responses revealed that priming affected cortical activation strength significantly in the bilateral middle STC, both for the semantic and the phonological conditions (Vartiainen et al. 2009). Similar findings, that is, STC involvement in both semantic and phonological processing have been reported in numerous MEG studies (Simos et al. 1997; Helenius et al. 1998; Marinkovic et al. 2003; Uusvuori et al. 2008). Here, we chose the left STC, which could be identified in all subjects, as a reference region for the connectivity analysis to determine whether the corticocortical interactions between the left STC and other brain areas would be modulated by semantic or phonological priming and to quantify their spatiospectral configurations. Furthermore, we employed Granger causality (Granger 1980) to estimate whether STC might have a salient role as a receiving or driving node in either one of the priming conditions. Our study thus addressed the role of coherence as a neural mechanism to increase computational efficiency, the spatiospectral relationship of the cortical networks supporting the task facilitation in phonological and semantic priming, and the role of the left STC in phonological and semantic processing.

Materials and Methods

Subjects and Paradigm

The following is a concise description of the experimental design and recording of the data, for details, see Vartiainen et al. (2009).

Subjects

Eleven right-handed Finnish-speaking subjects (mean age 25 years) with normal or corrected to normal vision participated in the experiment. Informed consent was obtained from all subjects, in agreement with the prior approval of the Helsinki and Uusimaa Ethics Committee.

Stimuli and Experimental Design

The stimuli consisted of lists of 4 words presented visually at 1-s intervals and with a 2.1-s interval between lists. The first 3 words in each list were related either semantically or phonologically (shared initial letters/phonemes). The last word of a list was either congruent or incongruent with the expectation set by the preceding words. Figure 1a illustrates the experimental design. The subjects were instructed to press a button when they detected a word list in which one word appeared twice (6% of the trials, not included in the analysis). The stimuli were bisyllabic 4- to 5-letter common Finnish nouns beginning with a consonant, selected from a Finnish newspaper corpus (WordMill Lexical Search Program; Laine and Virtanen 1999). Each word was shown for 300 ms on a back-projection screen placed at a distance of 1 m from the subject's eyes (visual angle < 4°). The word lists were presented in a pseudorandomized order so that neither phonological nor semantic lists appeared more than 3 times in a row.

MEG Recording

The data were recorded in a magnetically shielded room using a 306-channel neuromagnetometer (Elekta Neuromag Oy, Helsinki, Finland). The system is composed of 102 sensor elements, each containing 2 orthogonal planar gradiometers and 1 magnetometer. The signals were band-pass filtered at 0.03–200 Hz and digitized at 600 Hz. Horizontal and vertical eye movements were monitored with electrooculography (EOG). Trials in which either the horizontal or vertical EOG amplitudes exceeded 150 μV were rejected. The number of accepted trials was

113–168 (across subjects) for the second and third words (congruent and incongruent trials merged for each priming type) and 47–82 for the congruent fourth word.

Data Analysis

Preprocessing

The data were preprocessed using the Signal Space Separation (SSS) method (Taulu et al. 2004; Taulu and Simola 2006). SSS divides the measured MEG data into components originating inside the sensor array versus outside or very close to it, using the properties of electromagnetic fields and harmonic function expansions. The temporal extension of SSS (tSSS) further enables suppressing components that are highly correlated between the inner and close-by space, such as mouth movement artifacts. In this study, the harmonic expansion orders of the inside and outside components were 8 and 3, respectively. The tSSS inner and close-by components were calculated in 16-s time windows, and components with waveform correlation exceeding 0.9 were removed. SSS was also used to transform the individual MEG sensor data into an equivalent head position, thus enabling group-level analysis of the sensor-level data.

Selection of a Cortical Reference Area

The analysis of the evoked responses by means of multidipole modeling (Hämäläinen et al. 1993) revealed, consistently, 6 active brain areas in the occipital cortex and bilateral occipitotemporal and STCs (Vartiainen et al. 2009). Only 2 of these, the transient occipital activation at around 100 ms and the sustained bilateral superior temporal activation at around 400 ms showed stimulus effects (Vartiainen et al. 2009). The early occipital stimulus effect likely reflected listwise adaptation of low-level visual activation. The cognitively interesting effects were concentrated to the STC, particularly in the left hemisphere: The peak amplitude of the sustained response was significantly reduced from the second to the third word, both for the phonologically and semantically related word lists (analysis of variance, $P < 0.05$) (Fig. 1b). Furthermore, the response was significantly stronger to the incongruent than congruent list-final word, for both types of priming (semantic list, $P < 0.05$, ascending and descending slope of the sustained response; phonological list, $P < 0.05$, ascending slope). The left STC was readily identified in all subjects (unlike the right STC). As the involvement of the left STC in semantic and phonological processing has also been reported in numerous other studies (Simos et al. 1997; Helenius et al. 1998; Marinkovic et al. 2003; Uusvuori et al. 2008), the individually identified left STC source area was chosen as the reference region for investigating corticocortical interactions.

Identification of Time–Frequency Windows

We hypothesized that the observed reductions of the evoked-response levels in the STC following priming would be accompanied by simultaneous increases in information transfer within corticocortical networks. The analysis was focused on the second and third words of the lists: The list-initial word was preceded by a longer interval than the other words in the trial, which may influence the neural response. The list-final word had a markedly lower signal-to-noise ratio (SNR) (division into congruent and incongruent trials, thus half the number of trials as compared with the second and third words).

Sensor-level analysis was used as a computationally tractable means (204 gradiometer signals instead of cortical time courses at about 2000 grid points) of determining candidate time-frequency windows for the eventual testing of significant priming effects at the cortical level. As field spread effects can lead to spurious coherence detection (Schoffelen and Gross 2009), the sensors most prone to these effects were excluded from the analysis (sensors within 9 cm of the reference sensor, 10 sensor pairs closest to the eyes as they are the most likely to pick up any remaining eye-movement artifacts). Time-dependent coherence was calculated for all gradiometers, using Morlet wavelets (Tallon-Baudry et al. 1997) of width 7. The analysis was conducted in the time range of significant priming-related activation effects (from 250 to 650 ms following stimulus presentation, at 17 ms steps; Vartiainen et al. 2009) and in a frequency range from 5 to 25 and from 60 to 90 Hz (at 1 Hz steps). This range covers the frequency
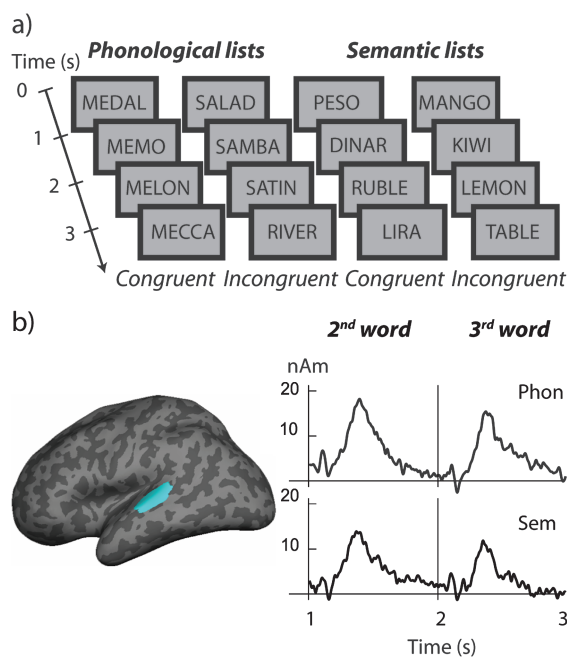
Figure 1. Experimental design and main findings from the evoked-response analysis. (a) Examples of the 4 list types used in the experiment. (b) The mean location of the left STC source area across 11 subjects and the time course of neural activity during the list second and third words. The brain is tilted 10° from the horizontal plane.

bands—theta, alpha, beta, and (high) gamma bands—that have most reproducibly shown either modulation of oscillatory activity (Kaiser et al. 2004, 2007; Klimesch et al. 2005; Schnitzler and Gross 2005; Hoogenboom et al. 2006; Medendorp et al. 2006; Osipova et al. 2006; Jensen et al. 2007; Nieuwenhuis et al. 2008; Hanslmayr et al. 2009; Jerbi et al. 2009; Sauseng et al. 2009; Van Der Werf et al. 2010) or corticocortical connectivity (Kujala et al. 2007; Freunberger et al. 2008; Ghuman et al. 2008; Gregoriou et al. 2009; Händel and Haarmeier 2009; Anderson et al. 2010; Palva, Monto, and Palva 2010; Hipp et al. 2011) in visual and cognitive tasks; furthermore, this range avoids frequencies in which the SNR is too low to allow reliable analysis of corticocortical connectivity (very high-frequency activity) or which can easily be contaminated by artifacts (low-frequency activity and frequencies close to that of the line noise). The reference sensor was the gradiometer closest to the individually identified STC source area that (of the 2 orthogonal sensors at one location) showed the largest stimulus effects. After alignment of the sensor data to an equivalent head position, this was the same sensor in all subjects. Since power-level differences between 2 conditions can yield spurious connectivity in MEG interaction analysis (Schoffelen and Gross 2009), we tested whether the MEG sensors showed significant power-level differences (paired t-test, $P < 0.01$). When significant power differences occurred in at least 3 neighboring time-frequency bins in a sensor, that sensor was excluded from further analysis.

Time-frequency windows in which priming elicited significantly higher coherence between the reference sensor and the other sensors for the third than second word were identified using a cluster-based random permutation test (Nichols and Holmes 2002; Laaksonen et al. 2008), separately for the phonological and semantic conditions. First, the original statistics was obtained by calculating the group-level t-statistics (paired t-test) between the second and third word for each sensor and each time-frequency bin. The mean t-values of time-frequency clusters (more than 8 adjacent bins with $P < 0.01$) were stored for each sensor. Next, the individual coherence values for the second and third words were permuted in all possible combinations: for 11 subjects, this results in 2048 possible permutations. For each permutation, a new t-statistics (paired t-test) was calculated, and the highest mean t-value among the time-frequency clusters (consisting of more than 8 contiguous bins with $P < 0.01$) was stored for each sensor separately, resulting in 2048 maximum statistics values per sensor; the different spatial leakage properties of different sensor combinations prevent considering all sensors within a single permutation test. Subsequently, the original cluster t-values were compared with the distributions of the 2048 maximum t-values to obtain the corrected P values for each cluster (in the maximum statistics sense, accounting for the number of time-frequency bins). Bonferroni correction was further applied to these P values to account for the number of MEG sensors. Time-frequency clusters with $P < 0.05$ (maximum statistics and Bonferroni correction) were considered to represent a significant modulation of coupling. A similar analysis was conducted to test the opposite hypothesis that the reduction of activity in the STC would be associated with reduced information flow, indexed by a decrease in coherence from the list second to third word.

Imaging of Corticocortical Coherence

Sensor-level interaction estimates are more prone to produce spurious interaction results than source-level estimates (Schoffelen and Gross 2009), and the sensor-level results leave the cortical origins of the effects ambiguous. Therefore, coherence was subsequently mapped at the cortical level. Corticocortical coherence between the left STC and all other brain regions was estimated in the sensor-based candidate time-frequency windows using event-related Dynamic Imaging of Coherent Sources (erDICS, Laaksonen et al. 2008). erDICS is a beamforming technique (Robinson and Vrba 1997; Gross et al. 2001) for the spatial mapping of oscillatory power and coherence as a function of time, with respect to stimulus or task timing. erDICS uses a linear transformation, obtained by minimizing a constrained optimization problem, to transform the sensor-level data into a cortical representation. The sensor-level data are represented with a time-dependent cross-spectral density (CSD) matrix, which is obtained by calculating, for all sensor combinations, a product of the time-frequency representations

of the trial time series. The resulting single-trial CSDs are averaged into a mean CSD. The time-frequency representations are obtained by using Morlet wavelets (Tallon-Baudry et al. 1997). In this study, the CSDs were calculated using Morlet wavelets of width 7 in the candidate time-frequency windows determined at the sensor level. The cortical estimates of coherence were calculated between the individually determined active area in the left STC and approximately 2000 grid points covering the surface of the entire brain. The grid was constructed by creating a regular grid at 6-mm intervals in an atlas brain, limited within 1 cm from the surface of the brain, and then transforming the grid to the individual brains using an elastic transformation (Schormann and Zilles 1998). Thus, every grid point and connection was spatially equivalent across subjects, allowing robust group-level analysis.

Group-Level Analysis of Corticocortical Coherence

Brain areas agreeing with the primary hypothesis were identified at the group level based on a significantly higher coherence between the left STC and the rest of the cortex for the third than second word. Permutation tests (Nichols and Holmes 2002) were performed separately for the phonological and semantic word lists using the spatially equivalent coherence maps across subjects. The analysis included a total of 1759 connections that were evaluated for each time-frequency window. The grid points within 3.5 cm of the average STC reference region were excluded from the analysis, as were the most anterior frontal cortical areas that are prone to artifacts from eye movements and have relatively poor sensor coverage (and thus spatial resolution). In the permutation testing, the original t-statistics (paired t-test) were first calculated for each connection. Subsequently, the individual coherence values for the second and third words were permuted in all possible combinations: for 11 subjects, this results in 2048 possible permutations. At each permutation, a t-statistics (paired t-test) was calculated for each connection, and the maximum t-value across connections was stored, resulting in a distribution of 2048 t-values across permutations. The original t-values were then compared with this distribution, and t-values exceeding the 95% threshold were considered to represent a significant modulation of coupling. Furthermore, possible power modulations between the list second and third words in the areas showing modulation of coherence were tested using a paired two-sided signed rank test.

Quantification of Interactions for Identified Connections

The connections surviving the group-level permutation testing were further quantified by determining whether an increased interaction between the left STC and another brain area reflected reciprocal interactions or influence exerted primarily by the STC on other areas or vice versa. We estimated partial Granger causality (Granger 1980; Geweke 1982; Guo et al. 2008) for the connections that showed significant modulation of coherence following priming, using a Matlab Toolbox developed by Seth (2010). Partial Granger causality extends the standard Granger causality in a manner analogous to partial correlation, and it manifests superior performance to standard Granger causality in case of confounding external inputs or latent (unrecorded) variables (Guo et al. 2008). The present study called for application of Partial Granger causality (as opposed to standard Granger causality) as it was unlikely that our specific focus on the modulations of the time-frequency coherence would lead to the identification of all cortical areas that are involved in semantic and phonological processing. The time series for the reference region and the other connected nodes were estimated by beamforming the sensor-level time series (of the third word in the list) to the cortex. The linear transformation used in the beamforming was solved separately for each source area and separately for each time-frequency window of interest. This procedure consisted of 2 steps. First, the orientations of the sources in each location were estimated using a CSD averaged in a 4-Hz wide and 200-ms long window centered at the middle of each time-frequency window of interest. Second, the leadfields of these source configurations (position and orientation) were used together with broadband CSDs (0–700 ms and 5–90 Hz) to evaluate weights for each MEG sensor for the construction of cortical-level time series.

Subsequently, the time series were detrended, and the mean response across trials was removed. Partial Granger causality was

then calculated from –50- to 750-ms poststimulus at 10-ms steps in 100-sample windows (ca. 330 ms). In the causality estimation, the model order was determined separately in each window using a Bayesian information criterion (Seth 2005). The mean model orders varied from 14 to 23 across subjects and from 17 to 21 across corticocortical connections. In addition to the directed influences, difference of influence was obtained by subtracting the causal influence estimates directed to the reference region from those directed away from the reference region. For the directed components, 95% confidence limits were estimated using bootstrapping for each subject in each time window to determine whether the influences were significant. In the bootstrapping procedure, a number of time windows matching the original number of trials were randomly drawn (with replacement) from among the time window pool across trials, and directed influences were then calculated for the resampled data. The procedure was repeated 1000 times resulting in a distribution of directed component values from which the 95% confidence limits could be calculated. Group-level significance was determined by testing whether the lower level of the confidence limit exceeded zero systematically across subjects (binomial test, $P = 0.033$, 9/11 subjects). For a connection in which a directed component was significant, the difference between the influence terms was further tested for significance at the group level using a one-sample t-test (against zero, $P < 0.01$, at least 5 contiguous time bins).

Results

Modulation of Coherence Due to Priming

At the sensor level, phonological priming was associated with significantly increased coherence from the list second to third word in a single time–frequency window, centered at 533 ms and 66 Hz. Semantic priming also showed coherence increase, evident in a single window centered at 333 ms and 8 Hz. No significant decreases of coherence were observed in either phonological or semantic priming.

Corticocortical interactions were evaluated in the 2 sensor-based candidate time–frequency windows and with the individually identified left STC as the reference region (Brodmann area [BA] 22; mean Talairach coordinates –61, –26, 3). The group-level analysis revealed distinct cortical areas for phonological and semantic priming (Fig. 2). In phonological priming, coherence with the left STC increased from the second to the third

a
Phonological priming

533 ms, 66 Hz

b
Semantic priming

333 ms, 8 Hz
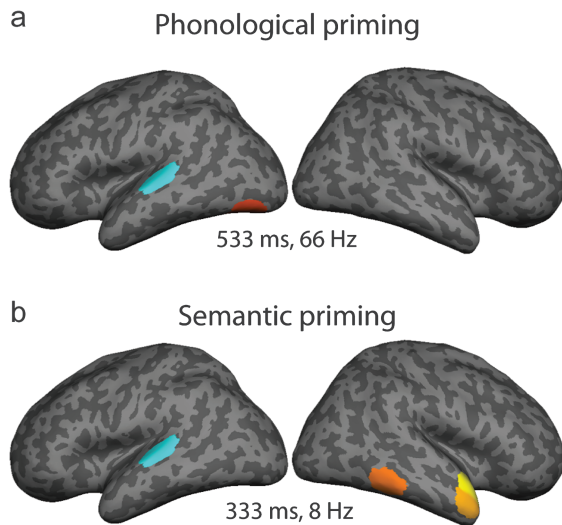
Figure 2. Brain areas showing significantly increased coherence with stronger (*a*) phonological and (*b*) semantic priming. The reference area in left STC is plotted in blue. The brains are tilted 10° from the horizontal plane (to display inferior areas).

word in the left occipitotemporal cortex (OTC; BA 19; Talairach coordinates –34, –79, –10). Semantic priming was accompanied by enhanced coherence between the left STC and the right frontotemporal cortex (BA 38; 48, 10, –19) and the right inferior temporal cortex (BA 20; 60, –50, –14). None of the identified areas showed significant modulation of oscillatory power between the list second and third words.

The areas identified based on their coherence modulation with the left STC did not correspond particularly well to the source locations that had been identified based on the level of activation (Vartiainen et al. 2009). As an important exception, the left OTC node in the phonological condition agreed well with the area identified as active (distance 0.6 cm). In the semantic condition, the minimum distance between areas showing modulation of coherence and identified as active was 3.9 cm.

Direction of Modulation

The Granger causality analysis between these coherent nodes revealed a significant directed influence (binomial test, $P < 0.033$) from the left STC to the left OTC (Fig. 3*a*). This connection also showed a clear dominant direction of influence from STC to OTC in the time window from 150 to 390 ms ($P < 0.01$, one-sample t-test, Fig. 3*b*). In the semantic network, no significant directional influences were observed.

Discussion

Both phonological and semantic priming resulted in systematic increase of corticocortical interactions, a pattern opposite to

a
Significant influence

Phon

b
Dominant direction of influence

Phon
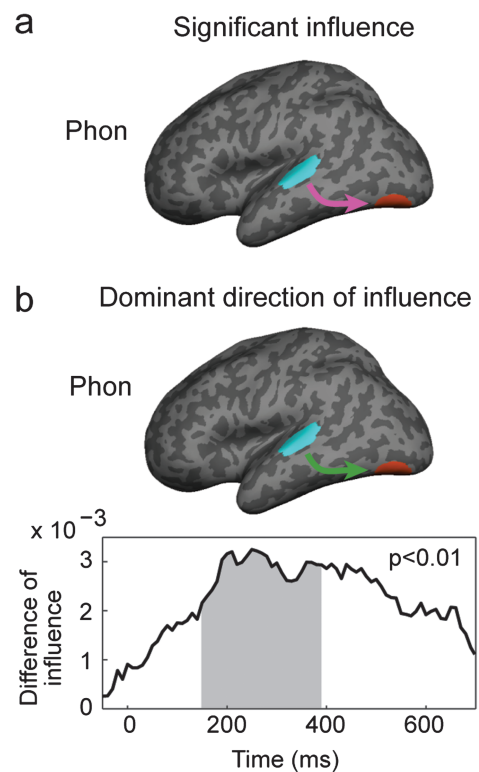
Figure 3. Characterization of interactions for the identified areas. (*a*) Connections which showed significant directional influences for the third words in the lists. (*b*) Connections showing significant differences in their directed influences and the time course of the difference term. The brains are tilted 10° from the horizontal plane (to display inferior areas).

the observed reductions in neural activation, that is, evoked-response amplitudes; these findings suggest that coherence may be the neural mechanism that directly facilitates the typically reported increased task efficiency with priming. Furthermore, although phonological and semantic priming both influenced the activation level in the left STC, the identified interacting phonological and semantic network nodes were separate, and the interactions were modulated in different time–frequency windows. Analysis of causal interactions further demonstrated that the STC had a driving role in the phonological task. Together, our results suggest that modulation of neural interactions may lie at the core of semantic and phonological priming of written words.

Coherence as a Neural Mechanism to Facilitate Task Performance

In the present study, we hypothesized that the reduced neural activity levels commonly observed in experiments related to priming would reflect reduced computational demands at the level of local neuronal assemblies, as relevant information would be processed and transmitted more efficiently at the network level. Previously, such effects have been observed in object repetition (Ghuman et al. 2008). Alternatively, one could hypothesize that the reduction in activity levels might result from less effective information transfer that reduces the recruitment of the local assembly. Assuming that increased corticocortical coherence directly measures higher effectiveness of information transfer, our results yielded evidence supporting the first hypothesis. Although priming in a word list reduced the activation levels (Vartiainen et al. 2009), we found that coherence was significantly increased between the left STC and 3 other network nodes. Significant coherence decreases, on the other hand, were not observed. Comparable behavioral priming experiments have commonly shown improved task performance, indexed by faster reaction times (Rossell et al. 2003; Kircher et al. 2009). The present results suggest that coherence may be a relevant neural mechanism that facilitates efficient behavior related to priming. The reduced neural activation would, in turn, reflect reduced local computational demands, resulting from the more efficient interareal neural communication. In priming, activity within the relevant cortical network may become more synchronized as compared with an unprimed state, and the subsequent processing of the test stimulus (if it matches the prediction) becomes more efficient. In the present study, as behavioral data were not collected, for example, in the form of reaction times, the exact relationship between the observed coherence changes and efficiency of behavior could not be determined. Future studies will need to address directly, using a parametric design, the relationship between behavioral benefits and changes in corticocortical connectivity and activation levels.

Notably, the separate phonological and semantic connectivity patterns of the left STC and its role as a driving node in phonological priming—with no clear role as either a driving or receiving node in semantic priming—agree with the view that a flexible pattern of coherence may enable an area to show distinct connectivity during different tasks despite the constancy of its anatomical wiring (Fries 2005).

In phonological priming, the significant coherence increase occurred in the gamma band, which has been proposed to form a fundamental computational mechanism in the brain (Fries et al. 2007). Modulation of gamma-band activity is frequently reported in intracranial recordings (Fries et al. 2001; Lachaux et al. 2005). In MEG, gamma-band activity has typically not been detected beyond the sensory and motor cortices (Hoogenboom et al. 2006; Cheyne et al. 2008; Tecchio et al. 2008), probably due to the low SNR of the high-frequency oscillations (Dalal et al. 2009). Recently, corticocortical interactions in the gamma band have been reported both in intracranial recordings (Gregoriou et al. 2009) and in MEG (Siegel et al. 2008; Hagiwara et al. 2010; Palva, Monto, Kulashekhar, et al. 2010). Our results suggest, in accordance with intracranial findings (Jerbi et al. 2009; Jung et al. 2010), that gamma-band activity has functional significance in reading also beyond sensory regions. Furthermore, they suggest that in noninvasive recordings gamma-band activity may be detectable by means of interaction measures which can effectively increase the SNR of the data. Increased sensitivity to weak oscillatory activity via interaction analysis has been observed earlier in both motor and reading tasks (Gross et al. 2002; Kujala et al. 2007, 2008).

In semantic priming, the significant effects were limited to a lower frequency range (centered at 8 Hz). In an earlier study of continuous reading, long-range corticocortical coherence was observed in the 8–13 Hz range, with the most prominent phase coupling centered at around 9 Hz (Kujala et al. 2007). The agreement between these findings suggests that the observed interactions during continuous reading may have reflected more semantic than phonological processing, a conclusion that makes also intuitive sense. Furthermore, the findings indicate that aspects of reading that are specifically related to meaning may utilize lower frequency interactions than aspects related to phonological content.

Cortical Connectivity and Concepts of Reading

The neural underpinnings of reading have typically been investigated using activation measures. Hemodynamic studies have often implicated separate cortical structures in phonological and semantic processing, whereas EEG/MEG have shown spatiotemporal convergence for these processes. Our interaction analysis, while centered at the left STC, revealed separate networks, which facilitated the phonological and semantic processing. Furthermore, the time- and frequency-domain differentiation of the increased interaction (semantic vs. phonological effects at ~330 vs. ~530 ms and at ~8 vs. ~65 Hz, respectively) indicates that the information processed in the left STC may be markedly different in the 2 tasks. Based on activation studies on reading, the earliest phonological priming effects occur at 250 ms (Grainger et al. 2006), and behavioral data suggest that written words can be recognized within ~500 ms (for a review, see Tyler et al. 2002). Accordingly, the late phonological interaction effect after 500 ms is likely to reflect postlexical integration of all available information in the context created by the preceding words, not more efficient phonological processing during word recognition as such.

The analysis of causal influences further suggested different roles for the left STC in phonological and semantic processing. Most prominently, in the phonological condition, directed influence was detected from the left STC to the left OTC. By contrast, in the semantic network, no significant directed influences were detected. These findings suggest that, in reading, the left STC may have a more top–down modulatory role in phonological than semantic processing.

The left STC-OTC connection is a highly interesting one. This pathway seems to be emphasized in phonological processing of written words (Richlan et al. 2009; Graves et al. 2010). MEG studies have indicated that activation of the left OTC (~150-ms poststimulus) reflects prelexical processing (Tarkiainen et al. 1999) and that neither phonological nor semantic content influences its activity (Cornelissen et al. 2003; Wydell et al. 2003). fMRI investigations, however, have suggested that this general area (the so-called visual word form area; Cohen et al. 2000) is sensitive to phonological content (Cohen et al. 2002). In the present study, directed influence was detected at ~150–390 ms specifically from the left STC to the left OTC during the third words of the phonological lists. This effect thus follows the OTC letter-string activation at ~150 ms, overlaps with the ascending slope of the STC response (lexical-semantic processing; Vartiainen et al. 2009), and precedes the observed increased coherence between STC and OTC at ~530 ms. The late coherence effects and the marked top–down influence on the left OTC activity could account for some of the apparent discrepancies between the imaging methods. Bottom-up effects are likely to be emphasized in the transient phase-locked MEG/EEG responses at ~150 ms in the OTC, whereas a top–down phonological influence on OTC activation might be more readily picked up by fMRI, which integrates neural activity over longer time intervals.

Perhaps against expectation, neither priming condition increased interaction between the left STC and the left frontal cortex. fMRI studies have linked both phonological and semantic processing with various frontal structures (Vigneau et al. 2006), and the left STC and inferior frontal cortex are anatomically connected (Petrides and Pandya 2009). The noneffect could mean, for example, that the STC-frontal coupling remains unchanged throughout the word lists or that the frontal node is spatially too variable across individuals to appear in the STC-centered connectivity maps. It should also be noted that the experimental paradigm used here involved implicit phonological and semantic processing and, thus, may not recruit areas involved in selection or manipulation of lexical and nonlexical information, the type of tasks often used in fMRI studies.

Our data-driven analysis revealed no spatial overlap between the phonological and semantic networks (apart from the common STC reference). However, the approach did not directly assess differences between phonological and semantic processing; for example, it may be that coherence modulations occurred in both conditions in the same regions but that they reached significance only in one of the conditions. Furthermore, the relatively strict statistical testing applied in the identification of the time–frequency windows may have led to a sparse view of both the temporospectral connectivity pattern and the cortical areas involved in priming. It is also important to note that as our analysis was based on a single cortical reference region, it would not necessarily reveal nodal areas that are not directly connected with the STC (and might show more overlap between the semantic and phonological conditions). The left STC was selected as the reference region as it was the only cortical region in which the evoked responses showed significant task-relevant effects. However, as coherence may also be modulated without significant changes in activity levels (Gross et al. 2002; Kujala et al. 2007), it is possible that some other reference region could have been even better

suited for identifying priming-related corticocortical networks. However, testing multiple reference regions would be problematic, as the examination of the entire time–frequency space in a maximum statistics framework is computationally extremely demanding.

Conclusions

Our results show that priming was accompanied by increasing corticocortical coherence; the level of neural activation was simultaneously decreased. These findings support the idea that corticocortical coherence is a direct facilitatory neural mechanism that enhances the efficiency of processing relevant information. While the usual activation analysis indicates strong overlap of cortical areas involved in phonological and semantic processing, facilitation via phonological versus semantic priming seems to be supported by distinct cortical networks. Moreover, the temporal and spectral differences in the phonological and semantic priming, as well as the driving role of the left STC during phonological processing, suggest that the left STC, while involved in both semantic and phonological analysis, has a fundamentally different role in the 2 tasks.

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Notes

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