# Electrophysiological Signature of Suppression of Competitors during Interference Resolution

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# Abstract

The electrophysiological evidence for suppression to date primarily draws upon traditional retrieval-induced forgetting and Think/No-Think paradigms, which involve strategic and intentional restriction of thought. Here event-related potential (ERP) signatures of suppression were examined using a novel task, which unlike traditional paradigms, does not include an initial priming step or intentional thought restraint. Participants were instructed to verbally generate semantically related responses to cue words (e.g., "pizza"), and unrelated responses to others. According to an inhibitory account of interference resolution, semantic competition from automatically activated target words must be resolved in order to generate an unrelated response, whereas no resolution is required for generating related responses. In a subsequent phase, accessibility for target words (e.g., "PEPPERONI") that required suppression, words that did not require suppression, as well as new control words was measured using a lexical decision task. We observed a sustained late positivity for unrelated responses in the generation task, and early negative amplitudes of suppressed items in the lexical decision task. These findings are consistent with inhibitory mechanisms operating at retrieval to suppress competitors and show that such processes operate on automatically activated items that are not presented in the context of an experiment, representative of retrieval situations that occur in everyday life.

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## 1. Introduction

Memory retrieval is the process by which previously encoded information is recovered from long-term memory. Several classic models of memory retrieval rely primarily on activation of events in response to cues available (e.g., Neeley, 1977; Anderson, Bothell, Byrne, Douglass, Lebiere, & Qin, 2004; Mensink & Raaijmakers, 1988). Alternative views suggest that a single activation-based measure is insufficient when cues trigger more than one candidate for response – there must be an additional mechanism to resolve the competition (Bjork, 1989; MacLeod, Bjork, & Bjork, 2003). We and other researchers have argued that retrieval of target memories is promoted by active suppression of interfering alternatives (e.g., Anderson & Spellman, 1995; Anderson, Bjork, & Bjork, 1994; Aslan & Bäuml, 2011; Healey, Campbell, Hasher, & Ossher, 2010; Healey, Ngo, & Hasher, 2014; Norman, Newman, & Detre, 2007; Storm, 2011). This process serves to narrow the focus of activation to the target memory trace.

Behavioral evidence for suppression in memory retrieval comes from several sources including early research on directed forgetting (e.g., Anderson, 2003; Levy & Anderson, 2002; Bjork, Bjork, & Anderson, 1998), as well as from Retrieval Induced Forgetting (RIF) paradigms (Ciranni & Shimamura, 1999; Anderson et al., 1994). In the typical RIF procedure, participants first study lists of exemplars (e.g., orange, banana) belonging to distinct categories (e.g., fruit) and then repeatedly practice retrieving half of the items in a category (e.g., orange) through a cueing process that includes the category name as well as an initial letter. Contrary to a facilitation mechanism, but consistent with an inhibitory one, delayed final recall of all studied exemplars revealed impairment for unpracticed items (e.g., banana) from within a practiced category relative to baseline controls (e.g., Anderson, 2003; Anderson & Bjork, 1994; Anderson

& Spellman, 1995). Additional research has provided further support to the inhibitory account by illustrating that a single semantic retrieval attempt of an unstudied exemplar competitor (even without retrieval success) is sufficient to induce RIF of the studied exemplar (Hellerstedt & Johansson, 2016; Storm, Bjork, Bjork, & Nestojko, 2006).

Yet another paradigm pointing to the role of inhibition at retrieval is the Think/No-Think task (e.g., Anderson and Green, 2001). In this paradigm, participants typically first study cue-target word pairs until they reach a minimum accuracy threshold in repeated cued recall. Then, some cue words are presented in green to indicate a “think” condition or red to indicate a “no-think” condition. In the “think” condition, participants are instructed to silently retrieve and think of the correct word. In the “no-think” condition, participants are instructed to suppress the associated target word. The remaining cue words are not presented and assigned as baseline controls. Across several studies, participants showed evidence of suppression of “no-think” items, as indexed by reduced memory for these items relative to baseline controls (see Anderson & Hanslmayr, 2014 for a review).

In an electrophysiological study using the same Think/No-Think paradigm, Waldhauser et al. (2012) showed that suppressed words (from the no-think items) displayed a frontal, positive-going slow wave in the 650-900ms window, similar to findings from research on processes that regulate the accessibility of unwanted memories (Mecklinger, Parra & Waldhauser, 2009; Bergström, Velmans, De Fockert & Richardson-Klavehn, 2007). These findings suggest that intentional suppression can lead to reduced memory trace strength for no-think items. Other electrophysiological studies have similarly identified markers of inhibitory mechanisms during competitive retrieval. Using different paradigms (such as the RIF paradigm) that require suppression of a previously learned item during retrieval, these studies have shown sustained positive-going event-related potentials (ERPs) and/or reduced late negative ERP effects indicative of typical semantic retrieval (e.g., Cansino, Ruiz, Lopez-Alonso, 1999; Nessler, Johnson, Bersick, & Friedman, 2006), suggesting that control processes are inhibiting the retrieval of competitors during late time windows (typically starting 500ms post stimulus onset; Hellerstedt & Johansson, 2014; Johansson, Aslan, Bäuml, Gäbel, & Mecklinger, 2007; Rass, Landau, Curran, Leynes, 2010; see also Hellerstedt & Johansson, 2016 for neural evidence of inhibitory control during competitive retrieval attempts, and Hanslmayr, Staudigl, Aslan, & Bäuml, 2010; Staudigl, Hanslmayr, & Bäuml, 2010 for similar inhibitory control evidence based on theta oscillations).

Previous research thus provides behavioral evidence of suppression, which coincides with enhanced late positive slow wave over frontal areas. However, studies to date have mostly used explicit procedures to investigate suppression and often required the intention to not think about or not remember some items (Blaxton & Neely, 1983; Healey et al., 2010; Higgins & Johnson, 2009; Radvansky, Zacks, & Hasher, 2005; Storm, 2011). By contrast, we recently reported evidence of behavioral suppression effects in a truly *incidental* situation using naming time (Healey, Hasher, & Campbell, 2013; Healey et al., 2014) and lexical decision (Ngo & Hasher, 2017) as implicit measures.

In this paradigm, participants were presented with cue words (e.g., “PIZZA”) that were selected to activate strongly associated target words (e.g., “PEPPERONI”). In response to some cue words, participants were told to generate a related word, and in response to others, they were told to generate an unrelated word. Based on classic priming work, we reasoned that reading the cue word would automatically activate its related target word and, therefore, generating an unrelated response would require competition to be resolved. We hypothesized that resolving this competition would entail suppressing the automatically activated related target word. Critically, unlike other paradigms where to-be-suppressed information is studied and retrieved in multiple attempts, competitors in this semantic interference resolution paradigm are never explicitly presented; they are just spontaneously activated during a single retrieval attempt. Then, without explicitly asking participants to retrieve previously learned information, suppression of competitors is measured using naming or lexical decision times as sensitive, implicit measures of accessibility (see e.g., Forbach, Stanners, & Hochhaus, 1974). Evidence of reduced accessibility of competitors is then the product of a spontaneous process in memory retrieval. This procedure is representative of situations in everyday life, for example, when two last names compete for retrieval in response to a familiar first name. Finally, it is important to note that suppression measured through reduced accessibility is not likely a deliberate process as observed in the Think/No-Think paradigm, rather, it is an automatic, spontaneous process that aids retrieval by resolving competition or interference (i.e., more similar to the suppression measured in RIF paradigms).

Across two studies, response times to related words in the unrelated condition were measured and compared to response times for words in the related condition, the latter not requiring suppression (Healey et al., 2014; Ngo & Hasher, 2017). Both studies showed reduced accessibility of related words in the unrelated condition, consistent with evidence for the role of suppression in rejecting a high probable response. Moreover, these suppression effects were shown to be reliable measures of group and individual differences. Older adults, who are known to have difficulty resolving interference (e.g., Amer, Campbell & Hasher, 2016; Hasher & Zacks, 1988; Lustig, May, & Hasher, 2001), showed a smaller suppression effect than the younger adults. Even among younger adults, some individuals showed a larger suppression effect and others showed a smaller effect: those who showed a larger effect performed better on operation span, a measure of working memory capacity known to correlate with other episodic memory measures (e.g., Hertzog, Dixon, Hultsch, & MacDonald, 2003; Kane & Engle, 2000).

The current study uses a variant of the semantic interference resolution paradigm (Ngo & Hasher, 2017) to explore electrophysiological evidence of differential processing for targets and interfering competitors in real time. The methods were modified here to obtain sufficient trials for EEG measurement. Specifically, similar to the previous study, the two-phase paradigm (i.e., generate a related response to some words and an unrelated response to others followed by a lexical decision task) was used. This procedure was doubled to create two alternating generation and test phases. Considering that our paradigm has not been used in the context of ERP measurements, we adopted a data-driven approach with no specific hypotheses regarding ERP markers of suppression or reduced accessibility. However, based on previous electrophysiological findings on inhibitory mechanisms during competitive retrieval (e.g., Johansson et al., 2007; Rass et al., 2010), we expected sustained late positivity, indicative of a suppression process, for unrelated responses in the generation task. Moreover, similar to the finding that stronger behavioral suppression effects are associated with better performance on memory tests (Healey et al., 2014), we predicted that participants who show stronger behavioral suppression effects should also show stronger frontal modulations.

## 2. Results

### 2.1. Overview

Following the procedures of Ngo & Hasher (2017), participants first verbally generated a related response to some cue words and an unrelated response to others (e.g., “PIZZA”), then completed a lexical decision task on the strongest associates of each cue word (e.g., "PEPPERONI") – see Figure 1. Since the cue words were chosen to activate strong associates, suppression was expected for associates of cues that required unrelated responses, and not those that required related responses. A baseline measure of the lexical decision task was obtained using counterbalanced control words that were not seen in the context of the experiment. In order to obtain a sufficient number of trials for EEG processing, both Phase 1 (verbal generation) and Phase 2 (lexical decision task) were repeated with new word pairs, selected and counterbalanced with the same criteria as Healey et al. (2014). Participants completed the first two phases immediately prior to the subsequent two phases.

### 2.2. Behavioral Results

The response time data for the generation tasks and the lexical decision tasks were averaged across phases. Consistent with previous findings (Healey et al., 2014; Ngo & Hasher, 2017), participants were significantly faster to generate a response in the Related condition ($M$ = 697ms, $SD$ = 245ms) than in the Unrelated condition ($M$ = 1124ms, $SD$ = 464), $t(23) = 6.45$ $p < .001$, $d = 1.15$ (see Figure 2). For the lexical decision task, however, a repeated measures ANOVA showed no differences in reaction time for the three trial types (Related, Unrelated and Control), $p = .3$ (see Figure 3), contrasting the results of previous studies. Post-hoc analyses showed similar findings for each block of generation task and lexical decision task.

### 2.3. Electrophysiological Results

#### 2.3.1. Generation task

ERPs recorded during the generation task were characterized by an early positive wave that started at about 100ms post stimuli onset, followed by a negative wave at 170ms and a positive deflection at about 200ms for both word types (related and unrelated) in parietal-occipital sites. This modulation was followed by a prolonged positivity for items in the Unrelated condition compared to Related condition, which persisted until the end of the trial (Figure 4). The early sensory evoked responses (i.e., P1, N1, and P2 waves) at occipital and parieto-occipital sites were comparable for related and unrelated words. A cluster-based permutation statistic revealed a significant difference in ERP amplitude between Related and Unrelated conditions (see Table 1). The ERPs elicited in the Unrelated condition were more positive over the central and left parietal areas between 703 and 930 ms after stimulus onset (Cluster 1, Table 1). This modulation showed an inversion in polarity over the right frontal and fronto-polar scalp area (Cluster 2, Table 1). The cluster-based permutation statistic also revealed two additional clusters that were comparable in distribution to that observer in the first cluster but peaked at a later latency (Cluster 3 peaked at 1033ms; Cluster 4 peaks at 1213ms). Both were characterized by greater positivity in the Unrelated than the Related condition over the parietal scalp area.

### 2.3.2. Lexical decision task

The ERPs elicited during the lexical decision task consisted of early visual sensory evoked responses, which were comparable across all stimulus types (i.e., Related, Unrelated, Control, and Nonwords). These sensory evoked responses elicited by word stimuli were followed by a late positive wave (i.e., late positive complex (LPC)) that peaked at about 500ms after stimulus onset over central-parietal and parietal scalp areas. The LPC elicited by nonword stimuli peaked at about 550-600ms after stimulus onset.

The clustered-based permutation ANOVA with four word types yielded several spatio-temporal clusters (Table 2), with the most prominent difference between 363 and 523ms post-stimulus onset over the central-parietal scalp region. This captures the latency shift mentioned previously and was characterized by greater negative amplitudes for nonwords compared to words from the Related, Unrelated, and Control conditions ($p < .0001$ in all cases, see Figure 5 and Table 2). The polarity was inverted at frontal sites for nonwords (Cluster 2, 389-514ms, $p <$ .001).

The observed negativity for nonwords compared to words is consistent with previous ERPs reported in visual lexical decision studies (e.g., Curran, 1999; Holcomb & Neville, 1990). This modulation was followed by two ERP differences at 718-802ms (Cluster 3, Table 2) and 701-857ms (Cluster 4, Table 2) post-stimulus onset. Both of which separated Related trials from the other trial types (Pairwise comparison, Table 2). Finally, a very early modulation was evident at 135-213ms along the right central electrode sites (Cluster 5).

Planned pairwise comparisons between nonwords and other trial types revealed similar results: items from the Nonword condition showed more negative amplitudes (all *p*s < .001) than the other word types over left central-parietal electrode sites around 300-500ms (see Clusters 1 and 2 for Related vs. Nonwords, Unrelated vs. Nonwords, and Control vs. Nonwords comparisons in Table 2). Nonword trials also maintained more negative amplitudes than Control items at 719-801ms and Unrelated items at 732-803ms ($p < .001$, see Cluster 3 of Nonword vs. Control and Nonword vs. Unrelated in Table 2). Lastly, from the post-hoc comparison between trials in the Related and Unrelated conditions, an early negativity was detected for Related trials in right central electrode sites (170-199ms, $p < .011$).

Since the lexical decision ERP results were driven mostly by differences from the Nonword condition, nonwords were excluded in the subsequent analysis to examine the critical trial types that may have more refined distinctions. Using only three word types (Related, Unrelated, Control), only one early modulation was evident at 135-207ms post-stimulus onset in the right central electrode sites: Related items showed more negative amplitudes than Unrelated and Control items (p = .029; see Figure 6). With respect to identifying a signature of suppression, the critical contrast of interest between items in the Unrelated condition vs. baseline (Control condition) was examined in a post-hoc pairwise comparison – trials from the Unrelated condition showed more negative amplitudes than control words at 242-289ms at fronto-central regions ($p$ = .014; see Figure 7 and Table 3). The remaining pairwise comparisons revealed a pattern of greater negative amplitude for Related items at 170-199ms compared to trials in the Unrelated ($p$ = .011) or Control condition ($p$ = .022) at 167-195ms, similar to the early modulation observed in initial analysis.

### 2.3.3. Behavioral and neural indices of suppression

As indicated by the behavioral results, suppression may not have been successful on every trial that required interference resolution. In a separate ERP analysis, we examined only participants who displayed optimal behavioral suppression performance in order to obtain a clearer representation of a suppression ERP signature. To identify good and poor suppressors, a suppression score (see Healey et al., 2014, Ngo & Hasher, 2017) was calculated for each participant by regressing lexical decision reaction times for items in the Unrelated condition on items in the Related condition. Then, participants were divided into two groups based on a median split on the residuals.

ERP analysis for the lexical decision task for good suppressors showed that control items have more positive amplitudes than the related and unrelated items in the left frontal-central sites ($p$ = 0.014). Only on the critical contrast of interest (Unrelated vs. Control condition) did the observed modulation remain significant (230-290ms, $p$ = .010). Poor suppressors, as identified by the residual median split, did not show any significant ERP differences across the scalp. On the generation task, good suppressors exhibited a similar pattern of results as reported in the group data: unrelated trials showed more positive amplitudes than related trials at 560-650ms ($p$

= .012), and again in left central-parietal sites at 745-940ms ($p < .0001$), but also more negative amplitudes in left frontal-central sites at 650-715ms, $p < .0001$. Poor suppressors also exhibited the main positive latency for unrelated trials in the left central-parietal sites, however, the effect reached electrodes further left of the hemisphere and towards the frontal areas. The positive amplitudes for unrelated trials appeared in a late 1150-1350ms window close to the central-parietal sites.

## 3. Discussion

The aim of the present study was to investigate the neurophysiological correlates of inhibitory mechanisms involved in suppressing irrelevant information that competes with the retrieval of target items. To this end, we tested participants on a task that required generation of a semantically related or unrelated word in response to a cue – a novel paradigm given that to-be suppressed information in the unrelated condition is never presented in the context of the experiment. Access to the primed or suppressed information in the related and unrelated conditions, respectively, was subsequently tested in a lexical decision task. The main electrophysiological findings can be summarized as follows: First, participants demonstrated a late positivity (starting at 700ms post stimulus onset) in central and left parietal sites for the Unrelated relative to the Related condition during the generation task. Second, participants showed more negative amplitudes (~ 200-300ms post stimulus onset) in fronto-central sites for unrelated (suppressed) relative to control items in the lexical decision task. Finally, participants showed an early negativity (150-215ms) in right central sites for related items relative to suppressed and control items during the lexical decision task.

The late positivity for the Unrelated condition in the generation task provides neurophysiological evidence of irrelevant item suppression during memory retrieval. In particular, this positivity was only evident in the high interference Unrelated condition that required the suppression of competing items for successful task performance. Support for the suppression role of this neural signature comes from other studies that have used similar tasks with inhibitory demands. For example, several studies have reported a similar positive-going slow wave (primarily at frontal sites, however) for no-think trials in the Think/No-Think paradigm (Bergström et al., 2007; Mecklinger et al., 2009; Waldhauser et al., 2012). This slow wave was hypothesized to reflect an inhibitory mechanism that restricts the access of unwanted or irrelevant memories (see Mecklinger, 2010). Similarly, in an RIF paradigm, sustained ERP positivity during retrieval practice was associated with the extent of induced forgetting of (suppressed) unpracticed items in a subsequent recall task (Johansson et al., 2007; see also Hellerstedt & Johansson, 2014, 2016; Rass et al., 2010). Taken together, the evidence suggests that inhibitory mechanisms, reflected by sustained positive-going ERPs, are involved in the suppression of automatically activated competing items that interfere with the memory retrieval of target items. This suppression might be characterized as a selective retrieval mechanism that allocates attentional resources to the retrieval of targets at the expense of competitors, or as a post-retrieval monitoring process that downregulates competitors after their automatic activation. Considering that retrieval cues are likely to automatically activate all related items, we postulate that the reported sustained late positivity reflects inhibition of spontaneously activated associates (e.g., Healey et al., 2014; Ngo & Hasher, 2017).

Similar to prior EEG investigations of suppression using Think/No-Think paradigms in which no behavioral differences were observed (Tomlinson et al., 2009), or where no-think (suppressed) items differed only from think items but not from baseline (Marx et al., 2008), this paradigm also did not yield significant behavioral differences between item types. The participants were evening or neutral-type young adults tested during an optimal time of day. Despite this, the below-baseline suppression effect in the lexical decision task as seen in previous studies was not replicated. It is possible that changes in the length of the experiment caused by the additional trials or inter-subject variability in suppression abilities (see Healey et al., 2014) may have contributed to the non-replication. Further, in general, the suppression effect is a small effect due to the fact that competitors are not meant to be eliminated from memory, but rather competitor accessibility only needs to be reduced until the interference is resolved.

Nevertheless, the neural data for the lexical decision task demonstrated evidence of suppression for items from the Unrelated condition. Particularly in the median split analysis, the negative amplitudes of suppressed items (~ 200-300ms post stimulus onset), seen in good suppressors, are similar to previous reports of decreased positivity of the P2 component for suppressed / unpracticed items on a recognition task in a retrieval-induced forgetting paradigm (e.g., Spitzer, Hanslmayr, Opitz, Mecklinger, & Bäuml, 2009). This suggests that neurophysiological evidence of previous item suppression is apparent early (< 300 ms post stimulus onset) when processing such items, and that overcoming that suppression possibly occurs within that timeframe for effective stimulus processing. Consistent with that hypothesis, previous studies have demonstrated that effective interference resolution in working memory paradigms is restricted to 300ms post stimulus onset (e.g., Gazzaley et al., 2008).

The neurophysiological data from the lexical decision task also showed an early negativity effect (150-215ms post stimulus onset) for related relative to suppressed and control items. Although there was no behavioral evidence of priming of related items in the current or previous (Healey et al., 2014; Ngo & Hasher, 2017) studies, this negativity might indicate a priming effect not captured through behavioral measures. Previous studies have shown early effects of item repetition at similar time intervals (starting at 150 ms post stimulus onset), which have been linked to priming (e.g., Bergström, O'Connor, Li, & Simons, 2012; Curran & Dien, 2003; Rugg, & Curran, 2007; Tsivilis, Otten, & Rugg, 2001). It is important to note, however, that these effects are typically *positive-going*, unlike the negative amplitudes shown in the present study. Future work will be important in further investigating whether related items show a priming effect on subsequent tasks.

In conclusion, our findings provide neurophysiological evidence that inhibitory mechanisms suppress competing items at retrieval. These findings complement previous studies demonstrating inhibitory retrieval mechanisms (e.g., Johansson et al., 2007; Waldhauser et al., 2012) and show that such mechanisms operate on automatically activated items that are not actually presented but are merely thought about in the context of an experiment.

## 4. Methods and Materials

### 4.1. Participants

Participants were 24 young adults (14 females) aged 18-28 recruited through the Rotman Research participant pool (Age: *M* = 22.8 years, *SD* = 3.3; Education: *M* = 16.2 years, *SD* = 2.2). All participants were native English speakers and received monetary compensation. Given that young adults' general circadian preference and period of peak arousal is in the afternoon (Hasher, Goldstein & May, 2005; May, Hasher, & Stoltzfus, 1993; Yoon, May, & Hasher, 1999), and previous research suggesting that suppression effect is shown during an optimal time of day (Ngo & Hasher, 2017), all participants were screened for evening or neutral chronotype using the Morningness-Eveningness Questionnaire[1] (MEQ; Horne & Östberg, 1976; *M* = 43.1, *SD* = 10.0),

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[1] MEQ (Horne &Östberg, 1976) scores range from 16-86; scores below 41 are classified as evening-types, scores from 42-58 are neutral, and scores above 59 denote morning-type chronotypes. Standard deviations are in parentheses.

and tested between 1:00 pm – 4:00 pm . Participants also completed the Shipley Vocabulary test (Shipley, 1946) to ensure adequate English fluency (*M* = 33.3, *SD* = 3.3). Data from two participants who scored morning-type on the MEQ, and one participant who scored below 50% on the Shipley vocabulary test were replaced.

### 4.2. Materials

One hundred and fifty cue-target pairs (e.g., PIZZA-PEPPERONI) were selected from the University of South Florida Free Association database (Nelson, McEvoy, & Schreiber, 2004) using the same selection criteria as Healey et al. (2014). Each target (i.e., the words on the lexical decision task) was the strongest associate to its cue. The word pairs were equated on forward and backward association strength, word length, word frequency, normed naming time, standard deviation of normed naming time, concreteness, and the strength of the next highest cue-to-target association. Six 25-pair lists were created and randomly assigned to be the Related, Unrelated, and Control conditions with three lists (one of each condition) used in each half of the experiment. List-condition assignments were counterbalanced across participants. The control items were used as a lexical decision speed baseline against which to test the presence versus absence of suppression effects for words in the Unrelated condition. The average word length of the target words was used to generate 150 pronounceable non-words using the English Lexicon Project database for the lexical decision task (Balota et al., 2007).

### 4.3. Procedure

In accordance with the procedures in Ngo & Hasher (2017), there were two main tasks in the experiment: a verbal generation task and a lexical decision task (Figure 1). These two tasks were repeated for a total of four phases to obtain a sufficient number of responses for EEG analysis. In the generation task, participants were required to verbally generate semantically related or unrelated responses to cue words into a microphone. A fixation cross on a white screen appeared before each trial, then “Related” in green font or “Unrelated” in red font indicated the task for the next word for 1000ms. For the Related condition, participants were instructed to “say the first word that comes to mind that is meaningfully related or strongly associated to the cue word.” For the Unrelated condition, participants were instructed to “say a word with as little relationship to the cue word as possible.” Following the task command, a cue word in black font appeared on screen for 1500ms, and then a question mark appeared and remained on screen for up to 4000ms or until the microphone detected a verbal response. The end of each trial was indicated by a fixation cross in a 1,500ms interstimulus interval (ISI) which followed the offset of the question mark and signaled the start of the next trial. This generation task was completed in Phase 1 and repeated in Phase 3 with new stimuli. In each phase, two of three lists of 25 cue words were presented as Related and Unrelated trials, randomly intermixed using a single random order with the constraint that no more than two trials of the same type occurred consecutively. The remaining list served as Control items. Thus, participants were shown a total of 50 words in Phase 1, and another 50 words in Phase 3. Word list-condition assignments were counterbalanced across participants.

The subsequent lexical decision tasks were completed in Phase 2 and repeated in Phase 4, which was the measure of post suppression access of competitors. The list of stimuli included associates of each cue from their respective preceding generation tasks, as well as 75 nonwords (e.g., GRIKE). That is, critical target words were associates of the 25 Related, 25 Unrelated, and 25 Control cue words from the preceding generation phase. A baseline measure for the lexical decision task was obtained using the counterbalanced Control words that were not seen in the context of the experiment. Participants used a key press to indicate whether each of a series of letter strings presented on screen was a word or non-word. Each stimulus was presented on screen for up to 4000ms or until a response was given, followed by a 1500ms ISI. Participants practiced the tasks involved in the two phases of the experiment prior to the experimental trials to ensure proper understanding of the task instructions and appropriate timing of verbal responses into the microphone to minimize the number of missed trials.

### 4.4. Behavioral Data Processing

Following the reaction time data processing procedures used in Ngo & Hasher (2017), generation task trials and their corresponding target words on the lexical decision task were removed from analysis if a response could not be produced within the time allowed, if a response was repeated, or if unintentional sounds (e.g., fillers such as “um”) advanced the trial before a response was produced. The trimming rate was 2.3% of responses. Then, reaction time data in each phase were trimmed at 2.5 standard deviations of the mean per participant per condition. No additional trials were removed from the generation phases, and 2.4% of trials were removed from the lexical decision tasks.

### 4.5. Electrophysiological Recording and Analysis

Neuroelectric brain activity was recorded and digitized continuously using a Biosemi ActiveTwo system (BioSemi V. O. F., Amsterdam, Netherlands), with a bandpass of 0.16 – 100 Hz and sampling rate of 512Hz. The electroencephalographic (EEG) signals were recorded from an array of 76 electrodes, grounded by an active Common Mode Sense (CMS) and a passive Driven Right Leg (DRN) passive electrode. Ten additional electrodes were placed below the hair line (both mastoids, both pre-auricular points, outer canthus of each eye, inferior orbit of each eye, and two facial electrodes) to monitor eye movements and to cover the whole scalp evenly. The latter is important because an average reference was used (i.e., the average of all scalp EEG channels as the reference for each EEG channel) for ERP analyses. All off-line averages were computed using Brain Electrical Source Analysis software (BESA, version 5.2.4; MEGIS GmbH, Gräfelfing, Germany). For all averages, the epoch included 200 ms of pre-stimulus activity and 1,500 ms of post-stimulus activity to highlight the time course of neural activity following the probe. ERPs were averaged separately according to electrode position and target condition (Related or Unrelated in Phase 1; Related, Unrelated, Control and Non-words in Phase 2). Each average was baseline-corrected with respect to the pre-stimulus interval and digitally low-pass filtered at 40 Hz.

A set of ocular movements was obtained using the electrodes placed at the outer canthus and at the inferior orbit of each eye for each participant before and after the experiment (Picton et al., 2000). Averaged lateral eye movements, vertical eye movements, and eye blinks were calculated and used to generate components through principal component analysis. The scalp projections of these components were then subtracted from the experimental ERP averages to minimize ocular contamination such as blinks, saccades, and lateral eye movements for each individual.

The ERP data were subjected to non-parametric cluster-based permutation testing using BESA Statistics software (Statistics 2.0, MEGIS GmbH, Gräfelfing, Germany). A preliminary step identified clusters both in time (adjacent time points) and space (adjacent electrodes) where the ERPs differed between the conditions. The interval included the pre- and post-stimulus interval. For cluster building, we used 4 cm spacing between the electrodes, which led to around four neighbors per channel. We used a cluster alpha of .05 for cluster building. A Monte-Carlo resampling technique (Maris and Oostenveld, 2007) was then used to identify those clusters that had higher values than 95% of all clusters derived by random permutation of the data. This nonparametric permutation statistic is no longer subject to the multiple comparisons problem (for an in-depth overview of permutation statistics as implemented in BESA Statistics see Maris and Oostenveld, 2007). The number of permutations was set at 1,000. We performed two analyses: The first compared the two conditions in the generation phase according to trial type (Related vs. Unrelated), and the second used an ANOVA and paired *t*-tests to compare amplitude difference between the four conditions in the lexical decision phase (Related, Unrelated, Control, and Nonword). Only correct lexical decision trials were included in the analyses.

# Acknowledgements

We thank Ricky Chow for assistance in preparing the illustrations and all participants for their involvement in this study. This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada to CA.

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## Figure Legend

*Figure 1*. Summary of the paradigm.

*Figure 2*. Mean reaction time on generation tasks averaged across phases, as a function of word type (Related or Unrelated). Error bars show standard errors.

*Figure 3*. Mean reaction time on lexical decision tasks averaged across phases, as a function of word type (Control, Related, or Unrelated). Error bars show standard errors.

*Figure 4*. **a)** Group mean event-related potentials elicited by the Related and Unrelated words during the generation task. In this and the subsequent figures, the negativity is plotted upward. Grey areas indicate time intervals with statistically significant differences between conditions. POz = midline parieto-occipital. **b)** Topographical iso-contour maps (bird's-eye view) for Related, Unrelated, and the corresponding difference wave between the Related and Unrelated condition during the time window of the significant cluster # 1, 2, 3, and 4 from Table 1. The dark dots on the iso-contour maps indicate the electrodes that are part of the patio-temporal cluster.

*Figure 5*. **a)** Group mean event-related potentials elicited during the lexical decision tasks for Related, Unrelated, Control, and Non-words conditions. The grey area indicates the time interval with statistically significant differences between Non-words and the other word types ($p < .0001$). CP1 = left central parietal. **b)** Topographical iso-contour maps (bird's-eye view) for difference wave between the Related, Unrelated, Control condition and the non-words condition for cluster # 1 and 2 from Table 2. The dark dots on the iso-contour maps indicate the electrodes that are part of the patio-temporal cluster.

*Figure 6.* **a)** Group mean event-related potentials elicited during the lexical decision tasks for the three critical conditions (Related, Unrelated and Control). The grey area indicate time intervals with statistically significant differences between conditions (p < .029). C6 = right central. **b)** Topographical iso-contour maps (bird's-eye view) associated with the pairwise comparison. The dark dots on the iso-contour maps indicate the electrodes that are part of the patio-temporal cluster.

*Figure 7.* Topographical iso-contour map of the difference wave of critical contrast of interest (Unrelated and Control conditions) during the time window of the significant cluster at 242-289ms (Table 3). A significant modulation is shown in the left fronto-central electrode sites. Left panel is the top (bird's-eye) view and right panel is the right view.

## Figures

Figure 1

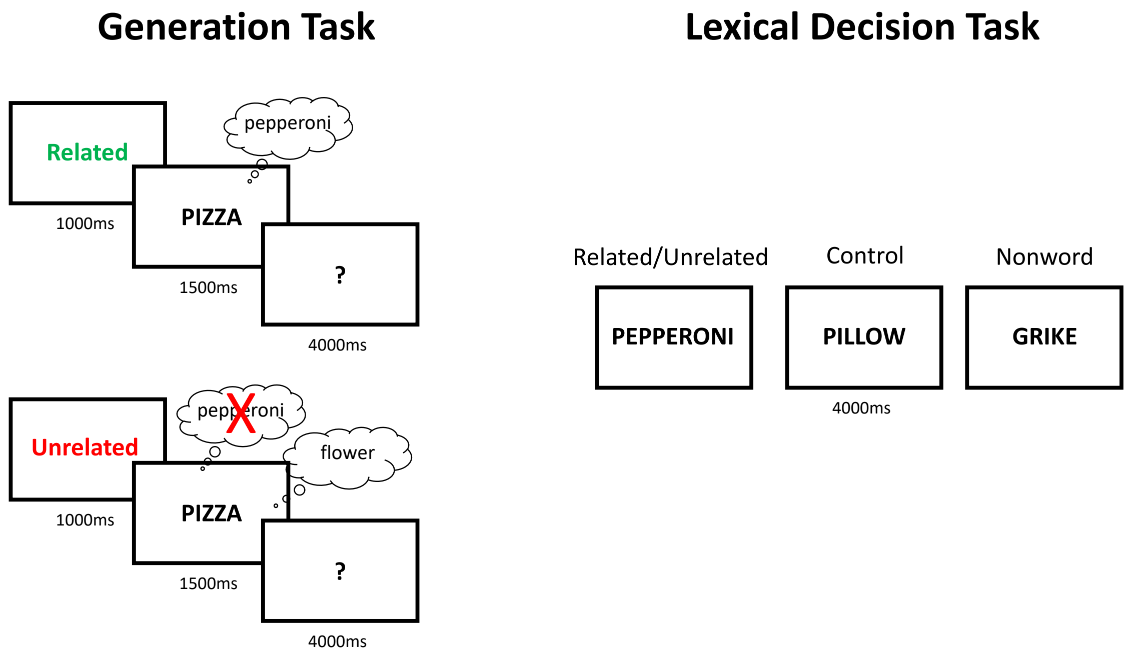


Figure 2

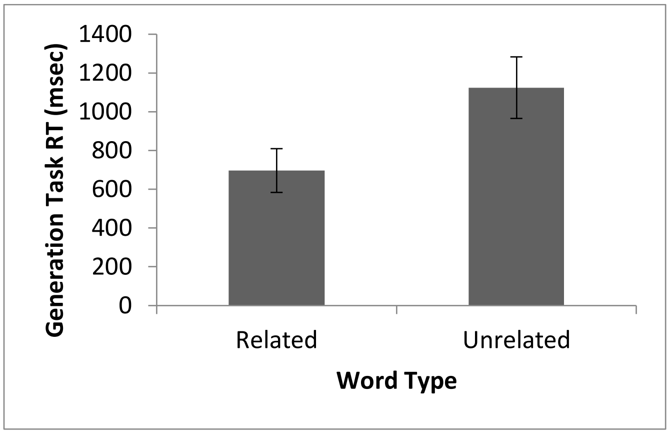


Figure 3

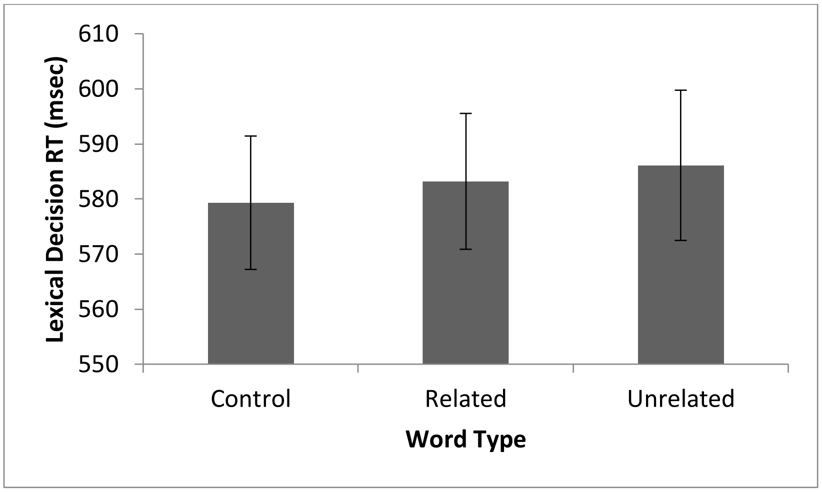


Figure 4

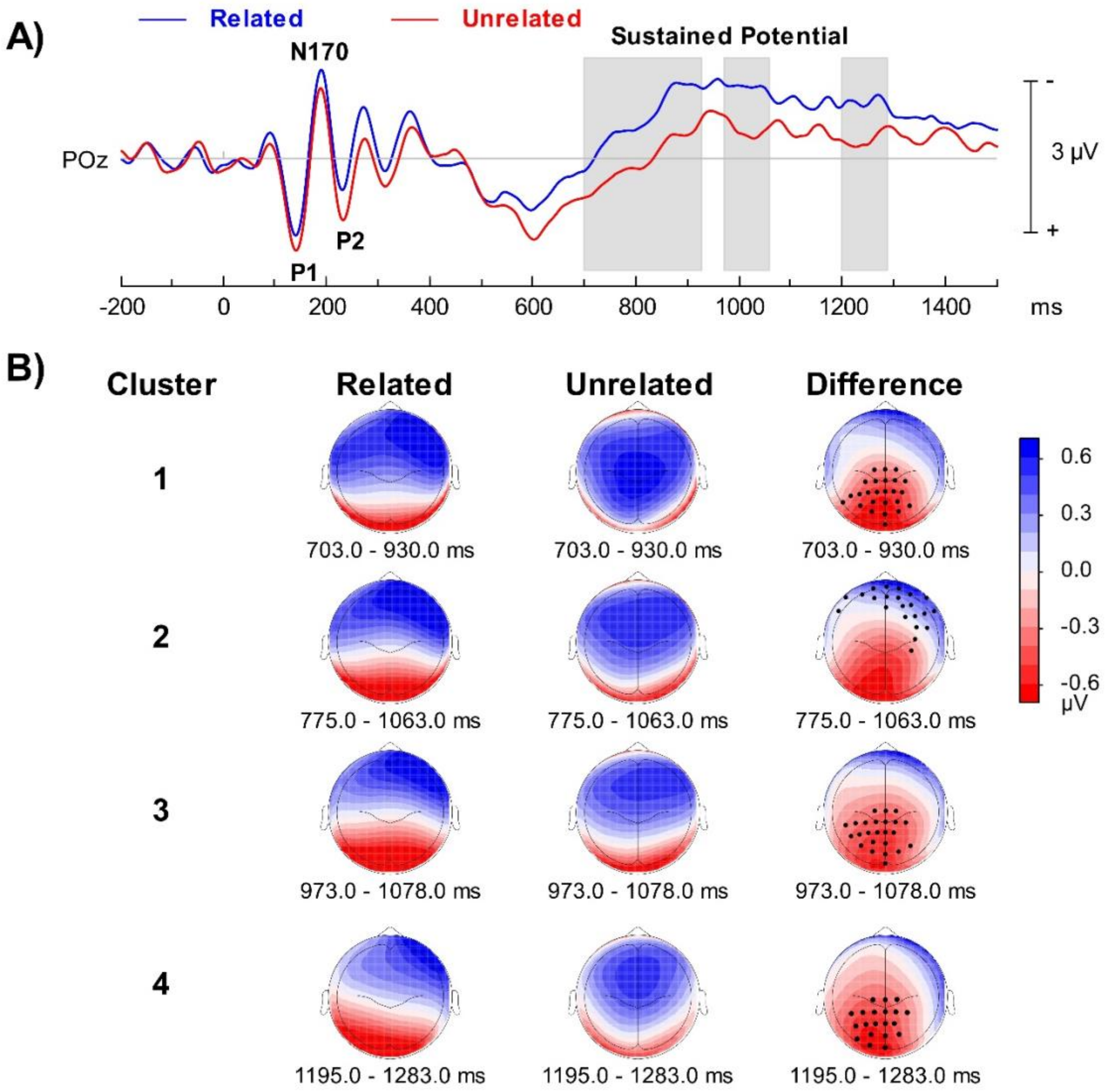

A)
Related
Unrelated
Sustained Potential
N170
POz
P1
P2
-
3 μV
+
-200
0
200
400
600
800
1000
1200
1400
ms
B)
Cluster
Related
Unrelated
Difference
1
703.0 - 930.0 ms
703.0 - 930.0 ms
703.0 - 930.0 ms
2
775.0 - 1063.0 ms
775.0 - 1063.0 ms
775.0 - 1063.0 ms
3
973.0 - 1078.0 ms
973.0 - 1078.0 ms
973.0 - 1078.0 ms
4
1195.0 - 1283.0 ms
1195.0 - 1283.0 ms
1195.0 - 1283.0 ms
0.6
0.3
0.0
-0.3
-0.6
μV

Figure 5

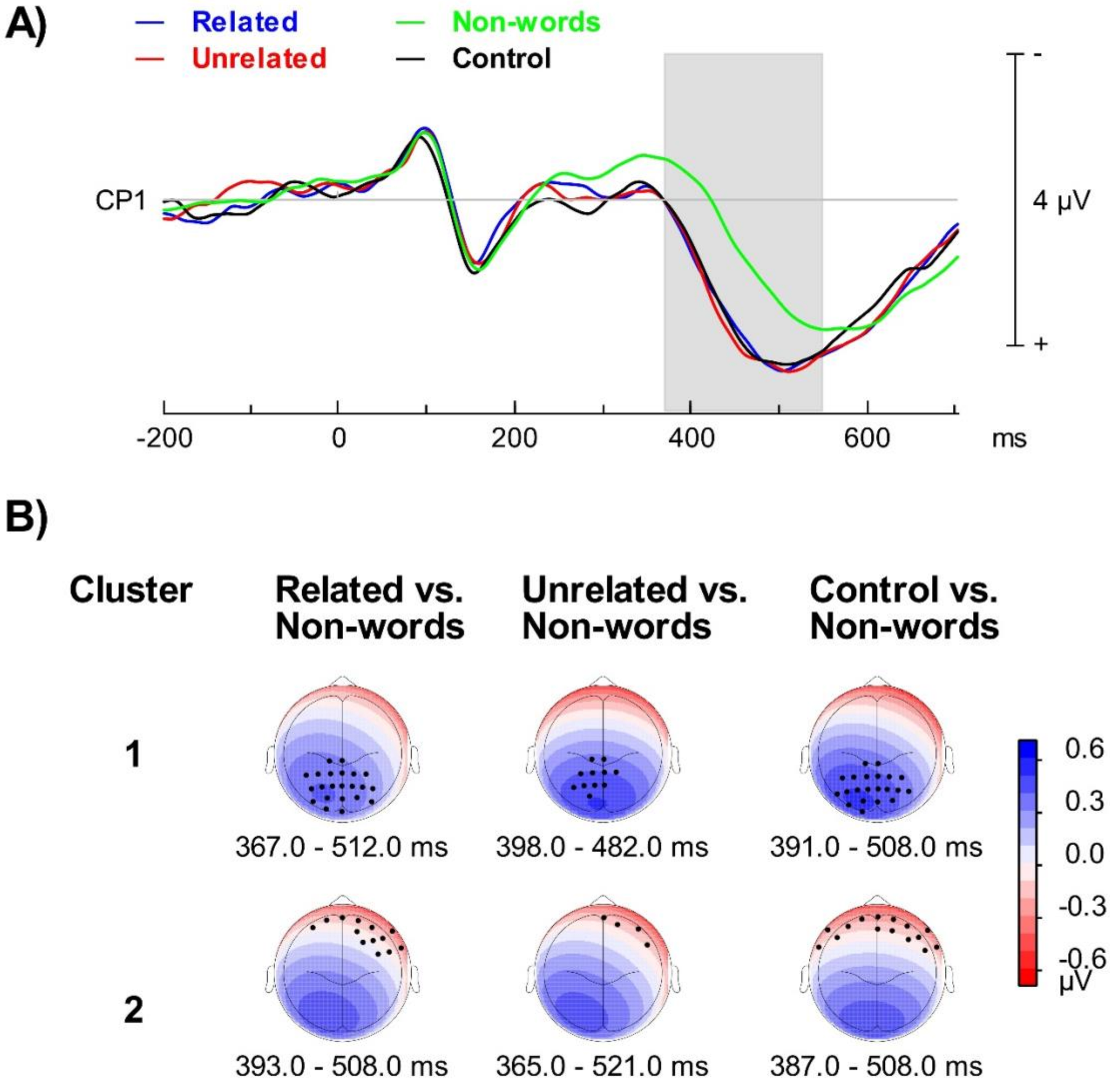

A)
Related
Unrelated
Non-words
Control
CP1
-
4 μV
+
-200
0
200
400
600
ms
B)
Cluster
Related vs. Non-words
Unrelated vs. Non-words
Control vs. Non-words
1
367.0 - 512.0 ms
398.0 - 482.0 ms
391.0 - 508.0 ms
2
393.0 - 508.0 ms
365.0 - 521.0 ms
387.0 - 508.0 ms
0.6
0.3
0.0
-0.3
-0.6
μV

Figure 6

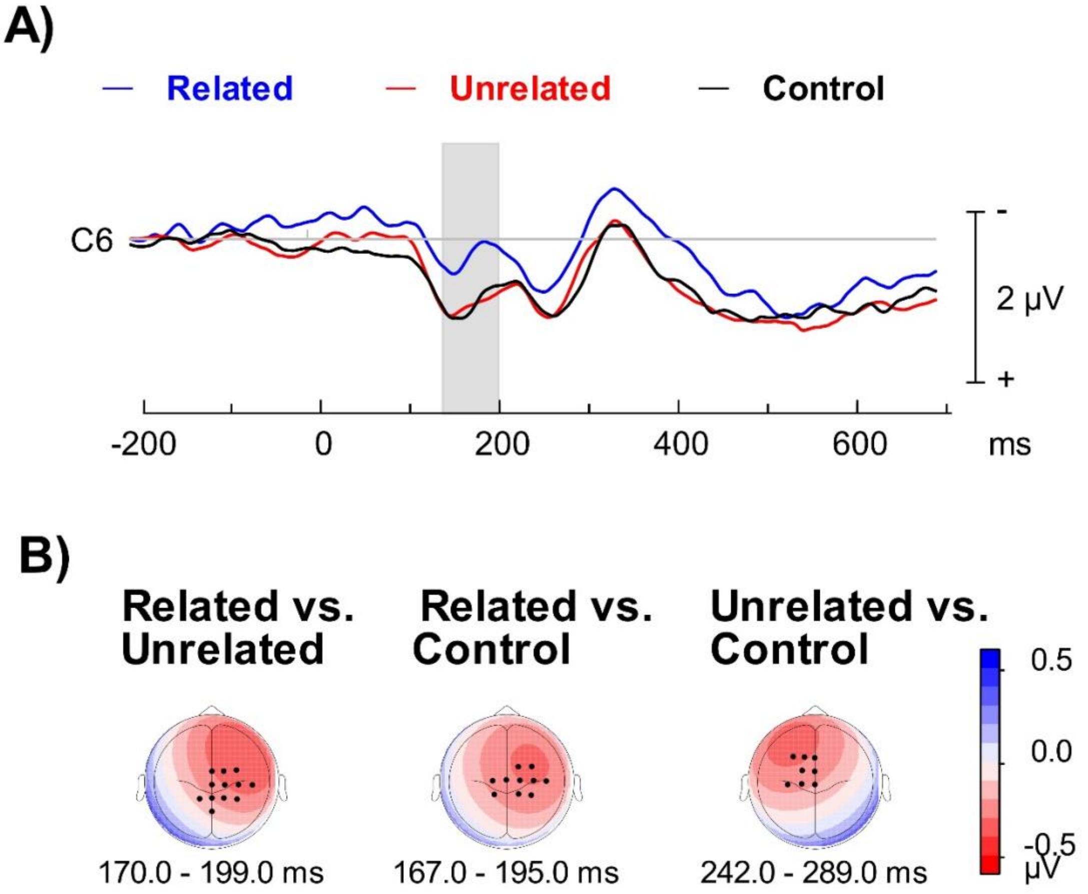
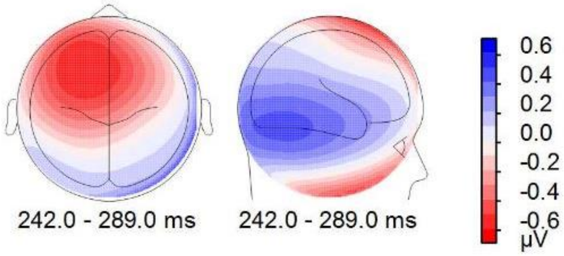

A)
Related
Unrelated
Control
C6
-
2 µV
+
-200
0
200
400
600
ms
B)
Related vs. Unrelated
Related vs. Control
Unrelated vs. Control
0.5
0.0
-0.5
µV
170.0 - 199.0 ms
167.0 - 195.0 ms
242.0 - 289.0 ms

Figure 7



## Tables

**Table 1: Summary of the channel level cluster-based permutation statistics for Related vs. Unrelated items in the Generation Task.**

| **Cluster** | **Latency (ms)** | ***p*-value** | **Electrodes** |
|---|---|---|---|
| **1** | 703-930 | $p < 0.001$ | C1, CP3, CP1, P1, P3, P5, P7, P9, PO7, PO3, O1, Iz, Oz, POz, Pz, CPz, Cz, C2, CP4, CP2, P2, P4, PO8, PO4, O2 |
| **2** | 775-1063 | $p < 0.001$ | FP1, AF7, AF3, FPz, FP2, AF8, AF4, AFz, Fz, F4, F6, FT8, FC6, FC4, C6, T8, CP6, P6, FT9, FT10, F9, F10, LO1, LO2, IO1, IO2 |
| **3** | 973-1078 | $p < 0.003$ | C1, TP7, CP5, CP3, CP1, P1, P3, P5, P7, PO7, PO3, O1, Iz, Oz, POz, Pz, CPz, Cz, C2, CP4, CP2, P2, PO8, O2 |
| **4** | 1195-1283 | $p < 0.006$ | C1, CP5, CP3, CP1, P1, P3, P5, PO7, PO3, O1, Oz, POz, Pz, CPz, Cz, C2, CP4, CP2, P2, PO4 |

**Table 2: Summary of the channel level cluster-based permutation statistics for pairwise comparisons of 4 trial types (Related, Unrelated, Control, and Non-words) in the Lexical Decision Task. Cluster 6 of the omnibus, although significant, was not included as it was a spurious cluster within the baseline interval.**

| Comparison | Cluster | Latency (ms) | *p*-value | Electrodes |
|---|---|---|---|---|
| **Omnibus** | 1 | 363-523 | $p < 0.000$ | FC5, FC3, C1, C3, C5, CP5, CP3, CP1, P1, P3, P5, P7, PO7, PO3, O1, Oz, POz, Pz, CPz, Cz, CP4, CP2, P2, P4, P6, PO8, PO4, O2 |
| | 2 | 389-514 | $p < 0.001$ | FP1, AF7, AF3, F3, F7, FC5, FPz, FP2, AF8, AF4, AFz, F2, F4, F6, F8, FT8, FC6, FT9, FT10, F9, F10, LO1, LO2, IO1, IO2 |
| | 3 | 718-802 | $p < 0.005$ | C3, T7, TP7, CP5, CP3, CP1, P1, P3, P7, PO3, Pz, CPz, P2, P4, P6, P8, P10, PO4 |
| | 4 | 701-857 | $p < 0.007$ | FP1, AF3, F1, FPz, AF8, AF4, AFz, Fz, F2, F4, F6, F8, FC4, FC2, FCz |
| | 5 | 135-213 | $p < 0.035$ | C1, CP1, P1, Pz, CPz, FC6, FC4, FC2, FCz, Cz, C2, C4, C6, T8, CP4, CP2 |
| **Related vs Unrelated** | 1 | 170-199 | $p < 0.011$ | CP1, Pz, CPz, FC4, FC2, FCz, Cz, C2, C4, C6, CP4, CP2 |
| **Related vs Nonwords** | 1 | 367-512 | $p < 0.000$ | C1, CP5, CP3, CP1, P1, P3, P5, PO7, PO3, O1, Oz, POz, Pz, CPz, Cz, CP4, CP2, P2, P4, P6, PO8, PO4 |
| | 2 | 393-508 | $p < 0.001$ | FP1, AF7, FPz, FP2, AF8, AF4, F4, F6, F8, FT8, FC6, FT10, F10, LO2, IO2 |
| **Unrelated vs Nonwords** | 1 | 387-508 | $p < 0.000$ | C1, CP3, CP1, P1, P3, P5, PO3, Pz, CPz, Cz, CP2 |
| | 2 | 398-482 | $p < 0.001$ | FP2, AF8, FT10, F10, LO2, IO2 |
| | 3 | 732-803 | $p < 0.001$ | FPz, AF4, AFz, Fz, F2, F4, F6, FC2 |
| **Control vs Nonwords** | 1 | 365-521 | $p < 0.000$ | C1, CP5, CP3, CP1, P1, P3, P5, P7, PO7, PO3, O1, POz, Pz, CPz, Cz, CP4, CP2, P2, P4, P6, PO4 |

|  |  |  |  |
|---|---|---|---|
| 2 | 391-508 | $p < 0.001$ | FP1, AF7, F7, FPz, FP2, AF8, AF4, AFz, F6, F8, FT8, FT9, FT10, F9, F10, LO1, LO2, IO1, IO2 |
| 3 | 719-801 | $p < 0.001$ | CP3, CP1, P3, Pz, CPz, P2, P4 |
| 4 | 242-301 | $p < 0.001$ | FC1, C1, C3, Fz, FC4, FC2, FCz, Cz |

**Table 3: Summary of the channel level cluster-based permutation statistics for pairwise comparisons of 3 trial types (Related, Unrelated, and Control) in the Lexical Decision Task.**

| Comparison | Cluster | Latency (ms) | *p*-value | Electrodes |
|---|---|---|---|---|
| **Omnibus** | 1 | 135-207 | $p < 0.029$ | C1, CP1, Pz, CPz, FT8, FC6, FC4, FC2, FCz, Cz, C2, C4, C6, CP4, CP2 |
| **Related vs Unrelated** | 1 | 170-199 | $p < 0.011$ | CP1, Pz, CPz, FC4, FC2, FCz, Cz, C2, C4, C6, CP4, CP2 |
| **Related vs Control** | 1 | 167-195 | $p < 0.022$ | C1, CP1, FC4, FC2, Cz, C2, C4, C6, CP4, CP2 |
| **Unrelated vs Control** | 1 | 242-289 | $p < 0.014$ | F1, F3, FC1, C1, C3, Fz, FCz, Cz |