Frontal Synchronization Facilitates Taxonomic Priming: Insights from N400 Source Estimation and Functional Connectivity

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Abstract

This study explored the cortical sources and functional connections underlying the N400 in relation to taxonomic priming. High-density EEG was recorded in 60 neurotypical individuals during an auditory categorical priming task. eLORETA source estimation was performed. Functional connectivity specific to the processing of primed and unprimed words was calculated between 68x68 ROI pairs. Significant N400 activation clusters were identified in an early time window (460-510ms) in the left frontal cortex (orbitofrontal, pars opercularis, pars triangularis, precentral), and in a middle time window (520-570ms) in the left posterior cingulate cortex. Significant connections for the processing of primed versus unprimed words were identified within the left frontal lobe, between left and right frontal cortices, and between left frontal and parieto-occipital cortices. Functional synchronization between frontal areas facilitates the top-down retrieval of lexical-semantic representations for primed words. This enhanced connectivity likely drives local frontal activation reductions for primed compared to unprimed word processing.

Keywords: N400, taxonomic priming, source reconstruction, functional connectivity

1. Introduction

Semantic knowledge is essential for giving meaning to language and achieving conversational language comprehension (Kutas & Federmeier, 2000; McRae & Jones, 2013). As outlined by the controlled semantic cognition (CSC) framework (Jefferies et al., 2013; Lambon Ralph et al., 2017), this conceptual knowledge, enquired through multimodal verbal and nonverbal experiences, is encoded and stored in *semantic memory representations*. Retrieval and selection of semantic knowledge are driven by top-down *semantic control*, which refers to "the ability to selectively access and manipulate meaningful information of the basis of context demands" (Jackson, 2021). According to the CSC framework, semantic knowledge is represented in modality-specific regions, and integrated in the (ventrolateral) anterior temporal lobe (ATL). This region serves as an amodal integration hub (cfr. hub-and-spoke model; for a review, see Patterson & Lambon-Ralph, 2016). Semantic control, in turn, is regulated by a distributed network including the (predominantly left) posterior middle temporal gyrus (pMTG), inferior frontal gyrus (IFG) and potentially inferior parietal cortex (IPC) (for reviews, see Diveica et al., 2021; Jackson et al., 2021). The degree of engagement of the semantic control network in the retrieval of a given semantic representation, depends upon task and context demands.

The integrity of semantic representations and the ability to retrieve and select semantic knowledge from the semantic system is generally assessed through *semantic priming*. This concept refers to the facilitated processing of a target word when this item is preceded by a semantically related prime word (McNamara, 2005). The facilitated retrieval of semantically primed items behaviourally manifests in shorter reaction times and increased accuracy for their identification compared to unprimed targets (Chen et al., 2014; Neely, 1991; Rossell et al., 2003). Semantic priming is achieved through either a semantic association or an overlap in semantic features between the prime and target word (McNamara, 2005). Accordingly, semantic knowledge is thought to be represented in two distinct systems in the long-term

memory, that is thematic and taxonomic relations (for a review, see Mirman et al., 2017). Thematic or associative relations are constructed based on the co-occurrence of semantic concepts in situations or events, e.g., beach - sun (Estes et al., 2011). Alternatively, taxonomic relations are based on shared features (e.g., colour, shape…), grouping items into categories (e.g., dog – cat). Although taxonomic relations develop later in childhood compared to thematic relations (Chou et al., 2019), evidence suggests that taxonomic thinking becomes "dominant" in adulthood (Berger & Donnadieu, 2006; Smiley & Brown, 1979). Judgement of taxonomic relations is overall considered to require greater cognitive effort, since these are not tied to any specific situational context and are therefore more abstract in nature (Kotz et al., 2002; Sachs et al., 2008). This enhanced cognitive demand is reflected in increased reaction times compared to thematic relations (Kalénine & Buxbaum, 2016; Maguire et al., 2010; Sachs et al., 2008).

1.1. The N400 in semantic priming

The N400 event-related potential (ERP) has been extensively studied in relation to lexical-semantic processing and is modulated by semantic priming (Kutas & Federmeier, 2011). This ERP component is characterized by a negative polarity that has its onset at approximately 250-300 ms after the presentation of a target word. The N400 reaches maximal values at around 400 ms post stimulus onset at centroparietal sites. Depending on the stimulus presentation modality, this maximum manifests as either a peak (visual) or a plateau (auditory). While the N400 scalp distribution is typically centroparietal in the visual modality, auditory presentations often elicit a more frontally distributed N400 (Kutas and Van Petten, 1994), with a slightly delayed peak latency, reflecting the additional temporal demands of speech processing (Pawlowski et al., 2019). The dominant account on the N400 states that its amplitude reflects the processing cost to retrieve lexical-semantic representations from long-term semantic memory (Lau, 2008). N400 amplitude in response to unprimed items is larger (i.e., more negative) compared to primed items (Cocquyt et al., 2022; Chen et al., 2014; Khateb et al., 2010), indicating a higher

retrieval cost for the former. This amplitude modulation is referred to as the N400 priming effect. Other accounts have hypothesized that the N400 might rather reflect the post-lexical integration of a processed item within a semantic context (Hagoort et al., 2008). Most likely, an interplay of automatic and controlled processes is reflected in the N400 priming effect (Hill, 2002; Neely, 1991). Steinhauer (2017) hypothesized that three processes contribute to the N400 amplitude reduction for primed targets: automatic spreading activation (ASA), controlled prediction and controlled semantic integration. ASA refers to the automatic prime-induced activation of linked 'word nodes' in long-term semantic memory (e.g., 'dog' pre-activates 'cat'). Prediction pertains to the controlled pre-activation of target words in working memory based on the semantic context outlined by a prime word. Semantic integration, in turn, refers to the controlled integration of the target word in the semantic context outlined by the prime word. Post-lexical integration can only be accomplished once both words have been accessed. The extent to which each of these mechanisms are involved, however, remains unclear and is likely dependent upon various factors (Kutas et al., 2013). The contribution of controlled prediction, for instance, is conditional to the semantic contiguity between prime and target. ASA, in turn, has been shown to be dependent upon the stimulus onset asynchrony (SOA) between the prime and target. In case of a long SOA (> 300 ms), ASA is reduced, while no controlled processes are activated at a SOA of 300 ms or less (Hill et al., 2002; Steinhauer et al., 2017). Recently, the N400 has also been framed within the context of predictive coding. According to this framework, the N400 effect reflects the prediction error between top-down lexical-semantic predictions and the features of the incoming words (Eddine et al., 2024).

1.2. The network for semantic priming

Areas in the frontal and temporal cortex have been demonstrated to govern semantic priming. A considerable amount of proof stems from (mostly event-related) functional magnetic resonance imaging (fMRI). Reviews by Holderbaum et al. (2019) and Lau et al. (2008) point to

two areas in specific to support automatic and controlled priming operations: the left MTG and the left IFG. Consistent activation of the posterior part of the MTG, and by extension adjacent areas in the superior (STG) and inferior (ITG) temporal gyrus, has been documented for unrelated compared to related target processing at both short and long SOAs. Activation of the IFG, especially the pars triangularis (BA 45) and pars orbitalis (BA 47), is specifically observed during semantic priming at a long SOA. Electroencephalography (EEG) and magnetoencephalography (MEG) source reconstruction of the scalp-recorded N400 potential has confirmed the presence of a dominant generator in the temporal lobe, governing lexical-semantic retrieval in a priming set-up (Geukes et al., 2013; Khateb et al., 2010). These reports, however, are less uniform on the precise location of this generator. In accordance with fMRI research, several studies identified an activation component in the left MTG, STG and ITG (Ghosh-Hajra et al., 2018; Khateb et al., 2010; Matsumoto et al., 2014; Silva-Pereyra et al., 2003). Performing electrocorticographic (ECoG) recordings in a group of individuals with epilepsy, Khachatryan et al. (2019) likewise designated the left superior and middle temporal gyri as the main generator region for the N400. Alternatively, combining evidence from MEG source localization and fMRI, Lau et al. (2013, 2016) attributed the N400 to an activation cluster in the ATL at both short and long SOAs. Apart from the temporal generator area, EEG and MEG studies point to additional generators in the left inferior temporal gyrus (Ghosh-Hajra et al., 2018; Matsumoto et al., 2014), the left insula (Khateb et al., 2010), the bilateral middle or superior frontal gyrus (Khateb et al., 2010; Silva-Pereyra et al., 2003), the posterior cingulate cortex (Khateb et al., 2010) and the putamen (Khateb et al., 2010). Combined results of fMRI, EEG and MEG research thus converge to a left dominant temporo-frontal network to underly semantic priming, albeit that the exact locations of these generator areas are still under debate.

The enhanced engagement of frontal and temporal cortices in the retrieval of unprimed compared to primed words has generally been interpreted in light of the hypothesis that the

N400 (at least partially) reflects the facilitated access of primed lexical-semantic items (Lau et al., 2008). The access and retrieval of unprimed targets (i.e., targets preceded by an unrelated prime) requires more engagement of the semantic control system, which resides in posterior middle temporal and inferior frontal cortices (Lambon Ralph et al., 2017). At short SOAs, only automatic processes aid the retrieval of semantic representations, which translates to the activation of the temporal cortex. At long SOAs, frontal cortices additionally mediate the top-down retrieval (anterior IFG) and selection (posterior IFG) of lexical-semantic representations (Lau et al., 2008).

The above-discussed literature purely focused on areas showing increased activation during semantic priming. Some researchers have further explored the functional interaction between frontal and temporal regions, engaged in semantic priming. Based on functional connectivity investigation of source localized EEG and MEG signals, Matsumoto et al. (2014) and Kujala et al. (2012) found evidence for enhanced synchronization between frontal and temporal N400 generators for the processing of related compared to unrelated target words. Matsumoto et al. (2014) identified a bidirectional causal flow between the left IFC and ITC in a sublimal (i.e., masked priming at short SOA) priming task. Adopting a categorical priming paradigm with a long SOA, Kujala et al. (2012) identified enhanced coherence between the left superior temporal, right frontotemporal and right inferior temporal cortex. The authors hypothesized that behavioural priming effects and reduced activation of frontal and temporal areas observed for primed compared to unprimed items, may result from a more efficient information transmission within the neural network in this condition, as manifested in enhanced neural synchronization. Also, some fMRI investigations targeted priming-related functional connectivity. Roelke & Hofmann (2020) demonstrated enhanced functional synchronization between the left inferior frontal cortex on the one hand, and the fusiform gyrus and the anterior cingulate cortex during the processing of word pairs with low compared to high semantic similarity.

The type of semantic relation adopted (taxonomic or thematic) is an aspect that has received minimal attention in the above-discussed semantic priming research. Reviews of fMRI investigations did not specify this relevant detail (Holderbaum et al., 2019; Lau et al., 2008). The majority of the EEG and MEG evidence, in turn, adopted prime-target pairs characterized by a thematic relation (Geukes et al., 2013; Ghosh-Hajra et al., 2018; Lau et al., 2013, 2016; Silva-Pereyra et al., 2003), resulting in an underrepresentation of insights on the processing of taxonomic relationships. This is remarkable, as a considerable amount of evidence suggests that taxonomic versus thematic relations might call upon distinct networks (for reviews, see Mirman, 2017). That is, findings of lager N400 amplitudes (Savic et al., 2019) and enhanced parietal alpha power (Maguire et al., 2010) for taxonomic versus thematic priming, as well as increased power over right frontal electrodes in the theta band for thematic priming (Maguire et al., 2010), point to a functional dissociation between these two systems. According to the dual-hub model (Mirman et al., 2017; Schwartz et al., 2011; Thye et al., 2021), irrespective of stimulus modality, the left ATL is specialized for taxonomic processing, while the left temporo-parietal cortex (TPC) is dominant for thematic processing. This functional dissociation has been hypothesized to arise from either topographic specialization, i.e., taxonomic versus thematic processing relying on different object features (colour and shape vs action and location), or architectural specialization, i.e., taxonomic versus thematic processing activating distinct computational processes (object identification vs event-based prediction) (Mirman et al., 2017). In contrast, a number of reports argue against this dissociation. Zhang et al. (2023) could not substantiate the dual-hub model based on their activation likelihood estimation (ALE) meta-analysis. The authors observed higher activation likelihood for thematic relations in the pMTG and supramarginal gyrus, but no effects for taxonomic relations in the ATL. Current evidence being dominated by fMRI research, some downsides of this technique could account for the results of this meta-analysis. While fMRI offers valuable information on account of its high

spatial precision, the technique comes with a limited temporal resolution, compromising its sensitivity to priming-related changes in neural activity. Secondly, some areas are especially sensitive to fMRI signal artifacts, interfering with the adequate measurement of activity in these regions (Lau et al., 2008). This is particularly the case for the ATL. Evidence stemming from positron emission tomography (PET; Visser et al., 2010) and intracranial recordings (Nobre et al., 1995; for a review see Lau et al., 2008), both insensitive to distortion artifacts, has put forward the ATL as a potential area of interest for semantic priming. Whether the processing of taxonomic relations engages the ATL thus remains a matter of debate to date.

1.3. The present study

Some N400 source estimation investigations have been performed, but results provide an unclear picture and explorations on the interactions of N400 generator areas are scarce. Additionally, the bulk of these studies have focused on the processing of prime-target pairs characterized by a thematic relation. Whether the processing of taxonomic relations calls on a partially distinct network remains unclear. The present study aimed to explore the cortical generators and map the functional cortico-cortical connections underlying the N400 in relation to the processing of taxonomic semantic relations. Source estimation and functional connectivity analysis were conducted on high-density EEG data, recorded during an auditory categorical priming task. N400 component-specific cortical activity was reconstructed using exact low-resolution brain electromagnetic tomography (eLORETA; Pascual-Marqui, 2011). eLORETA is characterized by a relatively low localization error (Jatoi et al., 2014) and minimal false positive results in connectivity calculations (Pascual-Marqui et al., 2018). EEG source reconstruction methods like eLORETA provide valuable insights into neural activity, through their spatial resolution is inherently limited by the inverse problem and the smoothing effects of the scalp and skull – an important factor to consider when interpreting results. According to a recent study by Depuydt et al. (2024), eLORETA achieves an estimated spatial resolution of

approximately 2 cm for ERPs, allowing for the identification of key cortical regions involved in cognitive processes, even if finer neural dynamics remain challenging to resolve. We studied cortical activation patterns in relation to time by considering the reconstructed activity in early, middle and late component-specific time windows. Functional connectivity was explored in source space by calculating the maximal cross-correlation of the source-reconstructed signal between 68 cortical regions for each of the experimental conditions (related versus unrelated target processing).

2. Methods

2.1. Participants

Sixty neurotypical individuals participated in the current study. In order to obtain a balanced group based on age and sex, representative of the population, twenty participants (ten males, ten females) were recruited within each of the following age categories: 20-39 years; 40-59 years; 60+ years. The mean age of the sample was 49.3 years (SD = 16.84), with the youngest and eldest participant being 23 and 80 years of age, respectively. Participants met the following inclusion criteria: (1) Dutch native speaker, (2) right-handed, as indicated by a score ≥ 8/10 on the Dutch Handedness Inventory (DHI; Van Strien, 1992), (3) self-reported normal hearing, (4) negative history of neurological, psychiatric and developmental disorders, (5) absence of any cognitive impairments, as determined by a score ≥ 26/30 on the Montral Cognitive Assessment (MoCA; Dautzenberg & De Jonghen, 2004), and (6) typical language function, as indicated by a score above the cut-off value for each of the subtests of the Dutch Comprehensive Aphasia Test (CAT-NL; Visch-Brink et al., 2014).

All participants gave their written consent prior to participating in this study. Approval for this study was granted by the Ghent University Hospital Ethical Committee (2018/0276).

Demographic details on the participants, grouped by age, as well as information on handedness and outcome on the MoCA, can be consulted in Table 1.

--- Table 1 about here ---

2.2. Experimental procedure

EEG recording – Continuous EEG was recorded at 128 electrode sites, placed using an EasyCap electrode cap (Brain Products GmbH, Germany). AFz served as the ground and FCz acted as the online reference. An abrasive electrolyte gel (Abralyte 2000, EasyCap) was applied to reduce impedances to < 20 kΩ. The EEG data were amplified by a BrainVision BrainAmp amplifier and digitized at a sampling rate of 500 Hz (BrainVision Recorder Software, Brain Products GmbH, Germany).

Stimuli – An auditory categorical priming task, adapted from Hagoort et al. (1996) by Cocquyt et al. (2022), was administered. The task comprised 120 Dutch word pairs, each including a prime and target word. In half of the pairs, the prime and target word were semantically related by being members of the same semantic category (e.g., cat – horse). In the other 60 pairs, the prime and target word were unrelated in meaning (e.g., pink – coffee). To ensure that none of the categorically related word pairs were characterized by a thematic relation, Hagoort et al. (1996) instructed twenty participants to list the first three words that came to mind for each prime words. Prime-target pairs were omitted from the experiment if the target word was listed by one or more of these subjects. To control for the effect of psycholinguistic variables, target words in the related and unrelated condition were matched for word frequency, phonological length, the number of phonological neighbours, concreteness, imageability, age of acquisition, valence, arousal, dominance and duration. For additional information on the stimuli, we refer to Cocquyt et al. (2022).

Paradigm – Using E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA), trials containing related and unrelated word pairs were randomly sequenced. Word pairs were binaurally presented at an average sound pressure level of 78 dB through ER-1 insert earphones. During the task, participants focused on a white fixation cross on a black background, presented on a Dell computer screen, to limit vertical and horizontal eye movements. The prime and target words were presented with a stimulus onset asynchrony (SOA) of 1800 ms, while the inter stimulus interval (ISI) between the two words ranged from 830 to 1520 ms to account for variations in word length. Following the presentation of the target word, participants were required to assess the semantic relatedness of the prime and target words through a button press response. A delayed response was adopted to avoid interference of movement artefacts and response-related potentials (van Vliet et al., 2014). Button presses were registered by a Chronos response box, on which participants were instructed to press a green button in case of a semantically related word pair and a red button in case of an unrelated pair. Following the button press, an inter trial interval (ITI) of 2500 ms was applied prior to the start of a new trial. The 120 trials were administered over seven blocks, each separated by a pause. The experiment was preceded by a practice block consisting of eight trials (four related, four unrelated pairs) to familiarize subjects with the task procedure. The time required to complete the task ranged between 15 and 20 minutes.

2.3. Electrophysiological data analysis

2.3.1. Data preprocessing

The processing of the target words constituted the focus of the electrophysiological data analysis. First, the eight practice trials preceding the actual experimental blocks were excluded from analysis. In a second step, we disabled bad electrode channels, which were automatically detected using the noisy channel detection methods implemented in the PREP pipeline (Appelhoff et al., 2022; Bigdely-Shamlo et al., 2015). Offline filtering was then performed

using a band-pass filter with a zero phase shift Butterworth filter, applying half-amplitude cut-off frequencies of 0.3 Hz and 30 Hz (12 dB/octave slope). In view of eliminating power line noise, a 50 Hz notch filter was additionally applied to the raw data. We then performed independent component analysis (ICA) to remove eye blinking and horizontal eye movement artifacts. In case bad electrode channels were disabled in step 2, these channels were interpolated after the ICA. We subsequently rereferenced the data to an average common reference before applying a baseline correction using a 200 ms window prior to the onset of the target stimulus. A 75 µV maximum gradient criterion, a 75 µV minimal/maximal amplitude criterion, a 200 µV maximum difference criterion and a 0.5 µV low activity criterion were then set for artifact rejection, resulting in the removal of 14% of trials (SD = 16%). Finally, epochs pertaining to the related versus unrelated target condition were segmented and averaged separately in light of the source reconstruction and connectivity analysis. Epochs associated with an inaccurate button press response were excluded for signal averaging and subsequent analyses. After both artefact rejection and the rejection of trials with incorrect responses, the mean number of related and unrelated trials used for averaging in our participant group equalled 49.4 *(SD = 10.65)* and 49.8 *(SD = 10.49)*, respectively.

2.3.2. ERP level analysis

To investigate whether the administered priming task did elicit an N400 effect in both the young (20-39 years), middle-aged (40-59 years) and older (60+ years) participants included in the current participant sample, amplitude and onset latency values were extracted from the scalp-recorded ERP signals. Specifically, the mean amplitude of the N400 in response to the related and unrelated condition was extracted in the 400-800 ms time window (i.e., the window of interest for the source reconstruction analysis) at three central electrode sites (C3, Cz, C4). N400 onset latencies were extracted as the 25% fractional area latency of the difference wave (unrelated minus related) at central sites in the 400-800 ms time window. A repeated measures

ANOVA, considering condition (related, unrelated) as a within-subjects factor and age group (young, middle-aged, older) as a between-subjects factor, was then performed to compare the mean N400 amplitude, calculated as the average of the values obtained at the three central electrodes, between the two conditions in each age range. A univariate ANOVA was performed to compare N400 difference wave onset latency between young, middle-aged and older adults.

2.3.3. Source reconstruction

Forward modeling – We used the MNE-Python software package (Gramfort et al., 2013) to conduct the ERP source reconstruction. Computation of the EEG forward model was performed using the Freesurfer's standard MRI template *fsaverage* (Fischl, 2012). We constructed a head model comprising three layers (i.e., the scalp, skull and brain). The outer skin, outer skull and inner skull were set as the borders for separating the distinct compartments. Electrical conductivity values were assigned to each of the three layers (scalp: 0.3 S/m, skull: 0.006 S/m, brain: 0.3 S/m). Subsequently, roughly 8200 equivalent current dipoles with a fixed orientation normal to the cortical surface were allocated to the cortex. The distance between neighboring dipoles was approximately 4.9 mm. Using the boundary element method (BEM; Hämäläinen & Servas, 1989), the EEG leadfield matrix was then computed.

Inverse modeling – We used exact Low-Resolution Tomography (eLORETA; Pascual-Marqui et al., 2011) as the inverse modeling method. This technique was applied to the preprocessed related and unrelated averaged trials, separately, for each individual subject. In light of the findings of Fulham et al. (2014), who indicated that dipole amplitude is proportional to noise, the signals were first converted to z-scores to account for the varying noise conditions across participants. For this purpose, we created a noise signal for each participant based on half of the related and half of the unrelated trials. We then shifted the polarity of 50% of these related and unrelated trials, yielding a signal representative of the noise, containing no ERP responses. This signal was then source reconstructed. This entire process was repeated 100 times, through

which mean and standard deviation values of the source reconstructed noise bias were attained for each individual participant. These values were used to normalize the original related and unrelated condition signals in source space.

Source clustering – Statistical clustering in source space was performed in three component-specific 50 ms time windows. The time windows were set around the 25%, 50% and 75% signed (negative) fractional area latency of the grand average N400 effect across all participants, calculated in the 400-800 ms time window. The selected 400-800 ms window approximates the window-of-interest used in prior investigations of the N400 priming effect (Cocquyt et al., 2022; Räling et al., 2015), and was further informed by visual inspection of the ERP plots averaged across participants. Based on this, clustering analysis was performed in the 460-510 ms, 520-570 ms and 630-680 ms time window. The data was averaged over the time dimension in all three windows for each subject. We applied two distinct approaches to test for significant source activation differences in the related versus unrelated condition. The first strategy comprised cluster-based permutation testing, where the significance probability was calculated under the permutation distribution using the Monte-Carlo method (Maris and Oostenveld, 2007). In this regard, we first conducted paired t-tests for each separate dipole, after which the dipoles that reached t-values superseding the data-driven imposed threshold of 10% were retained for clustering. Subsequently, we grouped these dipoles in potential clusters based on their spatial adjacency and determined the cluster size. To form the permutation distribution, we then randomly reassigned the related and unrelated condition across all participants 5000 times. For each permutation, the largest cluster size was determined. If the size of a cluster was part of the top 5% of the distribution, the difference between the related and unrelated conditions was considered to be significant. The second approach to test for significant source activation differences between the two experimental conditions comprised the implementation of paired t-tests for each separate dipole, followed by False Discovery Rate (FDR) correction

(Genovese et al., 2002) to account for multiple comparison. The two adopted approaches are complementary in that the cluster-based permutation testing maximizes power while controlling for multiple comparison, while the paired comparison with FDR correction approach allows for interferences to be made on individual dipoles, thus ensuring for more accurate conclusions on the spatial location and extent of the condition effect.

Data extraction – Based on the significant activation clusters identified in each of the 50 ms time windows, regions of interest (ROI) for subsequent analysis were defined. The Desikan-Killiany atlas (Desikan et al., 2006) was used to designate ROIs. This atlas distinguishes 34 cortical areas in each hemisphere. For each N400 activation cluster identified in the previous step, the ROI including the superior part of the dipoles in this cluster was singled out for further analysis. The time series of both conditions (related, unrelated), as well as the difference, was extracted from the source-reconstructed signal for these ROIs. For this purpose, we applied principle component analysis (PCA) decomposition to the ROI time courses. Finally, from these ROI-specific time series, we extracted the 20% signed fractional area latency (ms), as calculated in the 400-800 ms time window, of the N400 difference time series.

Statistical analysis – Statistical analysis was performed using IBM SPSS Statistics 29 (SPSS Corporation, Chicago, IL, USA). An alpha level of 0.05 was applied to determine statistical significance. Activation timing effects of significant source ROIs were explored through a repeated-measures Analysis of Variance (rmANOVA). Onset latency of the N400 source region time series was set as the dependent variable, while the ROI acted as a within-subject factor. As the factor 'ROI' included more than two levels, the Greenhouse-Geisser correction procedure was applied to account for inhomogeneous covariances. A Bonferroni correction procedure was adopted to the post-hoc pairwise comparisons.

2.3.4. Functional connectivity analysis

The functional connections governing the processing of taxonomic semantic relations (N400) were investigated between the 68 ROIs, through cortical parcellation based on the Desikan-Killiany atlas (Desikan et al., 2006). The time series for the related and unrelated condition were extracted from all 68 ROIs for each subject separately using Principal Component Analysis decomposition, in which the first mode of the decomposition was picked as the representative time series. We then calculated the maximal cross-correlation between the 68x68 ROI signal pairs in the time window of interest (400-800 ms). The cross-correlation function was normalized by the energy of the signal for the correlation coefficient calculations. We imposed a time lag restriction on the functional network calculation, so that the connection strength was set to the maximal cross-correlation coefficient for which the absolute time lag was between 6 and 100 ms. This was adopted in light of reducing source leakage or spreading effects. Lastly, we normalized the values within each functional network by using the following formula, where μ represents the mean and σ represents the standard deviation: $x_{norm} = (x - \mu)/\sigma$.

The Network Based Statistics method (Zalesky et al., 2010) was applied to identify significant functional connectivity differences for related versus unrelated target processing. NBS draws on a permutation approach to identify significant network components related to the experimental effect. Firstly, the algorithm performs paired t-tests for the 68x68 connections to identify connections of interest, superseding the $p < 0.01$ threshold. Next, within this set of connections, networks are determined. In a third step, significant networks, determined based on their size, are isolated using permutation-based univariate statistical testing. To describe the significant networks determined by the NBS method, we grouped the 34 ROIs in each hemisphere based on their location (i.e., frontal, temporal, parietal, cingulate and occipital) (Appendix 1). The number of connections between and within these five lobes in the left and right hemisphere was then quantified. To account for the varying number of ROIs between

groups, we divided the number of connections by the amount of possible links between and within groups.

3. Results

3.1. Priming accuracy

A paired samples t-test demonstrated that priming accuracy was significantly higher for related compared to unrelated trials ($t(59) = -2.212$; $p = 0.031$), with a mean difference of 0.83 points. The mean accuracy for the button press response associated with the semantic priming task in the entire participant sample ($n = 60$) equalled 57.5/60 (95.8%) for related trials and 58.3/60 (97.2%) for unrelated trials. None of the participants reached a behavioural accuracy lower than 75% for the identification of related and unrelated target items.

3.2. The N400 effect

We investigated whether the adopted categorical priming task elicited the expected N400 effect in both young, middle-aged and older individuals in the current participant sample. A repeated measures ANOVA, showing a main effect of condition ($F(1,57) = 47.166$; $p < 0.001$) but no main age group effect ($F(2,57) = 0.488$; $p = 0.616$) or condition by age group interaction effect ($F(2,57) = 0.194$; $p = 0.824$), indicated the presence of an N400 effect at central electrode sites in the 400-800 ms window in both young, middle-aged and elderly participants. N400 amplitude was on average 0.996 μV more negative for unrelated compared to related trials. Likewise, a univariate ANOVA, showing no main effect of age group ($F(2,57) = 0.973$; $p = 0.384$) on the onset latency of the N400 difference wave, indicated a comparable onset for the N400 effect across age groups. The time series of the N400 (effect) as recorded at the central scalp electrodes, is shown in Figure 1.

--- Figure 1 about here ---

3.3. Source reconstruction

Results of eLORETA source reconstruction for related trials, unrelated trials and the difference, in the broad time window (400-800 ms) are visualized in Figure 2. Spatial clustering in early (460-510 ms), middle (520-570 ms) and late (630-680 ms) component-specific time windows revealed five significant dipole clusters underlying the generation of the N400 effect (Figure 3). In the early time window, a combination of cluster-based permutation testing and fdr-corrected paired t-tests (Appendix 2) revealed a difference between the related and unrelated condition, mainly located in the left lateral orbitofrontal cortex, the left pars opercularis and left pars triangularis of the inferior frontal gyrus, and the left precentral gyrus. In the middle time window, significant activation differences between related and unrelated trials were predominantly identified in the left posterior cingulate cortex. In the late time window, no condition effect could be observed. The time series of the N400 source signal of the 34 cortical ROIs in the left and right hemisphere, are attached in Appendix 3.

--- Figure 2 about here ---

--- Figure 3 about here ---

Based on source clustering in an early, middle and late component-specific time window, a timing effect on N400 source activation was suggested, indicating later activation of the left posterior cingulate compared to left frontal sources. To further validate this effect, an ANOVA was performed, assessing the effect of ROI (left lateral orbitofrontal, left pars opercularis, left pars triangularis, left precentral, left posterior cingulate) on the onset latency of the N400 source region time series (difference). The ANOVA revealed a main effect of ROI ($F(3.004,177.244) = 3.994$; $p = 0.009$). Based on post-hoc pairwise comparison, the onset latency of the N400 difference time series in the posterior cingulate ROI was found to be on average 19.6 ms (95%

CI = 0.14 – 39.12; p = 0.047) higher compared to the pars triangularis, and 20.0 ms (95% CI = 0.52 – 39.6; p = 0.040) higher compared to the pars opercularis (Figure 4).

--- Figure 4 about here ---

3.4. Functional connectivity

Network Based Statistics identified a significant network for related (related > unrelated) but not unrelated (unrelated > related) target processing, at a threshold of $p < 0.01$ (Figure 5). The significant network for related processing encompassed 15 nodes, connected by 12 edges (p = 0.014). The network mainly comprised short connections within the left frontal lobe, connecting the frontal pole, pars orbitalis, pars triangularis, pars opercularis and lateral orbitofrontal cortex. Additional short-range connections linked left temporal areas, specifically the entorhinal and inferior temporal region. Long-range connections essentially linked the left frontal cortex (especially the pars orbitalis of the IFG) with right frontal (interhemispheric; the frontal pole and medial orbitofrontal cortex), left parietal (intrahemispheric; the precuneus) and left occipital (intrahemispheric; the cuneus) cortices.

--- Figure 5 about here ---

4. Discussion

We explored the neural generators and functional cortical connections that govern semantic priming of taxonomically related words. The N400 event-related potential was recorded at 128 scalp electrodes during the administration of an auditory categorical priming task in 60 neurotypical adults. eLORETA source estimation revealed significant N400 activation clusters in the left frontal cortex (lateral orbitofrontal, pars opercularis, pars triangularis, precentral) in an early (460-510 ms) component-specific time window and in the left posterior cingulate gyrus

in a middle (520-570 ms) time window. Through the calculation of the maximal cross-correlations between 68x68 ROI pairs, significant functional connections for related (related > unrelated) but not unrelated (unrelated > related) target processing were identified. Enhanced connectivity between areas within the left frontal lobe, between left and right frontal cortices, and between frontal and parieto-occipital areas characterized related target processing.

4.1. The cortical sources of semantic priming

Significant N400 source clusters were identified in the left frontal cortex and the left posterior cingulate cortex. As such, the present findings confirm earlier records of a left-dominant network for semantic processing in general (Binder et al., 2009), as well as the N400 elicited in relation to semantic priming in specific (Geukes et al., 2013; Ghosh-Hajra et al., 2018; Khachatryan et al., 2019; Khutas et al., 2010).

Areas in the frontal and temporal cortex have generally been reported to govern semantic priming mechanisms at long SOAs (fMRI evidence: Kircher et al., 2009; O'Hare et al., 2008; Matsumoto et al., 2005; Tivarus et al., 2006; Wible et al., 2006; EEG and MEG evidence: Ghosh-Hajra et al., 2018; Matsumoto et al., 2014). Likewise, the present results designate the IFG as a major generator of the scalp-recorded N400 priming effect. The IFG comprises three subregions: the pars opercularis (BA 44), the pars triangularis (BA 45) and the pars orbitalis (BA 47) (Petrides & Pandya, 2004). Distinct functionalities have been attributed to these subregions with respect to semantic processing. The anterior part of the IFG, comprising the pars orbitalis, has been associated with semantic retrieval. The posterior part, constituting the pars opercularis and pars triangularis, is associated with semantic selection, i.e., selecting amongst competing semantic alternatives (Moss et al., 2005; Noppeney et al., 2004; Thompson-Schill et al., 1997). The inferior frontal cortex, as part of the semantic control network (Diveica et al., 2021; Jackson et al., 2021), is thought to be implicated in the top-down mediation of semantic retrieval and selection (Lau et al., 2008). For primed targets, controlled semantic

retrieval is facilitated by the prime word, translating to reduced activation of the IFG in this condition. In contrast, for unrelated targets, the absence of this prime-driven facilitation results in an increased burden on semantic control processes (Rodd et al., 2005; Lau et al., 2008). This could account for the present observation of increased posterior IFG engagement for unrelated compared to related target processing, as this region mediates these controlled selection processes. While in accordance with previous literature, some caution is warranted in interpreting the above-discussed results. That is, localization errors are inherent to EEG source estimation techniques (Asadzadeh et al., 2020). As the IFG was segmented in three small, spatially neighbouring areas to study the subprocesses of semantic retrieval and selection, the potential impact of localization errors must be considered.

The present results could not substantiate earlier findings of a priming-related N400 generator in the temporal cortex, which is generally observed at the level of the pMTG, and is engaged in semantic priming at both short and long SOAs (Ghosh-Hajra et al., 2018; Holderbaum et al., 2019; Khachatryan et al., 2019; Khateb et al., 2010; Lau et al., 2008). This result is not unprecedented. Some fMRI studies targeting semantic priming at long SOAs could only identify a frontal generator (Kircher et al., 2009; Matsumoto et al., 2005; O'Hare et al., 2008). The strict clustering approach we adopted might explain the absence of any temporal activation cluster. In this context, a less conservative analysis, where fdr-corrected paired t-tests were performed for each cortical dipole, did reveal significant activation sites in the temporal lobe (see Appendix 2). Based on visual inspection of the activation maps, this activation appeared to be located bilaterally at the level of the posterior part of the MTG and was restricted to the middle and late time window. While this analysis argues for the presence of a temporal generator in the bilateral pMTG, the conservative clustering approach indicates that semantic control processes (retrieval, selection) might be dominant for semantic priming at long SOA. In addition to the pMTG, the anterior portion of the temporal lobe has been linked to semantic

priming (Lau et al., 2013, 2016) and the processing of taxonomic relations in specific (Mirman et al., 2017). The current results, however, do not substantiate this as no difference in activation was observed in this region between the two experimental conditions.

One additional cluster was identified in the left posterior cingulate cortex (PCC), exhibiting delayed activation compared to the IFG generators. Reports on the engagement of this area in semantic priming are scarce (Khateb et al., 2010; Kuchinke et al., 2009; O'Hare et al., 2008; Sachs et al., 2008), resulting in ambiguity regarding its precise function in this language-specific process. That is, the PCC is generally associated with the default mode network (Buckner et al., 2008; Raichle et al., 2015) and domain-general attentional operations (Corbetta & Shulman, 2002). The PCC can be broken down into a structurally and functionally segregated ventral and dorsal part (Vogt et al., 2006). Based on this distinction, two hypotheses can be put forward with regard to the role of the PCC in semantic priming. The ventral PCC, through its connection to the default mode network, is engaged in the encoding of information in the episodic memory (Leech & Sharp, 2014). As the retrieval of conceptual knowledge gives rise to episodic memory encoding, Binder et al. (2009) proposed that the PCC most likely acts as an interface between the semantic retrieval and episodic memory encoding systems. Several reviews have, indeed, designated the PCC as a key region in the general semantic network (Binder et al., 2009; Jackson et al., 2021). In this context, the diminished PCC activation for primed compared to unprimed words observed in the present study, could potentially signify facilitated episodic memory encoding in this particular condition. The dorsal PCC, in turn, has been implicated in response control. O'Hare et al. (2008) pinpointed the PCC as a generator source of the N300 in relation to semantic priming. The N300 is generally considered to be an index for the matching of visual input with stored semantic representations (Sitnikova et al., 2008, Yum et al., 2011). However, this strictly visual view of the N300 has been challenged, leading to unclarity about the exact processes reflected by this component, as well as the

dissociation between the N300 and the N400 (O'Hare et al., 2008). Based on the finding of PCC activation in the N300 time window, O'Hare et al. (2008) implied that the dorsal PCC could potentially mediate the allocation of a stimulus to a response category. For the priming task adopted in the current study, participants were indeed asked to judge whether target stimuli were 'semantically related' or 'unrelated' by a button press response. Enhanced activation of the PCC for unrelated compared to related target processing could, as such, reflect the process of determining a stimulus category and programming associated responses. This hypothesis could account for the delayed activation of the PCC compared to frontal areas, as categorization can only occur once semantic retrieval has been successfully accomplished. Arguing against this hypothesis, PCC activation linked to stimulus categorization is typically observed in go-nogo or oddball designs, where experimental conditions feature an uneven distribution of trials (Fize et al., 2000; O'Hare et al., 2008). Since the current study did not employ this type of design, this prompts the question as to why categorizing unrelated targets in particular would require enhanced PCC engagement. The current methodological approach did not allow for the segregation of the PCC in a ventral and dorsal part, preventing us from giving preference to any of the two above-discussed hypotheses. Alternatively, PCC activation could also be explained by the methodological choice to study a late 630-680 ms time window. In tasks that pose high semantic integration demands, a sustained (frontal) negativity, extending beyond 600 ms after stimulus presentation, can follow the N400 (Yacovone et al., 2021). This prolonged negativity, which has been hypothesized to reflect working memory (Coulson and Kutas, 2001) and cognitive control processes (Lee and Federmeier, 2009), among others, could potentially originate from a generator in the cingulate cortex.

4.2. The functional network of semantic priming

Enhanced functional connectivity among frontal areas, more specifically left intrahemispheric and left-right interhemispheric, was identified for related (related > unrelated) target processing.

As the left frontal cortex, in particular, showed significant source clusters for unrelated target processing, these connectivity results might at first seem counter-intuitive. Nevertheless, our findings align with observations by Kujala et al. (2012). The authors noted enhanced coherence between the STC, the frontotemporal cortex and the ITG for the processing of categorically related versus unrelated targets. This coherence increase coincided with reduced cortical source activation. Based on these observations, Kujala et al. (2012) hypothesized that semantic priming is driven by enhanced information transfer between distinct neuronal assemblies, a mechanism that is facilitated by functional synchronization of these assemblies. This, in turn, results in reduced local processing demands in these areas. Matsumoto et al. (2014) identified an enhanced bidirectional information flow between a frontal and temporal N400 generator for the processing of primed words, and thereby provided additional support for this hypothesis. The current findings, demonstrating a similar pattern of simultaneous decreased neural activation levels in the IFG and increased connectivity among frontal areas for related target processing, likewise support this notion. We can posit that the temporal alignment of neural activity in frontal areas might facilitate efficient neural information transfer in primed conditions (Kujala et al., 2012; Mottaghy et al., 2006). This enhanced synchronization may result in decreased local processing demands in regions engaged in the semantic priming network, reflected by the reduced source activation levels for the primed compared to the unprimed condition. Importantly, the area showing strongest connectivity was the left IFG. As previously discussed, this anterior part of the IFG is implicated in the top-down retrieval of semantic representations (Moss et al., 2005; Noppeney et al., 2004). Within the conceptual framework outlined above, the enhanced connectivity of this area in particular, suggests that in specific the process of controlled lexical-semantic retrieval is facilitated through enhanced neural synchronization in primed conditions.

In addition to the marked connectivity increase between frontal regions, enhanced synchronization for the processing of primed words was observed between the left pars orbitalis on the one hand and left parieto-occipital areas, specifically the precuneus and cuneus, on the other. These observations could be framed within the context of the hub-and-spoke model of semantic representations (Patterson & Lambon-Ralph, 2016). This account posits that semantic knowledge is represented in modality-specific regions (spokes), dedicated to auditory, visual, olfactory, emotional, … representations. These modality-specific representations are integrated in an amodal connector hub. Parietal and occipital cortices are suggested to house modality-specific representations relating to object praxis and vision (Ishibashi et al., 2011; Chiou & Lambon Ralph, 2019). Moreover, according to the feature reliance hypothesis (Zhang et al., 2023), taxonomic relations particularly rely on static visual features such as colour and shape, as objects pertaining to the same category often have a similar appearance (Dilkina & Lambon Ralph, 2012). In this context, enhanced connectivity between frontal and parieto-occipital cortices may signify the facilitated retrieval of modality-specific representations due to a preactivation by the prime word in the related target condition. The adoption of an auditory priming task in the current study further argues in favour of this theory, as the occipital engagement cannot be explained by this stimulus modality. Alternatively, synchronization between fronto-parietal regions could be framed in light of the (left) IFG showing language-related activation as part of both a domain-specific and domain-general control system (Bulut, 2023). Domain-specific control engages a left lateralized frontotemporal network, while domain-general control relies on a bilateral fronto-parietal network. In this respect, the fronto-parietal synchronization for related target processing, which we observed in both hemispheres, could signify engagement of domain-general control processes. Several domain-general functions, including emotional processing, action processing, working memory and cognitive

control have been attributed to the inferior frontal cortex (Belyk et al., 2017; Bulut, 2023; Clos et al., 2013).

4.3. Limitations and directions for future research

The present study shed light on the generators and functional networks underlying the N400, specific to the processing of taxonomic semantic relations. Some aspects of the adopted methodological approach and the implications thereof should be addressed in function of our study results.

Firstly, we recruited a group of participants within a wide age range (20-80 years) to provide results generalizable for the broad population. Most research addressing the neural basis of semantic operations targets young adults to avoid any confounding aging effects (Geukes et al., 2013; Ghosh-Hajra et al., 2018; Khateb et al., 2010; Kujala et al., 2012). In doing so, these studies provide results with limited generalizability and assign greater importance to age over other personal factors that have been demonstrated to impact semantic processing, such as sex (Baxter et al., 2003; Cocquyt et al., 2022; Daltrozzo et al., 2007) and education level (Paolieri et al., 2018). Notwithstanding the rationale for including both young and more elderly adults, we must be mindful of how this decision might potentially have impacted our study outcomes. That is, both structural (Fjell & Walhovd, 2010) and functional (Cabeza, 2002; Davis et al., 2007) brain networks undergo changes in function of time. The Posterior to Anterior Shift in Aging (PASA; Davis et al., 2008) and Hemispheric Asymmetry Reduction in OLDer adults (HAROLD; Cabeza et al., 2002) model posit that aging is accompanied by activation shifts on the posterior-anterior and left-right brain axes. In an ALE meta-analysis on age-related changes in the semantic cognition network, Hoffman & Morcom (2018) identified reduced levels of activation in the left inferior prefrontal, left posterior temporal and inferior parietal cortex in older adults. While the current amplitude and latency results do not point to any age-related differences in the N400 effect at the scalp level, this prompts the question as to whether the

absence of a temporal N400 source cluster in the present study could be driven by decreased engagement of this area in the elderly participants in our sample. In contrast, Tsolaki et al. (2015) was unable to objectify a shift in the maximal N400 generator region, located in the frontal cortex, in young versus elderly adults. In this study, however, the N400 was recorded in response to a non-semantic two tone oddball task. While this was outside the scope of the current investigation, follow-up research should further explore priming networks with respect to aging.

A second point that warrants some discussion, constitutes the selection of the Desikan-Killiany atlas (Desikan et al., 2006) for cortical parcellation in function of the source estimation and functional connectivity analysis. In selecting this atlas, a trade-off was made between ensuring an adequate number of ROIs to draw informative conclusions on the processes of interest, and avoiding overly small segmentation to account for EEG localization error. That is, while the eLORETA technique is associated with a relatively small localization error (Pascual-Marqui et al., 2018), this limitation is inherent to EEG source estimation (Asadzadeh et al., 2020). The Desikan-Killiany atlas, distinguishing 34 ROIs per hemisphere, provided the best fit in function of the imposed restrictions. A drawback of this atlas, however, is its limited segmentation of the lateral surface of the temporal lobe. This area is broken down into a superior temporal, middle temporal and inferior temporal region, with no distinction being made between anterior and posterior parts. In function of research on semantic processing, where distinct functionalities have been attributed to the posterior temporal cortex versus anterior temporal lobe, this poses a significant limitation. As our clustering approach did not reveal any significant activation clusters in the temporal cortex, this issue did not influence result interpretation at present. However, other atlases (e.g., Destrieux atlas, Destrieux et al., 2010; MarsAtlas, Auzias et al., 2016; Brainnetome atlas, Fan et al., 2016) should be considered for future research.

Lastly, we opted for an explorative approach on the functional connectivity analysis by considering all 68 ROIs. This allowed for the examination of the general functional dynamics underlying semantic processing without adopting any prior assumptions. Future research could enhance current understandings by further targeting functional interactions between specific N400 generator sites, such as the inferior frontal region and the posterior temporal cortex, as well as interactions between these regions and the posterior cingulate area. Exploring the direction of the interaction between these regions through directed connectivity measures (e.g., Granger Causality, transfer entropy) could likewise be informative for understanding priming network dynamics. The maximal cross-correlation, calculated in the current study, allows for determining directional connectivity. This measure has, however, proven to be little reliable in networks that show bilateral interactions (Bastos & Schoffelen, 2015). As this is the general trend for higher-order cognitive processes, directed connectivity was not explored in the current data set.

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During the preparation of this manuscript, the authors used ChatGPT to improve the style of writing.

Data availability statement

The participants of this study did not give written consent for their data to be shared publicly. Due to this, raw data cannot be made available.

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Declaration of interest statement

None of the authors reported a conflict of interest.

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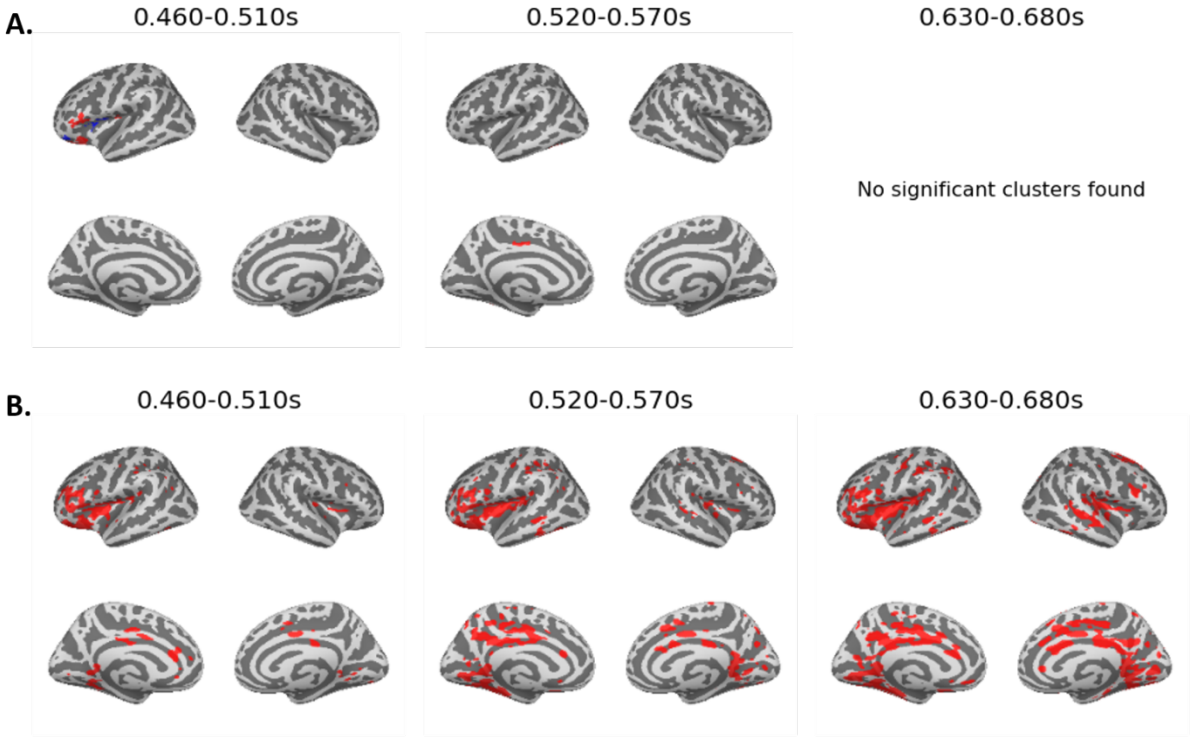
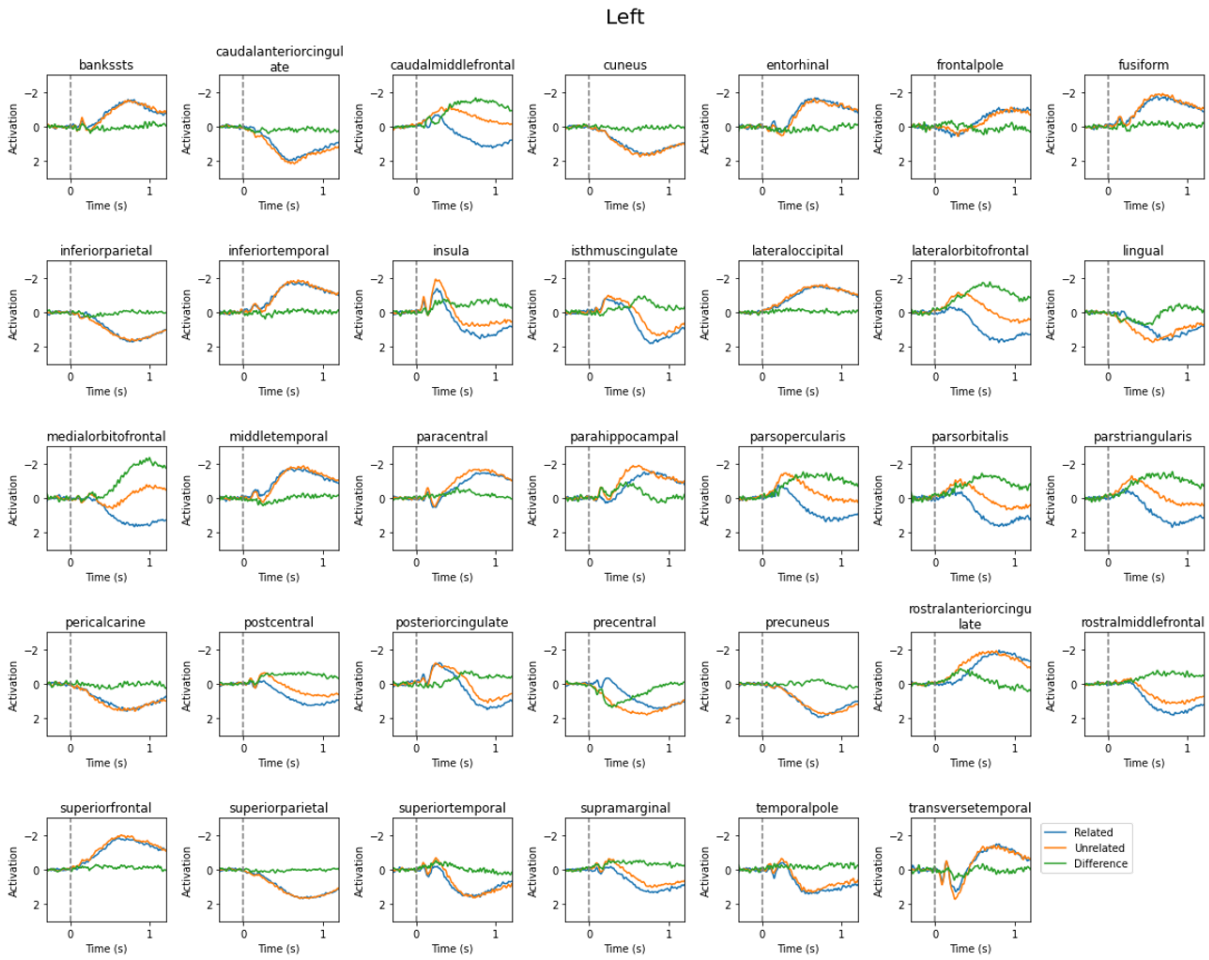
Appendix 1 Grouping of the 34 ROIs from the Desikan-Killiany atlas in frontal, temporal cingulate, parietal and occipital areas.

frontal	caudal middle frontal gyrus; frontal pole; lateral orbitofrontal cortex; medial orbitofrontal cortex; paracentral lobule; pars opercularis; pars orbitalis; pars triangularis; precentral gyrus; rostral middle frontal gyrus; superior frontal gyrus
temporal	banks superior temporal sulcus; entorhinal cortex; fusiform gyrus; inferior temporal gyrus; insula; middle temporal gyrus; parahippocampal gyrus; superior temporal gyrus; temporal pole; transverse temporal cortex
cingulate	caudal anterior-cingulate cortex; isthmus-cingulate cortex; posterior-cingulate cortex; rostral anterior cingulate cortex
parietal	inferior parietal cortex; postcentral gyrus; precuneus cortex; superior parietal cortex; supramarginal gyrus
occipital	cuneus cortex; lateral occipital cortex; lingual gyrus; pericalcarine cortex

Appendix 2. Significant N400 activation differences in eLORETA source activation maps for the unrelated versus related condition, identified based on (A) cluster analysis and (B) fdr-corrected pairwise dipole comparison. Analyses were performed in an early (460-510 ms), middle (520-570 ms) and late (630-680 ms) component-specific time window.



Appendix 3. Source waveform for each of the 34 ROIs in the left and right hemisphere in response to related targets, unrelated targets and the difference between conditions, averaged over all subjects.



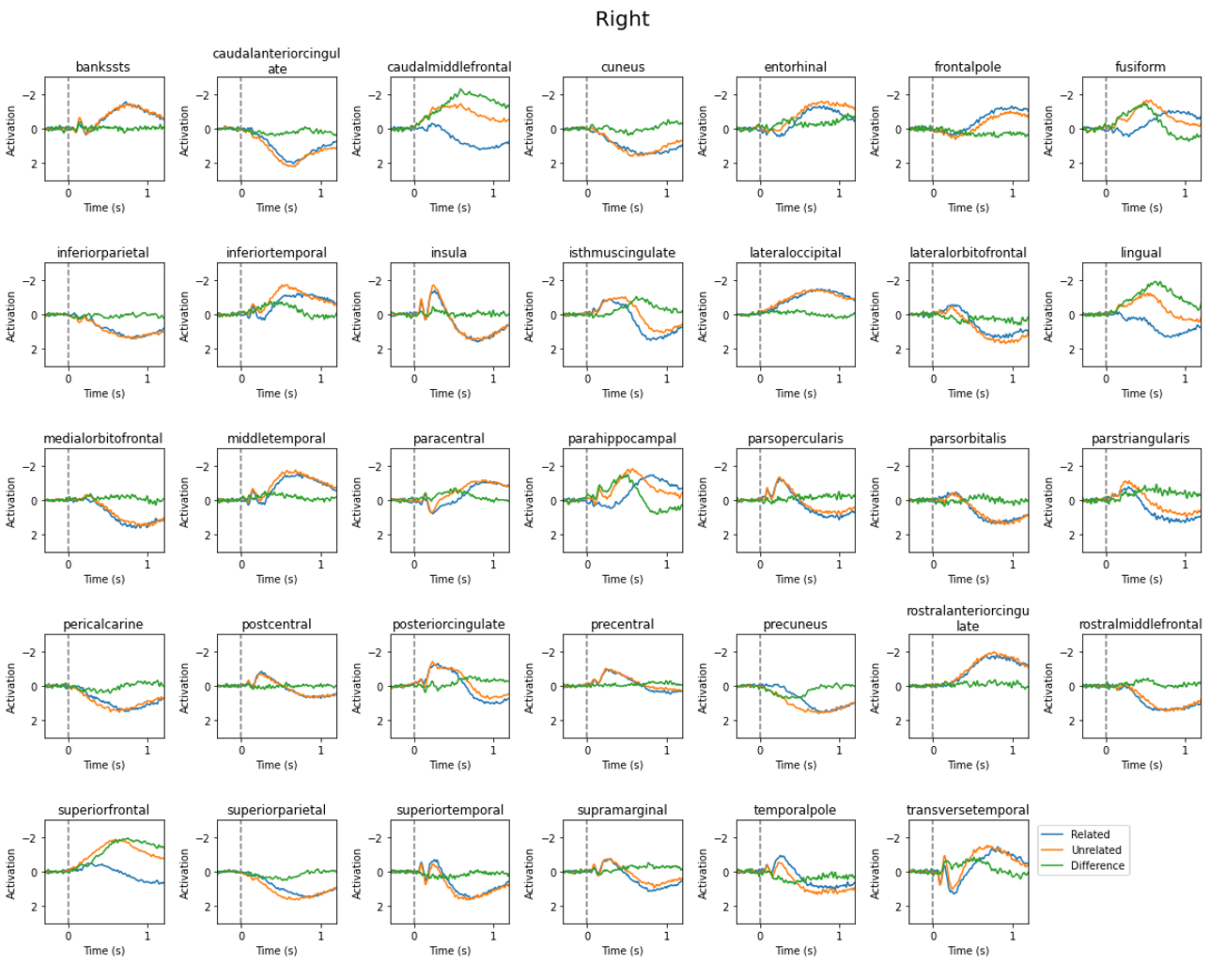

Right
bankssts
caudalanteriorcingulate
caudalmiddlefrontal
cuneus
entorhinal
frontalpole
fusiform
inferiorparietal
inferiortemporal
insula
isthmuscingulate
lateraloccipital
lateralorbitofrontal
lingual
medialorbitofrontal
middletemporal
paracentral
parahippocampal
parsopercularis
parsorbitalis
parstriangularis
pericalcarine
postcentral
posteriorcingulate
precentral
precuneus
rostralanteriorcingulate
rostralmiddlefrontal
superiorfrontal
superiorparietal
superiortemporal
supramarginal
temporalpole
transversetemporal
Activation
Time (s)
Related
Unrelated
Difference

Table 1

Participant information including demographic details, DHI scores and MoCA scores, presented per age group.

	Total sample	20-39 years	40-59 years	60+ years
N (male/female)	30 / 30	10 / 10	10 /10	10 /10
Age (years)	49.3 (16.84)	29.7 (4.74)	49.4 (5.62)	68.7 (5.11)
Education level[a]	1.8 (0.87)	1.4 (0.68)	1.8 (0.85)	2.3 (0.87)
DHI (/10)	9.8 (0.54)	9.8 (0.62)	9.7 (0.66)	10.0 (0.22)
MoCA (/30)	27.9 (1.36)	27.8 (1.16)	28.3 (1.59)	27.7 (1.27)

Note. Reported values are mean (standard deviation); DHI = Dutch Handedness Inventory; MoCA = Montréal Cognitive Assessment.

[a] Education level was rated on a four-point scale: 1 = higher education-academic, 2 = higher education-nonacademic, 3 = higher secondary school, 4 = lower educational school.

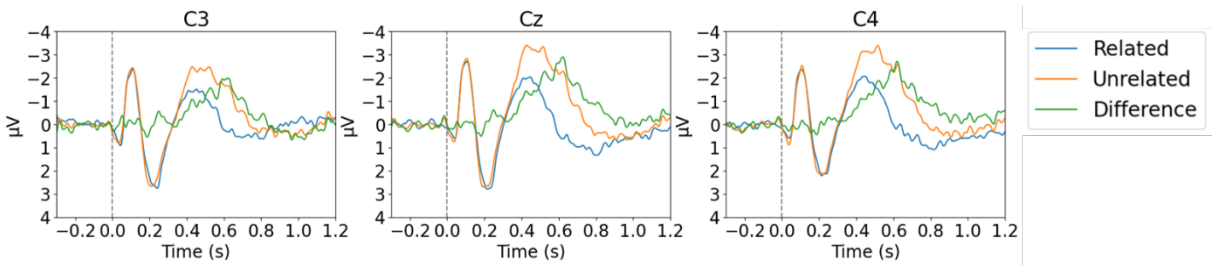


Figure 1

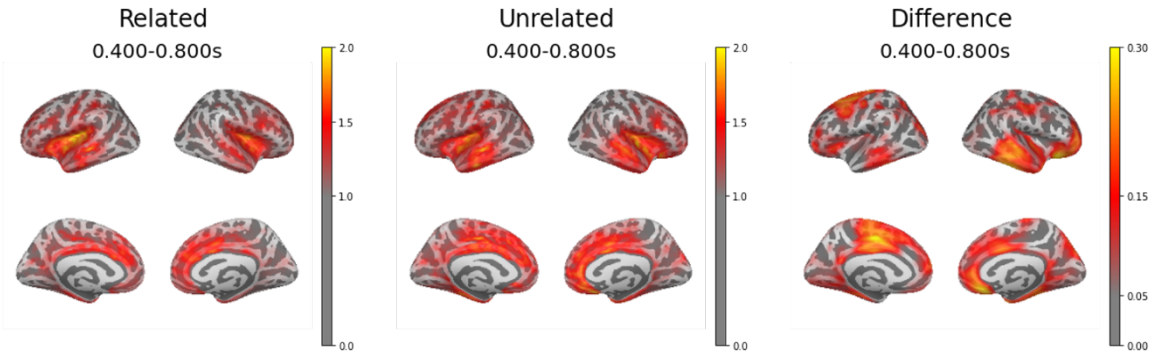

Related
0.400-0.800s
2.0
1.5
1.0
0.0
Unrelated
0.400-0.800s
2.0
1.5
1.0
0.0
Difference
0.400-0.800s
0.30
0.15
0.05
0.00

Figure 2

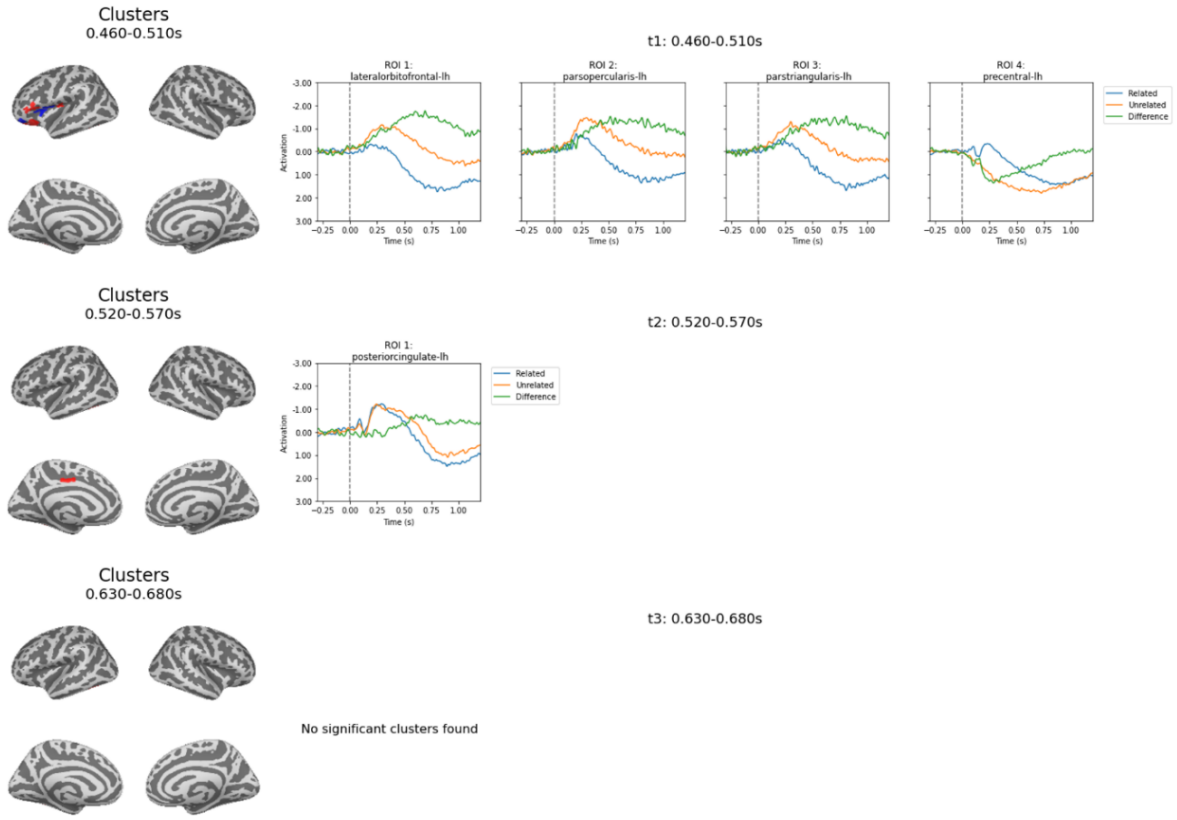

Clusters
0.460-0.510s
t1: 0.460-0.510s
ROI 1:
lateralorbitofrontal-lh
ROI 2:
parsopercularis-lh
ROI 3:
parstriangularis-lh
ROI 4:
precentral-lh
Related
Unrelated
Difference
Activation
Time (s)
Clusters
0.520-0.570s
t2: 0.520-0.570s
ROI 1:
posteriorcingulate-lh
Related
Unrelated
Difference
Activation
Time (s)
Clusters
0.630-0.680s
t3: 0.630-0.680s
No significant clusters found

Figure 3

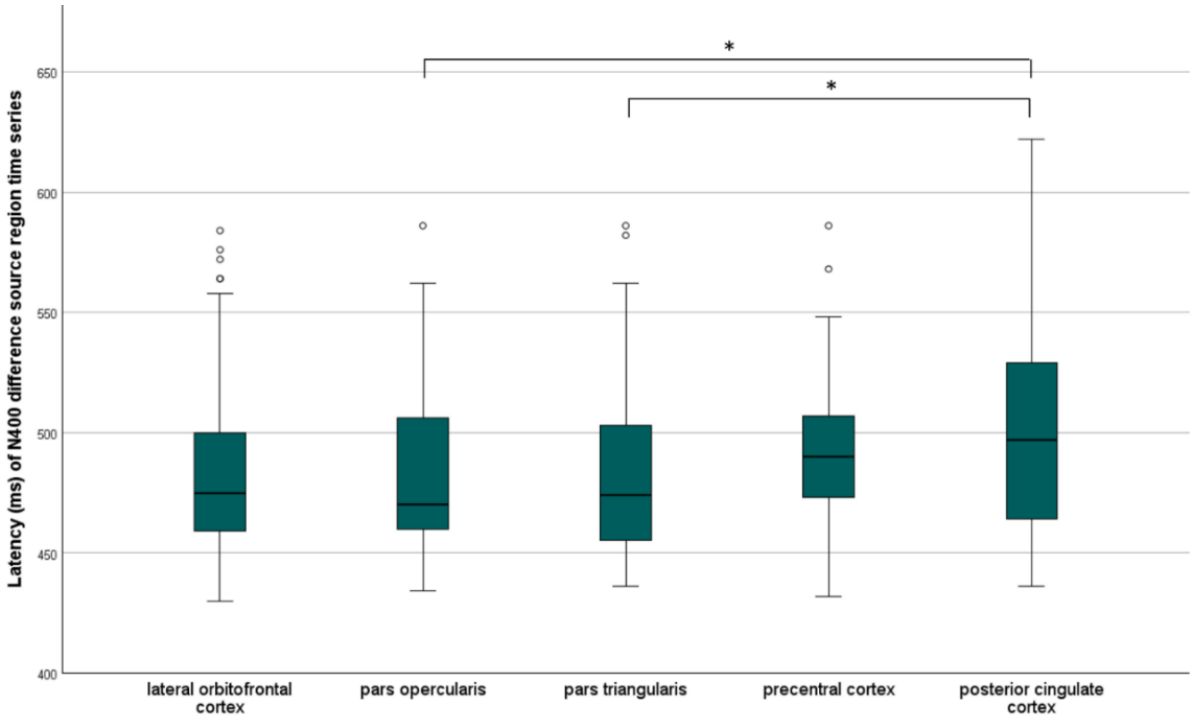

Latency (ms) of N400 difference source region time series
650
600
550
500
450
400
*
*
lateral orbitofrontal cortex
pars opercularis
pars triangularis
precentral cortex
posterior cingulate cortex

Figure 4

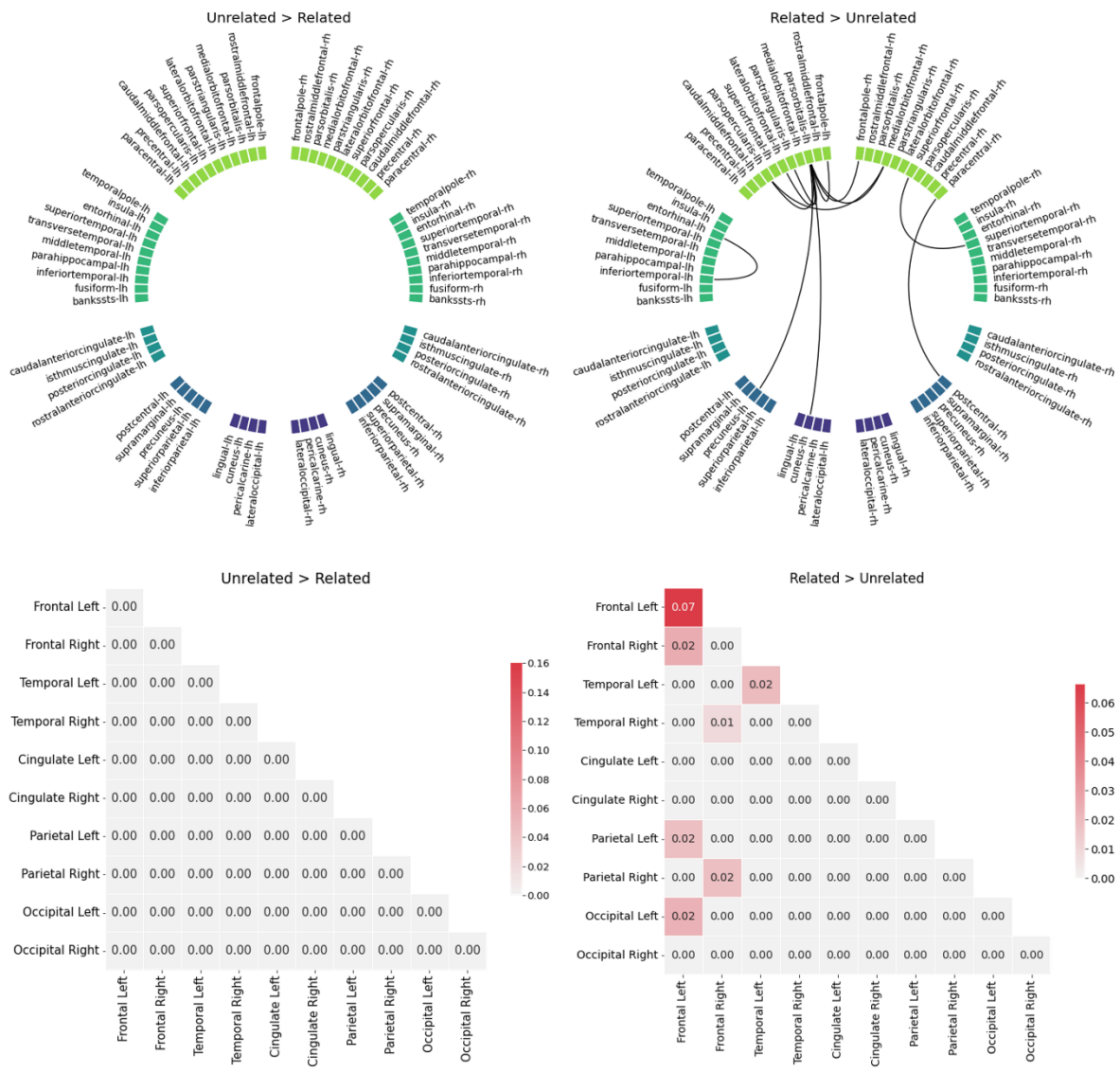

Unrelated > Related
Related > Unrelated
Unrelated > Related
Related > Unrelated
Frontal Left
Frontal Right
Temporal Left
Temporal Right
Cingulate Left
Cingulate Right
Parietal Left
Parietal Right
Occipital Left
Occipital Right

Figure 5

Figure captions

Figure 1. Grand average N400 effect elicited by the categorical priming task adopted in the entire participant group (n = 60), visualized at three central (C3, Cz, C4) electrode sites.

Figure 2. eLORETA activation maps of the N400 in response to related trials, unrelated trials and the difference in the 400-800 ms time window. Only the amplitude of the obtained activation was taken into account in the visualization, directionality of the different dipoles was ignored.

Figure 3. Results of clustering analysis on the eLORETA source reconstruction of the N400 effect in the early (460-510 ms), middle (520-570 ms) and late (630-680 ms) time windows. Figures represent the location of significant source clusters on the cortex (left) and these clusters' time series, as averaged over all dipoles of the cluster (right).

Figure 4. Box and whiskers plot of the onset latency (ms) extracted from the time series of the N400 effect source wave in five ROIs in the left hemisphere (lateral orbitofrontal cortex, pars opercularis, pars triangularis, precentral cortex, posterior cingulate cortex).

Figure 5. Functional N400 networks showing a significant condition effect based on Network Based Statistics applying a threshold of $p < 0.01$. The top figures represent significant network edges between 68 cortical ROIs for unrelated > related and related > unrelated target processing. Bottom figures represent the normalized connectivity matrix of significant network edges between frontal, temporal, cingulate, parietal and occipital areas in the left and right hemisphere.