A NEURAL ELECTROPHYSIOLOGICAL STUDY OF LEXICAL STRESS PARSING

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Based on past theory and empirical results on the processing of lexical-level suprasegmental information, a Cascading Inhibition model for lexical stress parsing was proposed, in which lexical stress is situated at a different level from segmental information in a hierarchical structure and influences lexical identification via two mediating levels. These levels were proposed to direct lexical identification in a parallel and statistical manner.

Because under this model, phonetic and lexical processing are both under the influence of lexical stress parsing, and because pre-attentive phonetic and lexical processing are both lateralized to the left hemisphere, two hypotheses were proposed: ***Hypothesis A***: Lexical stress parsing can modulate lexical selection without the presence of segmental information; ***Hypothesis B***: Lexical stress parsing is lateralized to the left hemisphere.

To test these hypotheses, Noun-Verb homonym pairs (e.g. **IN**sult vs in**SULT**) were used as targets in experimental listening conditions. Sentences that strongly predicted the Noun member (e.g. **IN**sult**)** of the pair were spliced to end with the Verb member (e.g. in**SULT)** to create lexical stress anomalies. In the critical conditions, when targets were low-pass filtered to remove segmental information, listeners had to rely on the Lexical Stress Pattern for lexical identification of the target. For control conditions, the prosody changes associated with a shift in sex of the speaker (Gender Shift) were investigated in an auditory oddball paradigm. It was predicted that processing nonlinguistic prosody such as Gender Shift, in contrast to lexical stress, would be lateralized to the right hemisphere.

Online EEG was recorded from right-handed young normal monolingual English speakers. For experimental conditions, the filtered Verb Lexical Stress Pattern induced larger N400 than filtered Noun Lexical Stress Pattern, and this component was left-lateralized, supporting both hypotheses. Global Field Power and source estimation demonstrated that the neural networks for parsing Lexical Stress Pattern were similar to those for processing segmental information. In control conditions, the P300 induced by Gender Shift was right lateralized. Overall, many features of the CI model were supported, but a direct influence from the prosody level to the lexical identification level is proposed to incorporate results from the current study.

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PREFACE

I wish to express my sincerest gratitude to my PhD advisor Dr. Connie Tompkins for her help in forming conceptualizations and theoretical perspectives of this study, and her guidance in my writing and most of all, allowing me to think and work in my own way. I would like to thank Dr. Deborah Moncrieff for her guidance in conducting the EEG experiment. It could not have worked without her. I would like to thank Dr. Sheila Pratt and Dr. Shari Baum for their extremely insightful comments, suggestions and criticism in my previous manuscripts.

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1.0 THE INFLUENCE OF LEXICAL STRESS ON LEXICAL SELECTION AND THE CASCADING INHIBITION MODEL

This chapter is aimed at introducing the theoretical framework for the proposed study hypotheses: (1) lexical stress influences lexical selection indirectly by activating the phonology of the word; (2) lexical stress parsing, the term used herein to describe the specific operations of suprasegmental information processing for online word recognition under the proposed cascading inhibition model, is hypothesized to be lateralized to the left hemisphere of the brain.

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A detailed discussion of linguistic prosody lateralization theories will be left to Chapter 2. The current chapter will be devoted to 1) reviewing previous studies that specifically focused on investigating the influence of lexical stress on auditory word recognition; 2) introducing the cascading inhibition model, and explaining the mechanism of how lexical stress parsing acts on lexical selection; 3) proposing the hypothesis of left lateralization of lexical stress parsing and comparing two previous studies with designs similar to that of the proposed study.

Thus, for addressing the above three aims, this chapter will be organized as follows:

Section 1.1 reviews past studies on lexical stress processing. By classifying the studies according to the tasks applied, an interesting pattern emerges. That is, for studies whose tasks tapped only phonological representations, significant influences of lexical stress on word recognition have been found consistently. On the other hand, influences of lexical stress were not found in studies that used “lexical concept activation” tasks, which involve the activation of both the phonological and semantic representations of target lexicon. These two kinds of studies will be discussed separately, followed by studies that have experiments involving both kinds of tasks, which addressed this task-related discrepancy specifically.

Section 1.2 first describes a working model for online auditory word recognition, an adapted version of the “cascading inhibition model.” This model is built on past working models and the results and implications of the studies reviewed in *Section 1.1*. It will also be explained how this model can accommodate past theoretical frameworks on lexical access. Then “lexical stress parsing” will be defined explicitly in the context of this working model.

At the end of this section, the statistical nature of lexical stress parsing will be discussed, primarily drawing on data from nonnative speakers and infants. This line of research reminds us that in real online language comprehension and language acquisition, suprasegmental information might be learned and used in a statistical manner, just like segmental information. It also implies that any model for online word recognition, including the cascading inhibition model, should be sensitive to statistical occurrences of lexical stress and should be capable of adapting to statistical change in the ambient language environment.

In *Section 1.3*, the current research questions will be proposed. Two empirical studies that pointed to the direction of this proposal will be examined. Then I will compare and contrast the current design with these two studies and discuss how the proposed current study will advance the literature on lexical stress processing.

In *Section 1.4*, critical points of this chapter will be summarized.

1.1 CLASSIFYING STUDIES OF LEXICAL STRESS PROCESSING

1.1.1 Rationale for classifying

The history of investigating the influences of lexical stress on word recognition has several theoretical turning points. Early studies concluded that lexical stress has no influence on lexical activation (Cutler, 1986; Cutler & Clifton, 1984). Pairs of words that are minimally contrasted by lexical stress (such as FORbear vs forBEAR, stressed syllable indicated in CAPS, same in the following) were found to be functionally "homophonous"(Cutler, 1986, p. 201). That is, upon hearing one of them,both members of a pairwere activated in the mental lexicon.

These influential early studies used an "associative priming" paradigm, in which the target word is not a member of the word pair itself, but a word that has a related meaning. For example, in Cutler (1986) study, a word pair minimally contrasted by lexical stress was "forbear" used as noun (first syllable stress) or as verb (second syllable stress). However, the target word was either "ancestor" (related to the noun) or "tolerate" (related to the verb).

Later, it was discovered that experiments that used "fragment priming" instead of "associative priming" yielded significant results of lexical stress. "Fragment priming" uses a portion of the word of interest as a prime and the same word as the target. Van Donseelar, Koster, and Cutler (2005) proposed that the underlying reason for the inconsistency in results is that these two paradigms tap different processes. Lexical stress can indeed facilitate the activation of the phonological representation of the target lexical entry, however, phonological representation activation does not necessarily guarantee activation of the related concept representation (Norris, Cutler, McQueen, & Butterfield, 2006). In comparing nine priming experiments that included both associative priming and fragment priming, Norris et al. (2006) proposed that the activation of phonological word representations and of lexical concept representations are two distinctive processes in word recognition.

Van Donseelar et al. (2005) and Norris et al. (2006)'s proposal led to the idea of reviewing the literature based on the nature of the tasks. By doing this, a very clear pattern emerged. **Studies involving tasks directly activating phonological representations found significant effects of lexical stress.** These tasks include fragment priming (Cooper, Cutler, & Wales, 2002; Friedrich, Kotz, Friederici, & Alter, 2004; Soto-Faraco, Sebastián-Gallés, & Cutler, 2001; van Donselaar, Koster, & Cutler, 2005), onset gating (Arciuli & Cupples, 2004; Lindfield, Wingfield, & Goodglass, 1999; Wingfield, Lindfield, & Goodglass, 2000), word shadowing (Slowiaczek, 1990), and phoneme migration (Mattys & Samuel, 2000).

In contrast, **studies that have tasks involving "activation of lexical concepts" did not find significant results of lexical stress.** These tasks include associative priming (Cutler, 1986; van Donselaar, et al., 2005), lexical decision for isolated words (Cutler and Clifton,1984), and monitoring of a phoneme target after the word of interest (Small, Simon, & Goldberg, 1988). *

In *Section 1.1.2* and *Section 1.1.3*, the results of these two kinds of studies will be reviewed respectively. Then I discuss two studies that use both kinds of tasks and summarize this portion of literature as a whole in *Section 1.1.4*.

1.1.2 Lexical Stress activates the phonological representation of a word

There is a technical difficulty in conducting fragment priming in English: words contrasted by lexical stress usually are contrasted by vowel reduction as well. For example, when the word "address" is used as verb, the unstressed first vowel is reduced to a schwa. When it is used as a noun, the stressed first vowel is not reduced. Therefore, listeners can use this property alone as a cue to contrast the pair. This vowel reduction phenomenon is so common that only 11 pairs of two-syllable words were claimed to be contrasted minimally by lexical stress alone (Cutler, 1986).

**Note*: In Small et al. (2005), the target phoneme was embedded after the word of interest. Previous research has shown that if the preceding word is accessed quickly, the target phoneme will be detected as well (Rastatter & Gallaher, 1982). Thus, though this appears to be a phonological task, it does not tap the phonological representation of the word of interest.

Perhaps for this reason, the first fragment priming study on lexical stress came from Spanish (Soto-Faraco, Sebastian-Galles, & Cutler, 2001). In Spanish, polysyllabic words that contrasted by lexical stress do not differ in vocalic features (i.e. no reduction in vowels).

In this cross-modal priming experiment, the first two syllables of three-syllable words were presented as auditory primes, at the end of neutral carrier sentences. Visual targets appeared immediately at prime offset. Participants were asked to make a lexical decision judgment (i.e. judging whether the target is word or nonword) for the visual target, and lexical decision times were measured from prime offset.

The target words were presented in three conditions: stress-matched, stress-mismatched, and control. In the stress-matched condition, the first two syllables of the targets were matched to the auditory primes in both segmental and suprasegmental information (e.g. prime: PRIN, target: PRINCIpe). In the stress-mismatched condition, the first two syllables of the target were matched to segmental information but not suprasegmental information of the auditory primes (e.g. prime: PRIN, target: prinCIPIO). In the control condition, the target syllables were segmentally different from the prime (e.g. prime: mos, target: PRINcipe).

The resultant reaction times were significantly faster for stress-matched targets than for the controls. Reaction times for the control condition, on the other hand, were significantly faster than for prime-target pairs with mismatched stress.

Two conclusions can be drawn from Soto-Faraco et al. (2001) study. First, matching of both segmental and suprasegmental characteristics speeded lexical decisions. Second, an inhibition effect occurred in the stress-mismatched condition. It is possible that when two lexical candidates were segmentally compatible with the prime fragment, information from the stress pattern gave an advantage to the stress-matched candidate, thereby biasing the competition process against the mismatched lexical item. The stress-mismatched candidate was therefore inhibited. As will be discussed later, this inhibition implies a selection process from a set of activated lexical candidates. However, one caution to consider is that the lengths of the visual targets were not rigorously controlled. The average difference between targets in the two conditions is about one to three letters. This could be a potential confound for interpreting the lexical decision times, in that the early stress targets were usually longer than their later stress counterparts. Thus, the late stress targets might have quicker response times simply because they are shorter, potentially creating an inflated interaction between conditions and stress patterns.

In sum, strong effects from lexical stress on lexical selection were found in Spanish. In order to see whether this effect was language specific, van Donselaar et al. (2005) and Cooper et al. (2002) did similar studies in Dutch and English, respectively.

In the Dutch study, the fragment primes were truncated to different lengths in two experiments. In the first experiment, the primes were three-syllable long. For example, when the target word is “okTOber” (October), the matched prime was “okTO” whereas the mismatched prime was “OCto” (from “Octopus”). There was also a control prime provided, for example, eufo- (from euforIE, “euphoria”). All the acoustic parameters of the targets, including total durations, averaged intensity and Fo were well controlled in this study.Young native Dutch speakers were instructed to make a lexical decision (word vs nonword) on the target word.

Again, the reaction times for the mismatched stress condition were significantly slower than the control condition, which were in turn significantly slower than the matched stress condition. The same pattern was also obtained in the error analysis, in which the matched stress condition had the fewest errors, and the mismatched stress condition had the most. In sum, the result pattern of three-syllable fragment priming in Dutch appeared very similar to the Spanish study.

In the second experiment of the same study, the primes were truncated to a shorter length: one syllable. Thus, participants could only hear whether the first syllable was stressed or not. The results showed that reaction times were significantly faster in the stress matched condition than control condition. However, the reaction times of stress mismatched condition did not differ significantly from the control condition. Therefore, it was suggested that though single-syllable primes can signal the lexical stress pattern sufficiently to facilitate the matched stress condition, the activation was not strong enough to resolve the competition between the matched prime and mismatched prime.

Cooper et al. (2002) circumvented the technical problem of prevalent vowel reduction accompanying weak syllables in English by constructing two-syllable fragment primes with vowel reduction at a fixed place, followed by three-syllable targets. An example for this was to use “ADmi-“as a prime, followed by “admiral” (first syllable stress) in the matched condition and “admiration” (third syllable stress) in the mismatched condition. Because in both three-syllable words the second vowel is reduced, listeners can only rely on the suprasegmental information for cues. In the control conditions, the primes were the first two syllables of multi-syllabic words that were equated for occurrence frequency with the matched and mismatched primes. For example, the control primes for the target “admiral” were explan- (truncated from explanation) and propo- (from proposition). Thus, the control primes neither matched the segmental nor suprasegmental information of the targets.

In this experiment, both English and Dutch speakers were instructed to do a lexical decision task, in order to see whether different linguistic backgrounds would affect the nature of reliance on suprasegmental information.

The results showed that, for English speakers, the matched condition yielded the fastest reaction times, and there was no significant difference in reaction times between the mismatched condition and the control condition. Dutch speakers showed a different pattern: both matched and mismatched conditions were responded to significantly faster than the control condition. However, the reaction times for the matched condition were still significantly faster than those for the mismatched condition.

In sum, these results suggest that while matched lexical stress in English can facilitate lexical processing by activating phonological representations, this information is not strong enough to cause inhibition of the mismatched stimuli. The exploitation of suprasegmental information of nonnative speakers was even weaker than that of the native speakers.

In a second experiment, Cooper et al. (2002) shortened the length of the prime to one syllable. For example, the stressed fragment "MU" was used to prime either "music" (matched) or "museum" (mismatched). The results showed that, for both groups, reaction times were significantly faster for the matched condition than for the mismatched condition, which was in turn was significantly faster than the control condition. This pattern showed that the exploitation of suprasegmental cues for lexical selection in native speakers was further attenuated by a shortened prime.

Viewing the Cooper et al. (2002) and van Donseelaar et al. (2005) studies together, it can be inferred that perhaps the adequacy of lexical stress information (indicated by the length of the fragment) and linguistic background are both critical factors to determine the effectiveness of phonological activation by lexical stress pattern. Cooper et al. (2002) explained the discrepancy between English and Dutch speakers from two perspectives. First, lexical stress may be exploited to a greater extent in other languages such as Dutch and Spanish than in English. Second, nonnative speakers and native speakers with smaller vocabularies may rely more on lexical stress information than native speakers with larger vocabularies because lexical stress information provides a potential resource for statistical strategies to compensate for limited processing capacity. I will discuss this strategic processing issue in *Section 1.2.3*.

Besides fragment priming, other tasks that primarily tap into phonological representations also found significant effects of lexical stress. For example, Connine, Clifton and Cutler (1987) used synthetic voice onset time (VOT) continua embedded in words and nonwords with different stress patterns to test the influence of lexical stress on lexical processing. At one end of the continua was a word, whereas the other end of the continua was a nonword. For example, in diGRESS/tiGRESS, diGRESS is a real word, whereas tiGRESS is not; in DIgress/TIgress, TIgress is a real word whereas DIgress is not. The results showed that it was easier for listeners to identify VOT changes that were embedded in real words than in nonwords. These results suggest that lexical stress influences the way listeners make phonetic discrimination.

In another approach, Lindfield et al. (1999) used onset gating to investigate how lexical stress information is exploited by the listeners for online language comprehension. The onset gating approach derives from evidence that online word recognition heavily relies on word-initial information. Many models of online word recognition emphasize the importance of word onset information for forming an activated cohort of candidates for further selection (e.g., Marslen-Wilson & Welsh, 1978; McClelland & Elman, 1986; Tyler, 1984).

By giving listeners small word increments one step at a time from the word onset, onset gating experiments can pinpoint when (at which gate) the listeners can isolate the correct word from the activated cohort (called the "isolation point") as well as when listeners can identify the selected word with confidence (called the "recognition point"). In other words, onset gating experiments simulate the continuous word recognition process by sampling discrete processing intervals.

Lindfield et al. (1999) used two- and three-syllable English words with different lexical stress patterns. Three conditions were constructed for gating, with increments of 50 ms between gates: onset only, onset with the word duration, and onset with word prosody. In the onset with word duration condition, the onset was followed by a period of white noise that gave information on how long the whole word was. In the onset with word prosody condition, the onset was followed by the low-pass filtered version of the rest of the word.

It was found that the onset with word prosody condition held significant advantage over the other two conditions throughout all the gates until a significant portion of the word was heard. Thus it was demonstrated that providing prosodic information could enhance word recognition when compared to providing only word onset information. Caution should be used in interpreting results from the onset plus duration condition, because the absence of effect may come from the unnaturalness of the white noise.

Arciuli and Cupples (2004) advanced onset gating research on lexical stress by addressing the stress typicality issue..Stimuli included both typically stressed words (trochaic nouns, e.g. "tension" and iambic verbs, e.g. "forget") and atypically stressed words (trochaic verbs, e.g. " follow" and iambic nouns, e.g. "saloon"). The authors constructed two conditions for gating:

onset only and onset plus low-pass filtered version of the remainder of the word. The gates were each 50 msec in duration. Study participants were either native or non-native English speakers.

For both native and non-native speakers, significant effects of stress typicality were found. The isolation points for typically stressed words were signficantly earlier than those for atypically stressed words. More importantly, this study had good control over multiple other factors that may affect the results. Acoustic duration, phonological neighborhood variables (neighborhood size, average frequency of neighbors, or onset density), and uniqueness points (the point at which the syllable sequence of the word becomes unique) were all equated between typically and atypically stressed words. After controlling these factors, typicality still held an advantage throughout many gates. However, the presentation conditions (onset only vs onset plus prosodic information) did not yield any significant effects. This study demonstrated that stress typicality can render advantages for processing in both the native and nonnative speakers. Listeners can identify typically stressed words with less information (shorter onsets) than atypically stressed words. In addition, the exploitation of the lexical stress information was heavily reliant on the initial portions of the words.

The two seemingly contradictory results of onset gating experiments actually may stem from the same underlying mechanism (Arciuli & Cupples, 2004; Lindfield et al., 1999). That is, listeners exhibited sensitivity to the lexical stress information, especially early in processing (at word initial gate). More importantly, participants were sensitive to the statistical occurrence of lexical stress patterns. The main effect of presentation condition in Lindfield et al. (1999) may come from the fact that this study only included nouns (both typical and atypical). Therefore, absent the statistical pattern of lexical stress related to grammatical category, listeners may rely more on the prosodic information after the onset gates (in the onset plus prosody condition) for spoken word recognition.

A few other studies that tapped into phonological representations obtained positive effects of lexical stress, as well. For instance, Slowiaczek (1990) instructed participants to shadow either correctly stressed or incorrectly stressed versions of the same word (for example “ANgry” vs “anGRY”) as well as nonwords. It was found that shadowing correctly stressed words was significantly faster than incorrectly stressed words, which was in turn faster than nonwords. This suggested that both segmental information and stress pattern are important for phonological processing. In another example, Mattys and Samuel (2000) used dichotic listening migration to probe early lexcial access. When two words were presented to both ears simutaneously, the perceptual migration of vowels happened more often with nonsense targets than with real words. Applying this finding, the authors suggested that mispronounciation of stressed syllables influenced phonemic perception whereas misprounciation of unstressed syllables did not.

Viewing all the above studies, three conclusions can be drawn. First, lexical stress can help activate the phonological representation of spoken words. Second, the degree of facilitation from correct (matched) lexical stress or inhibition from incorrect (mismatched) lexical stress depends on multiple factors, such as the amount of phonological information available (indicated by fragment prime length), which language is used, participant language proficiency, and stress typicality. Third, in online language comprehension, both segmental information and lexical stress pattern are critical in accessing the phonological representation of the target lexical entry.

Section 1.1.3 discusses a few studies that have tasks requiring "activation of lexical concepts." As will be seen, in these studies, the effects of lexical stress have been washed out. This absence of effects will be explained under the framework of the "three-constituent lexical representation" proposal by Hart and Perfetti (2008).

1.1.3 Lexical stress cannot activate related lexical concepts

In a few early associative priming studies, no effects of lexical stress were found. This led investigators to hypothesize that lexical stress was irrelevant in the pre-lexical stage of spoken word recognition (Cutler, 1986).

The initial drive of the Cutler (1986) study was to eliminate the confounding variable of vowel reduction. For that purpose, she chose 11 pairs of English words that are minimally contrasted only by lexical stress (i.e. no vowel reduction is involved). An example is FORbear-

forBEAR. These words were embedded in biasing sentences, and used as auditory primes in a cross-modal lexical decision task. A visually-presented target occurred immediately at the offset of the prime. Target words were semantically related to their primes, to the lexical stress counterparts of their primes, or to control words. Example sentences and targets include:

Noun-bias sentence: *Gritting her teeth, she reminded herself* ----*that her forbears had been hardy pioneer types.*

Matching target: ancestor
Mismatching target: tolerate
Controls: dictator (first syllable stressed), simulate (second syllable stressed)

Verb-bias sentence: *Gritting her teeth, she reminded herself* ---- *to forbear to mention her grievance.*

Matching target: tolerate
Mismatching target: ancestor
Controls: dictator (first syllable stressed), simulate (second syllable stressed)

Using these stimuli, two cross-modal associative priming experiments were conducted. In the first experiment, the target occurred right at the offset of the prime.For all statistical analyses of reaction times and errors in this experiment, the only significant effect was the main effect of relatedness. For example, upon hearing the prime “FOREbear”, both “ancestor” and “tolerate” were responded to equally quickly, and faster than the control targets.
In the second priming experiment, targets occurred 750ms after primes. Significant facilitation of the matched prime was found.

Viewing of the two experiment together, Cutler (1986) concluded that the words minimally contrasted by lexical stress were “functionally homophonous” (p. 201) . That is to say, the absence of effects in this experiment came from the fact that both words in the minimal pair were activated. Lexical stress had no effect in facilitating or inhibiting either of them in the pre-lexical stage of processing.

Cutler (1986) further proposed that lexical stress became important only in the lexical retrieval (i.e., selection) stage when both words in the minimal pair had been activated. Though the absence of effects in the first priming experiment may not completely be attributed to this hypothesized mechanism, her description of the scenario was nonetheless likely to be true: lexical stress may only be effective at the selection stage of lexical processing. One modification for this proposal is that activation (in Cutler's term "access") and selection (in Cutler's term "retrieval") are not necessarily serial stages of lexical processing. Instead, they are most likely to happen in a parallel way, as specified in the cascading inhibition model in *Section 1.2.1*.

Cutler (1986)'s study was very influential in that it was the first lexical stress study to have complete control of segmental confounds. However, the absence of priming effects from lexical stress may reflect the fact that associative priming was used. Priming success for phonological representations, found consistently in fragment priming studies in *Section 1.1.2*, does not necessarily ensure priming success for lexical concept representations.

As discussed in *Section 1.1.2*, van Donselaar et al. (2005) addressed the difference between fragment priming and associative priming. In the first two experiments of this study, both three-syllable and one-syllable fragments facilitated the processing of matched lexical stress. In addition, three-syllable fragments inhibited processing of stress-mismatched counterparts. The authors tested associative priming in the same study by including target words related to the primes. For example, when the prime was "paraDIJS" (paradise), the target word was "hemel" (heaven). In contrast to the robust effects found in the fragment priming experiments, lexical-semantic facilitation was not robust across items or subjects. Facilitation was found only for items that have a "unique interpretation" (p. 266). The authors proposed that fragment priming does not tap the same process as associative priming.

As indicated at the beginning of this chapter, Norris et al. (2006)'s comparison of nine priming experiments substantiates the argument that activation of phonological representations does not necessarily induce activation of related lexical concepts. Thus, the inconsistent results of lexical stress studies were in fact task dependent. Lexical stress may exert its effect by directly activating the phonological representation, and this phonological activation can assist with lexical selection.

This task-dependent difference also emerged in Cutler and Clifton (1984), though they did not discuss the discrepancy in detail. There are three experiments in this study. The first investigated the effect of anticipation of lexical stress on the speed of processing. Subjects were presented with trochaic words (such as “tiger”) and iambic words (such as “canoe”) in either a mixed list or a pure list and were instructed to do a lexical decision task. For both visual and auditory presentations, there was no main effect of list (mixed or pure), for either accuracy or speed.

The second experiment involved lexical decisions to words preceded by a lexical cue to their grammatical category (i.e. “the ----“ as a noun cue and “to----“as a verb cue). After accounting for the acoustic artifact of verbs being shorter than nouns, there was no effect of lexical stress.

In the third experiment, the task was to judge the acceptance of “stress-shifted” words. For example, SW (strong-weak syllable) words were mispronounced to be WS (weak-strong syllable) words and vice versa. Subjects were presented with normally- pronounced and mispronounced words, and instructed to make acceptability judgements. In this case, there was a significant main effect of pronunciation.

The discrepancy between experiments can be explained by the difference between phonological representation activation and lexical concept activation. In the first two experiments, the tasks required lexical concept representation activation, whereas in the third experiment, the task only involved phonological representation activation.

Small, Simon, and Goldberg (1988) used a phoneme monitoring task to investigate the influence of lexical stress on speed of lexical access. The target phoneme was embeded *after* the correctly or incorrectly stressed words. The rationale of this paradigm is that if incorrect stress slows lexical access, the detection of the following target phoneme will be delayed. Two conditions were constructed: homophonous and nonhomophonous. In the homophonous condition, a stress shift resulted in a different word (e.g. CONvert to conVERT) whereas in the nonhomophonous condition, a stress shift produced a nonsense word (e.g. PEAnut to peaNUT). Reaction times were affected for nonhomophonous pairs, but not for homophonous pairs. Thus, stress contrasted pairs again behaved as if they were functionally homophonous. Once more, this lack of lexical stress effect could be interpreted as a consequence of mandatory "lexical concept activation" of the preceding correctly or incorrectly stressed words, before the detection of the target phoneme.

1.1.4 Summary and implications for model building

Integrating the behavioral studies that investigated the influence of lexical stress on spoken word recognition, a task-dependent pattern can be seen. For studies that require only phonological activation, significant effects of lexical stress were consistently found. On the contrary, for tasks that required "lexical concept activation," the effects of lexical stress were washed out. From this pattern, one can infer that lexical stress is not directly connected to activation of lexical identity. There should be some mediating levels in between.

This pattern is consistent with Hart and Perfetti (2008)'s three-constituent lexical representation proposal. It proposes that every lexical item has three constituents stored in the mental lexicon: orthography, phonology and semantics. When all of these constituents are coherent, lexical entries can be accessed most effectively. Based on this proposal, correct lexical stress may function as a direct trigger for phonological activation. Then lexical identity selection could be indirectly facilitated when the phonological representation of the lexical entry is adequately activated.

1.2 CASCADING PHONOLOGY MODEL FOR LEXCIAL ACTIVATION AND SELECTION

1.2.1 The Cascading Inhibition model

Per the implications discussed in *Section 1.1.4*, lexical stress is not directly linked to the lexical identity representation. There needs to be some intermediate processing stages to mediate the activation. This hypothesis is consistent with the hierarchical phonology model of spoken word recognition.

Frauenfelder and Lahiri (1989) argued that phonological processing is a nonlinear process that is much more than the linear concatenation of phonetic segments. Further, they proposed a three-level hierarchical structure for lexical phonology, as depicted in *Figure 1-1*. In this model, the prosodic level serves as a domain to apply suprasegmental features and phonological rules; the skeletal level specifies the syllable slots that are ready to be filled in; and the phonetic level specifies phonemes (and allophones) as well as phonetic rules and coarticulations. *Figure 1-1* illustrates this hierarchy based on the word "pony."

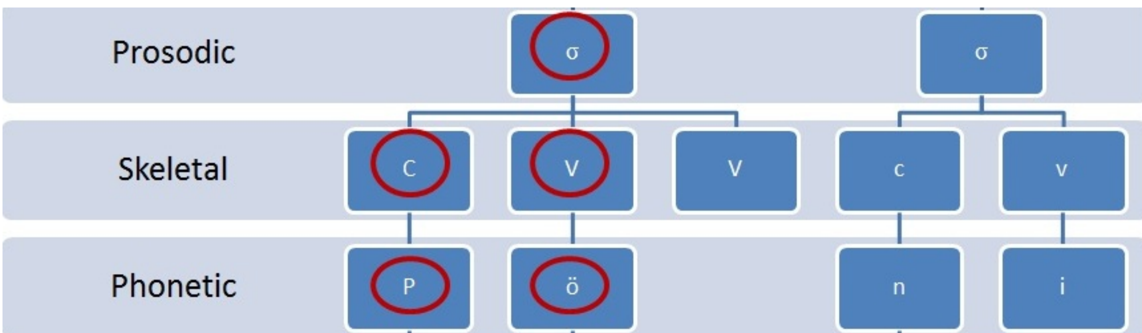

Figure 1-1. The three-level hierarchy of lexical phonology adapted from Frauenfelder and Lahiri (1989). The prosodic level specifies suprasegmental information, such as stress placement. The skeletal level specifies the locations of consonants and vowels. The phonetic level specifies the identity of the sounds and phonetic details for producing them (such as aspiration or nasalization).

Frauenfelder and Lahiri (1989) argued that this hierarchy is necessary for the identification of lexicon of every word in speech. There are multiple linguistic analyses that are supportive of such hierarchical levels (e.g., Clements & Keyser, 1980; Clements, 1985; Hayes, 1989; McCarthy, 1986; Nespor & Vogel, 1986). However, based on many experiments and real life experience, a pure hierarchical model would not work given the speed of language comprehension (Marslen-Wilson, 1989). Because it takes only about 200 msec for sensory input and sentential context to converge on a single lexical entry, a strict serial hierarchy would not work. Some form of functional parallelism must be embodied.

Combining the characteristics of the phonology hierarchical structure and functional parallel processing, an adapted cascading inhibition model (Marslen-Wilson 1989; McClelland & Elman, 1986) for lexical activation and selection is proposed here. "Cascading" refers to the spreading of activation from one level of the phonology hierarchy to another and finally to the lexical identification level. "Inhibition" means that inconsistent information from upper levels can help select the target lexical entry (at the lexical identificationlevel) by inhibiting candidates from the activated cohort. An illustration, based on the word "pony," is provided in *Figure 1-2.*

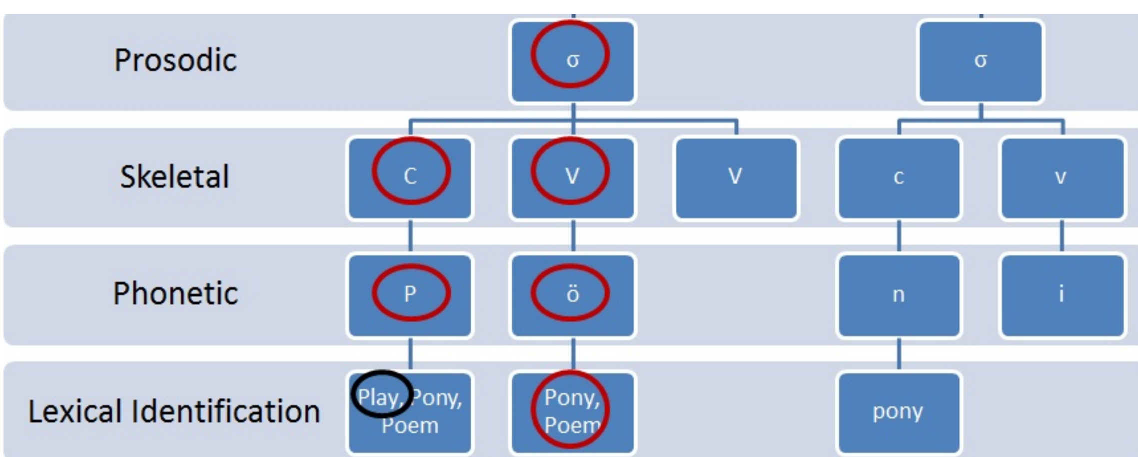

Figure 1-2. Illustration of the cascading inhibition model based on the word "pony." The activation of the word "pony" is cascading; the red circles indicate the spread of activation to parallel nodes, among levels. The result of the selecion process (inhibition) to reduce competitors is symbolized by a black circle. As the phonetics cascade, the second segment is specified as the [o] sound, the word "play," which is in the original cohort, will be inhibited.

In this cascading inhibition model, time is specified on the horizontal line. In addition to the prosodic, skeletal, and phonetic levels, a level of lexical identification is added. Characteristics of both hierarchical structure and parallel processing are incorporated here as well. The parallel processing characteristic is realized by simultaneous processing of multiple levels. That is to say, each level can initiate processing before any higher level completes processing for the whole word.

The lowest level is the lexical identification level, which is the ultimate outcome of the whole process. According to the contingency of perceptual choice proposed by Marslen-Wilson (1989), the identification of any given word not only depends on the information that this word is present, but also depends on the information that other words are not present. This calls for a process of elimination. As seen from *Figure 1-2,* given prosodic, skeletal and phonetic information, multiple word candidates are activated by the first word segment, forming a word initial cohort (for evidence on the importance of word onset to form the cohort, see McClelland & Elman, 1986). This cohort is defined as a pool of activated lexical entries. Lexical selection is the process of successive reduction of the active membership of this cohort of competitors, until one lexical entry is finally identified. The final point at which the target entry is picked out is defined as the recognition point* (Marslen-Wilson, 1989). Therefore, selection is the reduction process and the endpoint of selection is the recognition point. The recognition point is not only a function of the word's phonology, but also that of its nearest competitors.

I propose here that if anything from the incoming signal is not consistent with stored phonology at any level above lexical identification (i.e. prosodic, skeletal or phonetic level) for a given competitor in the cohort, that competitor will be inhibited. The extent of inhibition should be a statistical process, as should be the function of the entire model.

For example, a segmental error will cause stronger inhibition than a suprasegmental error because the phonetic level is in direct contact with the lexical identification level.

**Note*: this recognition point is not the same as the "recognition point" in onset gating experiments.

The cascading inhibition model, as a whole, can be viewed as an implementation of Hart and Perfetti (2008)'s more general three-constituent representation of lexical entry proposal. During spoken word recognition, two of the three proposed constituents will be activated: phonology and semantics. The phonology is represented in a hierarchical structure, and only the phonetic level is in direct contact with the semantic constituent. Lexical stress is situated at the prosodic level, and helps select lexical identity indirectly through the mediation of skeletal and phonetic levels. This is why tasks requiring "lexical concept activation" usually do not evidence a significant influence of lexical stress.

For the selection process, lexical stress could form constraints on the phonetic level to eliminate nondistinctive (allophonic) variations and help shape the best phonemic representations of the incoming lexical entry as quickly as possible. For example, vowel reduction could be easily accepted if the syllable is given a weak stress.

1.2.2 Definition of lexical stress parsing

"Lexical stress parsing" in the current study is defined in the context of a cascading inhibition model for spoken word recognition, as the processing of lexical stress patterns at the prosodic level, i.e. 1) *to identify whether the incoming syllable is stressed or not*, and 2) *to process the sequence of stressed and unstressed syllables*.

As described in the above model, lexical stress parsing can help shape online a phonological representation of a word at the phonetic level, and further help select the identity of the target from the activated cohort as quickly as possible. For example, parsing lexical stress can help listeners to segment the incoming word from the acoustic stream by the boundary marking functions of strong syllables, to estimate the number of syllables in the word, to expect the co-articulation pattern, and to accept the vowel reduction quickly at a weakly stressed syllable (Anderson & Jones, 1974; Cutler, 1986; Marslen-Wilson & Welsh, 1978;Mattys, 2005). All these benefits from parsing can help select the identity of the target before the whole word is heard (Cooper et al., 2005; Cutler, 1986; Cutler & Clifton, 1984; Mattys, 2005; Thiessen and Saffran, 2003)

1.2.3 Stress typicality may serve as a statistical strategy

Lexical stress encoding is an inseparable part of word encoding as people learn a language. Suprasegmental information is used very early to build phonological representations in the mental lexicon.

This conclusion has been investigated in the child language acquisition literature. Curtin (2010) found that infants could store word stress information and detect when stress was shifted. In addition, both the identity and the location of the stressed syllable were encoded. The author pointed out that "it is not a growing lexicon and the need to make increasingly fine distinctions that drive encoding of phonological properties" (p. 383). Instead, the phonological details "are always stored in the mental lexicon" (p. 383).

What is more intriguing is that suprasegmental pattern encoding obeys the same rules of segmental pattern encoding: it is sensitive to statistical constraints. Thiessen and Saffran (2003) found that 9-month-old English infants were able to rely on trochaic patterns as a cue to word segmentation in an artificial language. This is a natural result of the English stress placement distribution, in that the majority of English words have a trochaic stress pattern.

The statistical reliance on stress typicality has also been investigated in second language speakers. Davis and Kelly (1997) found that both native and non-native speakers were more likely to use pseudowords with trochaic patterns as nouns while using pseudowords with iambic patterns as verbs. In addition, error rates were correlated with reaction times. That is to say, there is no speed/accuracy trade-off. Typically stressed words can be processed both faster and with higher accuracy than atypically stressed words. Furthermore, Arciuli and Cupples (2003) found that reliance on this statistical typicality increased for non-native speakers and native speakers with lower vocabulary size. Thus, stress typicality might be used as a statistical strategy to compensate for limited vocabulary knowledge, especially for completing certain metalinguistic tasks such as grammatical category classification in the Arciuli and Slowiaczek (2007) study.

Accordingly, it is important to keep in mind that the cascading inhibition model possesses a statistical nature (Davis & Kelly, 1997; Saffran, Aslin, & Newport, 1996; Thiessen & Saffran, 2003). The structure of the phonology hierarchy is subject to change in relation to the distributional change in the language environment.

In order to minimize statistical strategic processing*, young native speakers in the proposed study will attend to stimulus sentences without doing any metalinguistic task. Rather, they will be instructed to listen attentively to answer a comprehension question at the end of a block of trials. Specific details are provided in Chapter 3.

*Note**: The use of "strategic processing" in the statistical learning literature does not necessarily involve consciousness or awareness. Rather, the statistical strategies are developed during infancy by learning from natural statistical occurrences in the language environment. They are used in adulthood rather automatically (Thiessen & Saffran, 2003).

1.3 CURRENT RESEARCH HYPOTHESES AND PREVIOUS EMPIRCAL EVIDENCE

1.3.1 Current research hypotheses and a brief overview of study design

It has been known for a long time that pre-attentive phonetic and lexical processing are both lateralized primarily to the left hemisphere* (Alho, Connolly, Cheour, Lehtokoski, Huotilainen, Virtanen, Aulanko, & Ilmoniemi, 1998; Barry, 1981; Frost, Binder, Springer,

Hammeke, Bellgowan, Rao, & Cox, 1999; Jordan, Patching, & Milner, 2000; Zahn, Huber, Drews, Erberich, Krings, Willmes, & Schwarz, 2000; Zatorre, Meyer, Gjedde, &Evans, 1996).
*Note**: Recent work has found that the right hemisphere is also involved in pre-attentive lexical processing (e.g., Beeman & Chiarello,1998) .

Based on this knowledge, the primary hypothesis of the current study is proposed: The parsing of lexical stress, which activates the phonological representation of a lexical entry, is lateralized to the left hemisphere as well. The theoretical assumption for this hypothesis is that lexical stress information needs to be available at loci in the cortex near those for lexical identity representation, to meet speed requirements of lexical identification in online language comprehension. A second hypothesis of the proposed study is that this lateralization pattern does not require the presence of segmental information, because the parsing of lexical stress at the prosodic level is a component of a word's phonological representation.

In order to test these hypotheses, filtered and unfiltered English noun-verb pairs that are contrasted primarily by lexical stress (e.g., CONvert vs conVERT) will be presented as target words to right-handed native speakers of American English. These targets will follow high-cloze noun-predicting sentences. In the filtered conditions, target words will contain only the suprasegmental information. The unexpected verb stress pattern following a noun-predicting sentence is hypothesized to elicit a deflection in ERP (event-related potential) waveforms and therefore provide important information on when and where lexical stress is processed in the brain. The unfiltered versions of the target words will serve as controls.

The specific design and issues related to ERP paradigm implementation will be discussed in Chapter 4. Below, I first review two similar previous studies that investigated the issue of lexical stress lateralization, both of which found left lateralization of lexical stress. Then, these studies will be compared and contrasted with the current study proposal to address how this current study will advance the understanding of lexical stress processing. The studies that showed counter-evidence of the left lateralization of lexical stress parsing will be reviewed in Chapter 2.

1.3.2 Two similar studies and the comparison with the proposed study design

1.3.2.1 Empirical studies that investigated lexical stress lateralization

Arciuli and Slowiaczek (2007) used a dichotic listening task to investigate the sensitivity of the two brain hemispheres to word stress. The stimuli were two syllable single words that were either typically stressed (10 nouns, 10 verbs) or atypically (but correctly) stressed (10 nouns, 10 verbs). The typically and atypically stressed words were matched in spoken frequency, number of phonemic neighbors, average spoken frequency of neighbors, uniqueness points, onset structure, and imageability.

These stimuli were presented to one ear and distractors were presented to the other ear. The distractors were the acoustically reversed versions of the same words. Right-handed young native English speakers were told to name the word they heard (and ignore the nonsense word) in experiment one and to classify the word by grammatical category in experiment two. Both experiments showed a significant interaction of stress typicality with hemisphere, as represented in *Figure 1-3* and *1-4* respectively. Post hoc analyses indicated that the left hemisphere was faster to process typically stressed words. In addition, whether the word was a noun or a verb did not matter.

This study demonstrated that suprasegmental information may be exploited in a statistical manner, giving an advantage for typically stressed words. More importantly, this study is consistent with the proposed study hypothesis that the parsing of lexical stress is lateralized to the left hemisphere.

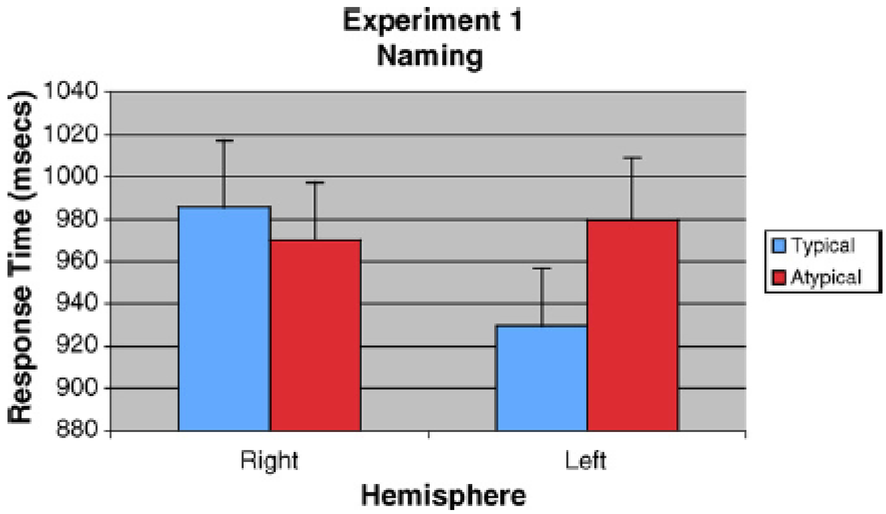

Figure 1-3. Average correct response times as a function of stress typicality and hemisphere in Experiment 1 of Arciuli & Slowiaczek (2007).

In interpreting the results, however, two issues need to be considered. First, the results are also consistent with the cue-dependent acoustic hypothesis, which proposes that the left hemisphere is specialized for processing temporal aspects of acoustic stimuli, whereas the right hemisphere is specialized in processing spectral aspects (Van Lancker & Sidtis, 1992). Acoustic analyses of the stimuli indicated significant differences in duration between the stressed and unstressed syllables. Thus, the left hemisphere involvement in this study may reflect only a specialization for processing fine temporal information. The distinction between the current study hypothesis and other theories of linguistic prosody lateralization will be elaborated in Chapter 2. Second, it was not clear whether the influence of lexical stress was exerted at the lexical activation or selection stage.

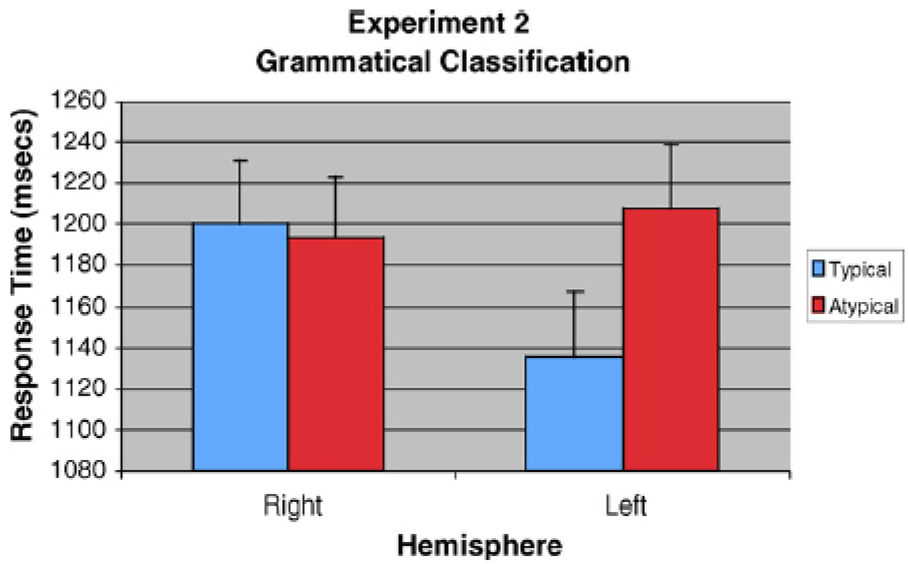

Figure 1-4. Average correct response times as a function of stress typicality and hemisphere in Experiment 2 of Arciuli & Slowiaczek (2007).

Another study that investigated the lateralization of lexical stress processing is an ERP study. Friedrich, Kotz, Friderici, and Alter (2004) borrowed Soto-Faraco et al.'s (2001) and van Donselaar et al.'s (2005) fragment priming method and applied it to German. The syllable "me" was pitch modulated to be either stressed or unstressed. Then, this modulated syllable served as an auditory prime, followed by a visually presented target. For the target, the first syllable was either (1) stress-matched with the prime (e.g. stressed "ME" followed by "Medium (medium)", or unstressed "me" followed by "mediZIn (medicine)"), or (2) mismatched with the prime (e.g. stressed "ME" followed by "mediZIN" or unstressed "me" followed by "MEdium"). In addition, a segmentally mismatched control condition was included. The participants were instructed to make a lexical decision judgment about the target as quickly as possible. What is unique about this study is that online EEG (Electroencephalography) was also recorded to investigate the underlying waveform changes associated with lexical stress patterns. The behavioral data showed significant facilitation of stress-matched primes. However, an inhibition effect of stress-mismatched primes was not found.

P350 (a positivity at 350 msec after stimulus offset) was found to be significantly smaller in the stress-matched condition than in the stress-mismatched condition. Moreover, the scalp distribution of stress-modulated P350 was left lateralized. In addition, the stress-related P350 scalp distribution was significantly different from the segment-related P350 elicited by the segmental mismatched control condition, in terms of both anterior-posterior distribution and amplitude. Specifically, the stress-related P350 effect was more posteriorly distributed and lower in amplitude than the segment-related P350 effect. An N400 (a negativity found 400msec after stimulus offset) was elicited by segmentally-mismatched stimuli, but not stress-mismatched ones.

Friedrich et al. (2004) concluded their study by saying that: a) pitch contour has a "modulating" role in word recognition (p. 307); and b) P350 is an indicator for "lexical activation" (p. 307). However, there are two important implications that Friedrich et al. did not discuss. First, **P350 may be an indicator for "phonological representation activation."** As discussed previously, pitch modulation of suprasegmental information may only directly activate the phonological representation of a lexical entry, whereas lexical concept identification is affected by the mediation of segmental features. Thus, it is quite possible that P350 is in fact a direct measure of phonological representation activation instead of "lexical activation." This possibility is also consistent with the fact that it occurred earlier than N400, which is a robust indicator of meaning violation.

Second, the absence of an N400 effect and inhibition for the stress-mismatched condition may stem from the short prime used in this study (one syllable long). In other fragment priming studies (Cooper et al., 2002;Soto-Faraco et al., 2001; van Donselaar et al., 2005), conditions with multi-syllable primes always produced stronger facilitation and inhibition effects than conditions with single-syllable primes. Thus, it is premature to conclude that mismatching lexical stress does not elicit an N400 effect.

1.3.2.2 Comparison of proposed study with these two previous studies

There are four considerations in the current study design compared to the above two studies. First, the proposed study will be the first to include a filtered stimulus condition to investigate lexical stress lateralization. By using filtered stress patterns, the contribution of segmental information can be eliminated. Second, using EEG methods like Friedrich et al. (2004), the specific time window(s) of lexical stress parsing can be observed, and underlying processes inferred. Third, different from the previous studies, this study will avoid metalinguistic tasks such as grammatical category classification or lexical decision judgment. Therefore it will more validly represent on-line stress parsing, and minimize potential confounds of strategic processing. Finally, unlike the two previous studies, the proposed study will include preceding sentence contexts to tap lexical stress processing as it is integrated with other aspects of information for online sentence comprehension.

1.4 SUMMARY OF CHAPTER 1

In this chapter, past empirical studies of the influence of lexical stress on word recognition were first classified into two categories: one that used phonological tasks and one that used tasks requiring lexical concept processing. The former category consistently showed significant influences of lexical stress on word recognition, whereas the latter category did not find robust influences. Based on this pattern, a working model of online auditory word recognition, the cascading inhibition model, was proposed. This model is an integration of past theoretical frameworks: the three-level hierarchy of lexical phonology (Frauenfelder & Lahiri, 1989) and the three-constituent representation of a lexical entry proposal (Hart & Perfetti, 2008). Under this model, activation of a phonological representation has a hierarchical structure, with the prosodic level at the top, specifying lexical stress patterns that help the lower phonetic level to form correct representations. The phonetic level, which specifies segmental information, is the one that has direct contact with the lexical identity representation of a word. Inconsistent or incorrect lexical stress can inhibit lexical identity activation via the mediation of phonetic information.

Under this theoretical framework, the current research hypotheses are proposed: lexical stress parsing, which influences lexical selection, is lateralized to the left hemisphere even in the absence of segmental information. Two previous studies that investigated similar issues were described. Both found the left hemisphere to be specialized for lexical stress processing. Then the current study design was compared and contrasted with the previous ones. Comparing the study designs, there are major methodologic contributions of the proposed study: a) the lateralization of lexical stress can be investigated without confounding segmental features by including filtered versions of the stimuli; and b) the processes of automatic online word recognition can be examined without metalinguistic tasks.

In the next chapter, previous theoretical frameworks and additional studies of linguistic prosody lateralization will be reviewed in detail. This literature will provide more insights and background on the current lateralization hypothesis, especially on how different kinds of suprasegmental information are organized in the brain.

2.0 LEXICAL STRESS LATERALIZATION

The focus of this chapter is the lateralization issue of lexical stress processing. Theoretical viewpoints, past empirical studies, and the application of the ERP paradigm will be handled in respective sections.

Section 2.1 introduces and compares the major linguistic prosody lateralization hypotheses. Lexical stress is one kind of linguistic prosody and therefore is considered under these hypotheses.

Linguistic prosody contains rich information that potentially interacts with hierarchical lexical processing and syntactic processing (Baum, Daniloff, Daniloff & Lewis,1982; Blumstein & Cooper, 1974; Bradvik, Dravins, Holtas, Rosen, Ryding, & Ingvar, 1991;Berhens ,1985; Bryan, 1989; Emmorey,1987; Heilman, Bowers, Speedie, & Coslett, 1984; Pell, 1998; Pell & Baum, 1997; Steinhauer, Alter & Friederici, 1999; Weintraub, Mesulam, & Kramer, 1981). Thus, understanding the lateralization of linguistic prosody processing can help us determine how the two hemispheres allocate resources to integrate various aspects of complex linguistic signals.

In *Section 2.2*, past lesions studies on lexical stress will be the focus. The first two parts of this section will review studies that were either consistent or in conflict with thelateralization hypothesis of the current study, respectively. Then in the third part, limitations of lesion studies will be discussed.

In *Section 2.3*, a few additional ERP studies will be considered to address two theoretical questions: (1) which ERP indices should reflect online lexical stress parsing; 2) how can ERP, a paradigm that is low in spatial resolution, address lateralization issues? The end of this section will consider interhemispheric interactions in prosodic information processing.

Section 2.3 only discusses the theoretical possibility of using ERP. The instrumentation and data analysis methods will be left to Chapter 4.

2.1 PAST HYPOTHESES OF LINGUISTIC PROSODY LATERALIZATION

Monrad-Krohn (1947) described prosody as the melodic line of speech produced by variations of pitch, rhythm, and stress of pronunciation. Therefore, prosody can express both emotional intents and linguistic functions. “Linguistic prosody” can be defined as, collectively, all of the frequency, tempo, and intensity changes perceived in speech that have phonological, lexical, semantic, or morpho-syntactic significance (Dogil, 2003).

Early research on prosodic comprehension reported that the right hemisphere had a dominant role in linguistic prosody processing under various task conditions (Baum et al. 1982; Bradvik et al. 1991; Bryan, 1989; Emmorey, 1987; Weintraub et al. 1981). As this line of work has been refined, a number of critical questions have arisen, including (1) are any kinds of linguistic prosody processing lateralized to the left hemisphere; (2) if so, why is it advantageous for some aspects of linguistic prosody processing to be lateralized to the left hemisphere and others to the right; and (3) how is linguistic prosody lateralization related to segmental information processing?

This section first compares and contrasts current lateralization hypotheses, together with the hypothesis proposed for this study.

2.1.1 Overview

Table 2-1 summarizes the main viewpoints of current prosody processing lateralization hypotheses, as well as under each hypothesis, the predictions of which kinds of prosody are left lateralized. In the following sections, each hypothesis will be elaborated, together with a brief review of the empirical studies that led to these proposals.

Table 2-1. Overview of the prosody processing lateralization hypotheses

Hypotheses	**Main Viewpoints**	**Predictions on left-lateralized kinds of prosody**
Functional hypothesis (Van Lancker 1980)	The processing of prosody that serves linguistic function is lateralized to the left hemisphere, and that signaling affective function is lateralized to the right hemisphere	All linguistic prosody
Acoustic hypothesis (Van Lancker & Sidtis, 1992)	The brain processes prosody in a bottom-up manner, with the left hemisphere processing the temporal aspects of the acoustic information and the right hemisphere processing the spectral aspects.	Temporal information of all kinds of prosody. Thus, quick-changing signals that have short durations are predominantly processed by left hemisphere.

Table 2-1. (Continued)

Lexicalization hypothesis (Packard, 1986)	This is a variation of the functional hypothesis. For linguistic prosody that is involved in lexical retrieval, the lateralization is to the left hemisphere.	Prosody for lexical processing will be lateralized to the left hemisphere.
Limiting domain hypothesis (Dickey, 1995)	The phonological processor is limited to a window about one syllable long at any given moment. Prosodic information can only influence lexical processing when it is shorter than one syllable. Prosodic features that are defined over domains larger than one syllable will not be recognized immediately by the syllable-limited processor.	Implies that prosody defined over a domain smaller than a "syllable chunk" will be left lateralized.
Lexical stress parsing hypothesis (Yang, this proposal)	Under the cascading inhibition model, lexical stress parsing, which regulates lexical selection, is hypothesized to be left lateralized.	Lexical stress is parsed in the left hemisphere for lexical selection. In addition, this lateralization pattern does not require the presence of segmental information.

2.1.2 Functional hypothesis and acoustic hypothesis

The first two main competing hypotheses about prosody lateralization are the functional hypothesis and the acoustic hypothesis. The functional hypothesis describes the allocation of prosody processing as a top-down cognitive process. Prosody that bears a heavy linguistic load is lateralized to the left hemisphere for processing, whereas prosody with less linguistic significance is processed in the right hemisphere (Van Lancker, 1980). Therefore, the functional hypothesis predicts that the brain can “recognize” the function of the incoming prosody and allocate brain resources accordingly.

In contrast, the acoustic hypothesis describes a bottom-up cognitive process of prosody lateralization: The brain does not ‘recognize’ the functions of incoming pitch variations. Rather, it processes prosody based on physical features of acoustic signal. Incoming prosody is separated into temporal and spectral dimensions online. The lateralization of processing is determined by the separation of spectral and temporal cues, with temporal prosodic cues primarily processed by the left hemisphere and spectral cues by the right (Van Lancker& Sidtis, 1992). The idea that left hemisphere is specialized for fine temporal information processing and the right hemisphere for fine spectral information processing also partially derives from drawing analogies to the visual system (Ivry & Robertson, 1998).

2.1.3 Lexicalization hypothesis

Packard’s (1986) lexicalization hypothesis differs in a subtle way from the canonical functional hypothesis. It proposes that the lateralization of processing for an element of prosody is determined by whether it is specified in the mental lexicon.

The original study (Packard, 1986) recorded the production errors made by Chinese patients with left hemisphere damage (LHD) and aphasia. The study compared the production errors for lexical tones and consonants and found that they are very similar in pattern and comparable in rates (e.g. rates and places of omission, insertion, etc.). In his own words, Packard asserted that “lexical tones in Chinese are phonemes in the same sense as consonants” (p. 220). Integrating his results, he inferred that linguistic prosody that can influence lexical access may be treated by the brain in the same way as segmental features: i.e., the processing of this type of prosody was left lateralized. A further extrapolation is that because the lexical stress pattern (or in Packard’s terms “which syllable of the word the stress occurs on”, p. 221) is encoded in the lexical entries in English, this aspect of prosody was predicted to be affected in English patients with LHD.

Thus, the underlying assumption of the lexicalization hypothesis is that because phonological impairments at the segmental level are generally the result of left hemisphere damage, and because processing errors for lexical level prosody were comparable to segmental errors for LHD patients, lexical level linguistic prosody (including lexical stress) is lateralized to the left hemisphere. However, Packard (1986) did not define the term “lexical access” in his report specifically enough to describe at which stage lexical stress exerts its influence or if segmental information has to be present for left lateralization.

Though cited many times by numerous studies of prosody lateralization, there are three major missing links in this study to establish a direct connection between lexical stress processing and left hemisphere lateralization. First, this study only analyzed the end product of patients’ utterances. Multiple upstream processes that could influence final production (which may or may not be language related) were not taken into account. For example, it is possible that the representations of lexical tones in these patients were not impaired, but the final motor schema or execution was influenced. Second, a production study is not a perception or comprehension study, and the brain circuits of perception and production of the same physical stimuli may largely differ. Third, this study only tested one tone language: Chinese. It is not clear whether the result pattern could be generalized to other languages, especially stress languages like English.

2.1.4 Limiting domain hypothesis

In line with the Cutler (1986) study, Dickey (1995) proposed that words minimally contrasted by stress patterns in English (e.g. **PER**mit vs per**MIT**, **FOR**bear vs for**BEAR**) are homophones. She argued that because both lexical entries are indistinguishable in initial lexical activation in cross modal priming (Cutler, 1986), lexical stress does not constrain lexical access. Further, she supported the view of Cutler & Norris (1988) and Cutler (1990) in that the differentiation between differently stressed words in English usually relies on vowel quality (i.e. full vowel in strong syllable and reduced vowel is weak syllable), not on the stress itself.

In order to account for the result pattern for both English (Cutler, 1986) and Chinese (Packard, 1986) studies, Dickey (1995) proposed a phonological processing "window" about onesyllable long. Phonological information realized within s syllable-sized unit will be immediately available for lexical activation, whereas the phonological features that are defined over multiple syllables will not be used for lexical access. These features will only be consulted in later stages of processing.

Dickey (1995) argued that the one syllable chunk of the phonological processer originates from two fundamental cognitive constraints: (1) the limitations of working memory; and (2) the elemental role that the syllable plays in human language structure building.

According to the limiting domain hypothesis, lexical tones fall within the syllable window, and therefore are processed in the same way as segments in syllables. Pitch accents and lexical stress, on the other hand, are defined over multiple syllables and are not used for initial lexical access.

Dickey (1995) tested her limiting domain hypothesis using Japanese minimal pairs. Some of these minimal pairs were contrasted by consonants or vowels, while others were contrasted by pitch accents. Native speakers were instructed to make discrimination judgments as quickly as possible (by pressing buttons to indicate whether the words in a given pair were the same or different). The reaction time results showed that minimal pairs contrasted by pitch accents took significantly longer to discriminate than those contrasted by segmental features. Thus, Dickey (1995) argued that the results supported her limiting domain hypothesis.

Dickey (1995) only tested a pitch accent language: Japanese. Without testing lexical stress, it is premature to conclude the existence of a syllable-size processing window constraint in stress languages such as English.

In addition, the "syllable-size" window hypothesis is contradicted by the results of onset gating experiments reviewed in Chapter 1, which calls for a revision of the limiting domain hypothesis. This point will be discussed in Chapter 3.

2.1.5 Lexical parsing hypothesis

The current study's lexical parsing hypothesis is the first attempt to integrate the prosody parsing mechanism with the prosody lateralization literature. Under the previously-described cascading inhibition model, lexical stress parsing is defined as the process of using suprasegmental features at the prosodic level of the phonology hierarchy to help select lexical entries through the mediation of skeletal and phonetic levels. The entire process is hypothesized to be lateralized to the left hemisphere.

In contrast with lexicalization hypothesis (Packard, 1986), this hypothesis states that lexical stress processing is not analogous to segmental processing. Furthermore, in the lexical stress parsing hypothesis, lexical stress processing plays an upper level modulatory role in lexical selection. The prosody level is different from the segmental level in that it is not "phonemicized."

Though this hypothesis agrees with Dickey's (1995) view that lexical stress is not immediately used for initial lexical activation, the explanation of the underlying mechanism is different. The lexical stress parsing hypothesis explains the results in current literature under the framework of the cascading inhibition model. That is to say, word stress information is not immediately used for lexical activation because it is stored at a different level in the phonology hierarchy, not because of constraints on the size of the processing window.

In sum, there are two theoretically novel points about this hypothesis. First, lexical stress parsing can modulate lexical selection without the presence of the segmental information. Second, the left hemisphere lateralization of lexical stress parsing does not rely on the presence of segmental information.

2.1.6 Summary

In this section, major hypotheses of linguistic prosody processing lateralization have been introduced and compared. Further, the theoretical novelty of the current lexical stress parsing hypothesis is explained and contrasted with other mechanisms.

In the next section, the discussion will focus on patient studies so as to examine how lateralized brain lesions affect lexical stress processing.

2.2 LESION STUDIES

The following two parts will review lesion studies which compared lexical stress processing in unilateral brain damaged patients (left hemisphere damaged, below as "LHD" and right hemisphere damaged below as "RHD") and non-brain damaged controls (below as "NBD"). *Section 2.2.1* will review studies that reported left hemisphere involvement. These studies comprise the majority of the literature and their results are consistent with the current hypothesis.

In *Section 2.2.2*, a few results that are in conflict with current hypothesis will be specifically examined. The possible underlying reasons will also be proposed.

In *Section 2.2.3,* cautions and limitations of these lesions studies will be discussed in general.

2.2.1 Study results that can be explained under the current hypothesis

An early study by Baum et al. (1982) administered word-level stress comprehension tasks to LHD patients and age-matched NBD controls. Participants listened to minimal pairs contrasted by lexical stress (e.g., "**HOT**dog" vs "hot **DOG**") in neutral carrier sentences. Simultaneously, participants were presented a triplet of pictures, in which two of the three depicted the stress-contrasted words. Participants were instructed to identify the pictures matching the auditory stimuli. It was found that LHD patients' performance was significantly compromised. In this study, there was no RHD group. Therefore, it was not clear whether the results were due to left hemisphere lesion or to brain damage in general.

Emmorey (1987) presented the phonemic stress discrimination task (for example, **HOT**dog vs hot **DOG**) to LHD patients, RHD patients, and NBD controls. The author found a significant decrease in performance in LHD compared to the control group, but RHD patients' performance was intact. Though stress discrimination does not guarantee comprehension, this study still provided evidence to suggest that left hemisphere may have a dominant role in processing lexical stress.

One caution is that both of these studies suffered from the contamination of segmental information and lexical identification processing. It is possible that LHD patients were actually impaired in segmental processing or lexical retrieval, rather than the lexical stress parsing. In order to control for these possibilities, Behrens (1985) used the same phonemic contrast set as in

Emmorey (1987) and filtered the stimuli at 200Hz. Dichotic listening tasks were administered to young NBD participants. She found a right ear (left hemisphere) advantage for natural stimuli but no ear advantage for the filtered stimuli.

It may appear that Behrens' (1985) results are in conflict with the current hypothesis, because the left hemisphere was only dominant when segmental information was present. However, the 200Hz filter has such a low cutoff that it might have introduced other artifacts. Specifically, the brain needs to "recognize" the incoming filtered stimulus as speech and process it accordingly.

In order to address the problem of using metalinguistic tasks in most of the studies and the possible discrepancy between metalinguistic and online processing, Wunderlich, Ziegler & Geigenberger (2003) compared the implicit and explicit processing of phonemic focus in German. For the implicit processing condition, LHD patients, RHD patients, and NBD controls were instructed to do a phoneme monitoring task. In the stimulus sentences, the target phoneme either was or was not stressed.

For the explicit processing condition, participants were asked to identify exactly where the focus was. For example, in sentences like "Leztes Jahr Flogen wir nach Italien (Last year we flew to Italy)," four semantic categories were specified: time (last year), actor (we), action (flew), and place (Italy). Participants were required to choose which semantic category was the focused one. Processing times were not limited and participants could ask for repetition.

The implicit processing results showed a main effect of condition: all groups identified phonemes faster in the stressed condition than in the unstressed condition. Further, a significant main effect of groups was found: LHD patients were significantly impaired compared to NBD controls whereas RHD patients' performance was comparable to the controls. Importantly, even after severely aphasic patients' data were removed from analysis, the LHD patients were more impaired than the RHD group. No significant interaction was obtained.

For the explicit task, both patient groups made significantly more errors than the NBD group. In addition, LHD patients made significantly more errors than RHD patients. Viewing both tasks together, RHD patients seemed to implicitly process phonemic focus in a normal manner. However, they were impaired in explicitly identifying which semantic category was focused. The authors proposed “a clear dissociation” between the two hemispheres (Geigenberger & Ziegler, 2001, p. 1183): the right hemisphere plays a fundamental role in extracting prosodic cues and in directly utilizing prosodic patterns whereas the left hemisphere contains a linguistic “module” to process the prosody (p. 1185). That is to say, the “phoneme focus” is possibly explicitly parsed in the left hemisphere to help shape phonemic representation and identify intended lexical candidates.

These results are also consistent with the current model. The phoneme monitoring task taps the prosodic level of the cascading inhibition model, and processing at this level is hypothesized to be lateralized to the left hemisphere. Thus, the comparable performance of RHD compared to controls and impaired performance of LHD would be expected. Walker, Daigle, and Buzzard (2002) also showed that LHD patients performed inferiorly to RHD patients in lexical stress processing.

One extreme case study was reported by Van Lancker-Sidtis (2004), involving a 57 year-old patient who underwent left hemispherectomy when he was five (after the critical period of language acquisition). He reportedly functioned normally as an adult, having graduated from college and become regularly employed. A range of linguistic tests was administered, and this individual scored within normal limits for ten of twelve. The only two tests that showed deficits were lexical stress comprehension and an active-passive test. The lexical stress comprehension test was adapted from Van Lancker and Sidtis (1992), and it assessed noun phrases vs compound nouns (e.g. green **HOUSE** vs **GREEN**house) and verbs vs nouns (im**PORT** as verb vs **IM**port as noun) contrasted by lexical stress. Thus, when functioning with only the right hemisphere, and when other prosodic and linguistic functions are fine, lexical stress parsing is still impaired. This one extreme example suggests that lexical stress parsing might be encoded in the left hemisphere early in development.

2.2.2 Study results that are in conflict with current hypothesis

Weintraub, Mesulam, and Kramer (1981) conducted an early study to test RHD patients and NBD controls on their ability to comprehend local phonemic stress. Participants were asked to choose pictures to represent compound nouns or noun phrases that were contrasted by phonemic stress (for example, **GREEN**house vs green **HOUSE**). The results revealed significant impairments of RHD patients relative to the controls. This pattern was interpreted as indicating the right hemisphere's involvement in prosodic processing of word-level stress.

However, the task was metalinguistic and therefore did not tap into online phonological processing. It is quite possible that RHD patients were impaired in other stages of the task rather than lexical stress parsing. As Wunderlich et al. (2003) pointed out, RHD patients were indeed impaired in explicit processing of phonemic stress.

Shah, Baum, & Dwivedi (2006) also provided some counter-evidence to the view of left lateralization of lexical stress parsing. The authors argued that, because most studies of lexical stress used metalinguistic tasks, results were influenced by other post-parsing processes. To address this problem, Shah et al. (2006) used an associative priming task to separate the processes of lexical stress parsing and lexical identification. The stimuli were word pairs, one prime followed by one target. The prime was either correctly stressed or incorrectly stressed, and the target was either a word related to the prime, an unrelated word, or a nonword. In total, six conditions were formed: Prime CS (correctly stressed)-Related (e.g. **CAN**cer-Disease), Prime CS-Unrelated (e.g. **PAIN**ter- Basis); Prime IS (incorrectly stressed)-Related (e.g. fe**MALE** – Woman); Prime IS-Unrelated (e.g. **CAFF**eine-Hotel); CS-Nonword-(e.g. be**LOW**- Nefius); IS-Nonword (e.g. fly**ING**-Zarfer). The stress placement (i.e. whether the first syllable or the second syllable was stressed) was counterbalanced for all conditions. LHD, RHD and NBD participants were instructed to make a word/nonword judgment for each target stimulus. In implicit tasks such as this one, the purpose is to see how the activation of the prime influences the activation of the target without metalinguistic analysis of the prime.

Results showed that for all groups, Related target priming was faster than Unrelated target priming for all stress conditions, which indicates that priming was successful. For Unrelated prime-target pairs, NBD controls' reaction times for IS and CS primes were not significantly different. The authors reasoned that the NBD subjects' apparent insensitivity to stress may be due to the relatively long inter-stimulus interval between prime and target (250ms), as well as the relatively slow RTs of these older adults. Thus, by the time subjects responded, the effects of any activation delay engendered by incorrect stress placement may have been overridden.

Overall, LHD subjects' RTs were slower for IS than for CS primes. However, close examination of the individual data indicated that only four out of the ten LHD patients showed this pattern. For the majority of the LHD group, performance was similar to that of the NBD group. That is, target RT was not significantly influenced by prime stress patterns. Because of the large within-group variability, no definite conclusion can be drawn from this dataset.

For RHD patients, Unrelated targets were responded to more slowly in the CS condition than in the IS condition. Therefore, the RH was hypothesized by the authors to be "more sensitive to conflicting prosodic aspects" (p.152). As the meaning of the CS prime is activated, RHD patients as a group were slower in inhibiting the unrelated meaning of the prime and, perhaps, in switching attention to the target meaning.

Caution is warranted in accepting these interpretations, due to large within-group variability for both LHD and RHD groups. As noted above, the overall pattern for LHD group is not the same as that shown by the majority of the group members. This discrepancy may indicate a skewed distribution. In fact, RT data for the Unrelated prime-target pairs in both patient groups were slightly positively skewed.

Several other cautions must be taken into consideration, too. First, if the LH is responsible for the lexical stress parsing process, LHD patients might be expected to show some disruption in performing these tasks. In the Shah et al. (2006) study, however, LHD patients appeared to perform similarly to NBD participants. As noted by the authors, this may be due to the long ISI and slower response time in older adults. LHD patients may have been able to compensate for some initial disruption in lexical stress parsing during the ISI or the response-making stage.

Second, it is possible that the LHD and RHD groups were not matched in the degree of severity of impairments caused by their brain damage. The LHD patients who could follow task instructions may be relatively high functioning in the first place. They might be more functionally comparable to older NBD adults.

Third, the control for metalinguistic analysis may not have been complete. In order for a priming study to successfully suppress metalinguistic strategies, the inter-stimulus interval needs to be very short. The fact that inhibition occurred suggests that the processing engendered by the experimental task was not entirely automatic. Specifically, the performance of RHD patients was actually influenced by the difficulty of inhibiting the CS prime. The inhibition process itself is a strategic, post-activation process.

The same outcomes could also be explained by an alternative possibility, in which processing at the prosodic level of the cascading inhibition model is indeed lateralized to the LH. When no metalinguistic task is required, the intact left hemisphere of RHD patients may parse the lexical stress pattern normally. The slower response in the CS condition than the IS condition, after a sufficiently long ISI, could possibly reflect the fact that the right hemisphere is involved in lexical inhibition processes as well (Aron, Robbins & Poldrack, 2004; Day, 1977; Hagoort, Brown, & Swaab, 1996; Nakagawa ,1991; Querné, Eustache, & Faure, 2000).

2.2.3 Summary of the lesion studies

Viewing all the lesion studies together, the majority of evidence suggests left hemisphere involvement in lexical stress parsing. However, several cautions should be taken in interpreting lesion studies in general.

First, processing in damaged brains does not necessarily reflect normal processes. The damage could influence many areas and processes, and therefore cause unpredictable plasticity and compensatory strategies.

Second, the severity of brain damage usually was not matched, or addressed, between LHD and RHD patient groups within and across studies. Because of the aphasic symptoms typically associated with left hemisphere damage, the LHD patients included in behavioral studies may be highly functioning, which may or may not be the case for the RHD group. This could be a potential source of biased sampling. Compoundedby the usual small sample sizes, significant results may come from a few extreme subjects.

Third, the majority of the studies used metalinguistic tasks which could be influenced by many processes other than online lexical stress parsing.

Given the inconsistencies in the lesion studies and the possibility of metalinguistic analysis involved, a study that tests the lateralization of online lexical stress parsing is necessary to resolve the disparities in the literature. With an ERP paradigm, online processing of conflict resolution (indexed by waveform deflections) can be easily tracked.

2.3 APPLICATION OF ERP

Event-Related Potentials (ERP) can reflect the online course of processing and integration of prosodic information with high temporal resolution (Handy, 2005; Luck, 2005). This section discusses the possibility of using this paradigm to answer this study's research questions.

A few studies will be discussed concerning three very important questions: First, what ERP indices are the candidates for lexical stress parsing? Second, how did these ERP indices distribute over the scalp in past studies, and how might this distribution reflect underlying neural processes? Third, to what extent do the two hemispheres communicate and interact with each other for processing prosodic information?

2.3.1 ERP index candidates

As mentioned in Chapter 1, Friedrich et al. (2004) did a cross-modal word fragment priming study to investigate how lexical stress influences lexical identification. They constructed four conditions, combining matched/mismatched prosody with matched/mismatched segments. The participants heard a word fragment (the first syllable) and identified the corresponding word target in a visual display. Behavioral results showed significant main effects of both lexical stress violation and segmental violation. However, there was no interaction between these two factors, which indicated the potential independence of semantic and prosodic processes.

Friedrich et al. (2004) supplemented the behavioral study with ERP methods, and compared the P350 (a positivity peak at around 350ms following stimulus onset) elicited by mismatched stress and mismatched segments. The magnitude of stress-related P350 was significantly smaller than that of the segment-related P350. In addition, the stress-related peak was largest at left posterior sites while the larger, segment-related P350 was maximal at left anterior regions. As proposed in Chapter 1, P350 is hypothesized to reflect phonological processing. Under that assumption, the Friedrich et al. results could be evidence of prosody and segments processed at different levels in the phonology hierarchy. For this reason, P350 will serve as an ERP index candidate for the proposed study.

Several other studies showed that N400 (a negativity that peaks around 400ms following stimulus onset) can indicate lexical incongruities caused by prosodic violation (Steinhauer, Alter, and Friederici, 1999; Steinhauer, Abada, Pauker, Itzhak & Baum, 2010) as well as those due to the more well-known violations of segmental information. Thus, N400 will serve as an indicator for lexical concept identification.

2.3.2 How ERP indicates lateralization

The validity of using scalp distribution to investigate lateralization issues has been investigated in previous studies using dichotic listening methods (Moncrieff, Jerger, Wambacq, Greenwald, & Black, 2004). Moncrieff et al. (2004) found that the topographic distribution of the ERP signal can reflect lateralized processing induced by lateralized presentation.

In addition, source localization method via dipole fitting will be implemented to estimate the localization of the response generators (Slotnick, 2005). Using implant artificial dipole, it has been demonstrated that the source localization procedure has an accuracy range of about 1cm (Cohen, Cuffin, Yunokuchi, Maniewski, Purcell, Cosgrove, Ives, Kennedy & Schomer, 1990). This accuracy is sufficient to address initial questions of lateralization.

2.3.3 Possible inter-hemispheric communication

A clear lateralization pattern in an ERP signal does not exclude the possibility that the pattern is due to the constant communication and cooperation of the two hemispheres in integrating prosodic and segmental information.

Friedrich, von Cramon and Kotz (2007) did an ERP study on patients with corpus callosum (CC) lesions to investigate the interaction between prosody and syntax processing in German. Three groups of participants were included (N=5 in each group): patients with lesions in the anterior two-thirds of the CC; patients with posterior one-third lesions; and healthy NBD controls. The stimuli were sentences with verbs that could be used as transitive or intransitive, which differ in the existence of prosodic boundaries. Specifically, there is an immediate prosodic boundary following an intransitive verb which does not exist after a transitive verb. A syntax and prosody mismatch condition was created by cross-splicing the initial portion of sentences with intransitive verbs, together with the latter portion of sentences that contained transitive verbs. In this mismatch condition, prosodic cues indicated that the verb should be intransitive whereas the syntax indicated the opposite.

The authors found that both healthy controls and anterior CC lesion groups demonstrated an N400 effect for this mismatch. The posterior CC lesion group, however, didn't show this effect. The posterior CC lesion group did have an N400 for a semantic violation in a control experiment. Therefore, the mismatch experiment suggested that the two hemispheres communicated prosodic information via the posterior portion of the corpus callosum. That was claimed to be why, in the posterior CC lesion group, the conflict between the prosodic and syntactic information could not be detected.

The Friedrich et al. (2007) study provides alternative insights for the proposed study. As we will discuss in detail in the next Chapter, the final targets of our stimuli also provide a stress-syntax interface. Specifically, the proposed study will use context sentences that predict a noun target, and the actual target will be either a noun or a verb. Thus, the expectation of the grammatical category of the target will be driven by syntax. Targets will be low-pass filtered so that lexical stress will drive the resolution of the target. If N400 is obtained under this experimental design, it might reflect an integration violation instead of a lexical selection violation.*

******Note*: Theoretically, some researchers hold that N400 reflects lexical access because it has been shown to be reduced by any factors that facilitate lexical access (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Holcomb & Neville, 1990; Lau, Phillips, & Poeppel, 2008) whereas others holds that N400 reflects an integration difficulty (Hagoort & Brown, 2000; Hagoort, Hald, Bastiaansen, & Petersson, 2004; van Berkum, Hagoort, & Brown, 1999). The current study is not aimed at distinguishing these two mechanisms of N400 elicitation.

3.0 INTEGRATION OF PAST THEORIES, THE CURRENT THEORETICAL FRAMEWORK, AND CURRENT HYPOTHESES

In Chapters 1 and 2, a cascading inhibition model was introduced as the theoretical framework of lexical stress parsing. This model incorporates some aspects of past theories that have been mostly supported in the literature, and discards other aspects that have been refuted by empirical results. In this way, the majority of the available data could be accounted for while the model could still be as parsimonious as possible.

Specifically, for the aspects incorporated, this model agrees with the limiting domain hypothesis (Dickey, 1995) that lexical stress is involved in the selection stage of lexical processing but not in the initial stage of activation, based on the evidence of multiple priming studies (Cutler, 1986; van Donselaar, et al., 2005). In addition, it agrees with the lexicalization hypothesis (Packard, 1986) in positing that the processing of lexical stress is left lateralized.

Two mostly unsupported aspects of these theories were discarded. The first is the implication from the lexicalization hypothesis (Packard, 1986) that processing of lexical level prosody (including lexical stress) and segments is fundamentally the same. Lexical stress is hypothesized by Packard to be phonemic and its processing to be as obligatory as that of consonants and vowels. As indicated by priming studies and some neuroimaging studies, this conjecture is unlikely. Temporally, lexical stress is not exploited in the same time window as segmental features (Cutler, 1986; van Donselaar, et al., 2005). Spatially, the scalp distributions of segmentally induced ERP deflections are qualitatively different from those elicited by lexical stress (Friedrich et al., 2004).

Second, the current model discards an explanatory mechanism of the limiting domain hypothesis that different processing strategies for segments and lexical stress arise from a window-size limitation of the processor. According to this hypothesis, lexical stress cannot be used immediately because it exceeds the "syllable-sized chunk" limitation (Dickey, 1995, p. 140). This window-size limitation is contradicted by multiple onset gating experiments reviewed in Chapter 1(Arciuli & Cupples, 2004; Lindfield, Wingfield, & Goodglass, 1999; Wingfield, Lindfield, & Goodglass, 2000). In fact, the processor can "use" the phonological information from lexical stress by the end of the first gate (50ms post onset), at which point correctly stressed words already hold significant phonological processing advantages over incorrectly stressed words. Therefore, the processing difference between segmental information and lexical stress cannot be attributed to a syllable-sized processing window. The processor can detect subtle differences between lexical stress patterns very early on; the detected information is just not used to activate the initial word cohort.

These controversies could be well resolved under the cascading inhibition model. Specifically, lexical stress processing is situated at a different level from, and does not make direct contact with, the lexical concept representation level. Thus, the spreading of activation (or inhibition) from the lexical stress level would not reach the lexical concept representation level in the very brief time period required for initial lexical cohort activation. Lexical stress processing information, therefore, could only be used later, at the selection stage of lexical processing.

Also, under the cascading inhibition model, though lexical stress parsing and segmental information processing are both likely to be left hemisphere lateralized, the former may involve different anatomical sites from the latter, because they are situated at different processing levels.

A range of hypotheses can be generated under this new model. Some of the most obvious ones are: lexical stress parsing will not be disrupted by the unavailability of segmental information; it is a parallel process with segmental processing; lexical stress may serve as an independent contributing factor in disordered language processing; and it may be selectively affected in left hemisphere damaged patients.

Each hypothesis is a step further than the previous, and each one needs to stand on the basis of the previous one. Thus, the current study will test two of the most fundamental hypotheses forming the basis of this framework. ***Hypothesis A***: Lexical stress parsing can modulate lexical selection without the presence of segmental information. ***Hypothesis B***: Lexical stress parsing will be lateralized to the left hemisphere.

The respective experimental conditions and control conditions to test each hypothesis are listed in *Table 3-1*. For both hypotheses, the critical conditions are (1) and (2). As indicated in *Table 3-1*, the "predicting statement" sentences for Conditions (1)-(4) will lead participants to expect a noun target (see Chapter 4 for details of the stimuli). The appearance of a verb stress pattern at the target position, therefore, will induce event-related potential (ERP) deflections due to expectation violation.

Specifically, in testing ***hypothesis A***, Condition (2) is hypothesized to induce a larger N400 (P350) when compared to Condition (1). In addition, if this effect is due to lexical stress parsing and not to artifacts from the removal of segmental information, Condition (4) will elicit a larger N400 (P350) than Condition (3) as well. Further, if lexical stress parsing is not influenced by the absence of segmental information, the amplitude difference between (3) and (4) is expected to be similar to the difference between (1) and (2), For testing ***hypothesis B***, it is predicted that the elicited N400 (P350) is lateralized to the left hemisphere (as indicated by peak-to-peak amplitude, GFP and source localization measures; Please see Chapter 4 for definition and implementation of these amplitude measures).

Conditions (5), (6) (7) and (8) are designed to serve as lateralization control conditions. Under the current design, if the experiment is under appropriate control, a P300 elicited by Conditions (5)-(8) under the oddball paradigm should be lateralized to the right hemisphere. The rationale is that, processing Gender Shift (i.e. the change of the speaker's sex) is demonstrated to be a right hemisphere function by both ERP (Jerger, Alford, Lew, Rivera, & Chmiel, 1995; Lattner & Friederici, 2003) and fMRI studies (Belin, Zatorre, Lafaille, Ahad, & Pike, 2000; Lattner, Meyer, & Friederici, 2005)

Table 3-1.Hypotheses and conditions

Hypotheses	**Experimental Conditions**	**Control Conditions**
A: Lexical stress parsing can modulate lexical selection without the presence of segmental information.	(1) Noun-predicting statement +Noun Stress target (filtered) (2) Noun-predicting statement +Verb Stress target (filtered)	(3) Noun-predicting statement +Noun Stress target (unfiltered) (4) Noun-predicting statement +Verb Stress target (unfiltered)
B: Lexical stress parsing (without segmental information) will be lateralized to the left hemisphere.	(1) Noun-predicting statement +Noun Stress target (filtered) (2) Noun-predicting statement +Verb Stress target (filtered)	(5) 70% Noun Stress target (filtered) + 30% Gender Shift (filtered) in an oddball paradigm (6) 70% Verb Stress target (filtered) + 30% Gender Shift (filtered) in an oddball paradigm (7) 70% Noun Stress target (unfiltered) + 30% Gender Shift (unfiltered) in an oddball paradigm (8) 70% Verb Stress target (unfiltered) + 30% Gender Shift (unfiltered) in an oddball paradigm

Alternative result patterns may occur: some could still be well explained by minor modification of the proposed model, while others will require a complete change. For example, in testing Hypothesis A, if the N400 (P350) differences are larger for Conditions (3) vs (4) than for

Conditions (1) vs (2), this could still fit under the current model, because amplitude differences may come from two sources: lexical stress parsing at the prosodic level of the model, and vowel reduction at segmental (phonetic) level. However, if N400 (P350) differences are significantly smaller for Conditions (3) vs (4) than for (1) vs (2), this will reflect a qualitative nonlinear change of lexical stress processing when segmental information is removed and refute the current model.

Similarly, in testing Hypothesis B, if the lexical stress-elicited ERP is a left hemisphere function, but at same set of electrode sites as segment-elicited ERP, the model can still explain these results: perhaps different levels of processing in the cascading inhibition model can be localized in the same regions, or ERP source localization does not have enough precision to distinguish nearby regions. However, if the ERP elicited is lateralized to the right hemisphere, it would not fit under current model.

Other hypotheses generated from the cascading inhibition model could be tested in future research by adding other control conditions, switching the testing population, or using a different experimental method. For example, by adding a segmental violation condition to the current experimental design, we could test whether lexical stress parsing is truly qualitatively independent of and different from segmental processing. Or by using fMRI, a more precise localization pattern of lexical stress parsing could be established.

However, it should always be kept in mind that lexical stress constitutes only one aspect of linguistic prosody. For real life online language processing, it must be parsed in the context of other levels of linguistic prosody and respective syntactic environment. For instance, because grammatical category could be influenced by lexical stress, an interaction of lexical stress with syntax and phrase level prosody is inevitable. Eventually, in building a more comprehensive model of linguistic prosody processing, interhemispheric interplay must be brought into the picture by considering factors such as the role played by corpus callosum (Friedrich et al., 2007).

4.0 EXPERIMENTAL METHOD AND DATA ANALYSIS

This chapter elaborates the experimental designand methods in detail, in five sections below. In *Section 4.1*, each hypothesis is re-stated with the specific experimental conditions and dependent measures for testing. *Section 4.2* describes the recruitment of, and inclusion and exclusion criteria for, participants. The stimuli construction, validation, and recording procedures are treated in *Section 4.3*. *Section 4.4* is devoted to procedures of the experiment as well as EEG (Electroencephalography) instrumentation. Finally, in *Section 4.5*, the data analysis methodis described.

4.1 THE HYPOTHESES AND EXPERIMENTAL CONDITIONS

The two hypotheses of the current study are: A) Lexical stress parsing can modulate lexical selection without the presence of segmental information; B) Lexical stress parsing is lateralized to the left hemisphere.

The respective experimental and control conditions to test each hypothesis are listed in *Table 4-1*. The description and explanation of conditions is in Chapter 3. The specific methods for obtaining and analyzing the dependent variables (ERP peak-to-peak amplitudes and Hemispheric Global Field Power) can be found in *Sections 4.4* and *4.5*, respectively.

Table 4-1.Hypotheses and conditions

Hypotheses	**Experimental Conditions**	**Control Conditions**	**Dependent measures**
A: Lexical stress parsing can modulate lexical selection without the presence of segmental information.	(1) Noun-predicting statement +Noun Stress Pattern (filtered) (2) Noun-predicting statement +Verb Stress Pattern (filtered)	(3) Noun-predicting statement +Noun target (unfiltered) (4) Noun-predicting statement +Verb target (unfiltered)	Peak-to-peak amplitudes of N400 and P350 at electrodes Cz (center midline), Pz (posterior midline)
B: Lexical stress parsing (with and without segmental information) will be lateralized to the left hemisphere.	(1) Noun-predicting statement +Noun Stress Pattern (filtered) (2) Noun-predicting statement +Verb Stress Pattern (filtered)	(5) Female produced filtered word as frequent standard stimuli (70%) in an oddball paradigm (6) Male produced filtered word as infrequent deviant stimuli (30%) in an oddball paradigm	Hemispheric Global Field Power (GFP) of N400, P350 and P300 computed from 26 electrodes at the each side (Left vs Right);

Table 4-1. (Continued)

	(3) Noun-predicting statement +Noun target (unfiltered) (4) Noun-predicting statement +Verb target (unfiltered)	(7) Female produced unfiltered word as frequent standard stimuli (70%) in an oddball paradigm (8) Male produced unfiltered word as infrequent deviant stimuli (30%) in an oddball paradigm	P300, P350, and N400 amplitudes at C3 (left central) and C4 (right central); and T7 (left temporal) vs T8 (right temporal)

4.2 SUBJECTS

Thirty-eight normalyoung native English speakers (18-35 years old) were recruited for this study from undergraduate classes or through advertisements. To determine their basic eligibility for the study, all potential participants were initially interviewed by telephone (Please see *Appendix A.1* for the script of this interview). Exclusion criteriaincluded self-reported neurological diseases, head injuries, auditory processing disorders, or use of hearing aids. Education level was controlled within the range of 8-20 years, to match the educational level of patient participants in most previous studies (e.g., Pell, 2006). In addition, potential participants for this study were asked about bilingualism, and individuals who have had more than minimal understanding of languages other than English were excluded in order to prevent possible interference from other prosodic systems.

Further screening procedures included audiometric screening, a randomized dichotic digit test and a handedness test (Please see *Appendix B* for specific procedures and criteria for all screening tests). The rationales for these screening procedures were, respectively: (1) normal peripheral hearing is necessary for completing the experiment and detecting the effects; (2) randomized dichotic digit data can help exclude the possibility of a central auditory processing disorder; (3) knowing handedness is necessary for interpreting the laterality data.

Four potential participants were excluded from the study by applying the above criteria: one had a high level of understanding in Mandarin Chinese; one was left-handed; one was wearing a hearing aid; and one had a random dichotic digit test score lower than the normal range.

Thirty-two young normal listeners with normal hearing and auditory processing, who passed all screening procedures, were tested in both experimental and control conditions (29 females and 3 males; mean age=22.33, standard deviation=2.327; mean years of education=15.80, standard deviation=1.643). An additional four young normal listeners were tested in control conditions only due to equipment problems or time limitations (3 females and 1 male; M age=22.11, SD=2.118; M years of education=16.41, SD=1.572).

Finally, all subjects tested were given a structured written questionnaire(please see *Appendix A.2*) about factors affecting ERP results: chronic illness, regular medications, smoking habits, exercise, and interval since last meal prior to recording (Cinciripini, Benedict, Van Vunakis, Mace, Lapitsky, Kitchens, Nezami, &Gjika, 1986; Grant &Judd, 1976; Koella & Czicman, 1996). This questionnaire was not used to exclude participants, but the information was gathered for potential *post hoc* data rejection or interpretation.

4.3 STIMULI

4.3.1 Stimuli creation

The "targets" for this experiment were two-syllable Noun-Verb (N-V) homonym pairs contrasted by lexical stress pattern, for example, **IN**sult vs in**SULT**. For each pair, 68 candidate "noun-predicting statements" were written to be syntactically and semantically predictive of the noun member (e.g.**IN**sult). An example noun-predicting statement is:

"He told her she looked old and dowdy and she thought his remark was quite a/an **______**" [**In**sult]

These statements were presented in a written cloze task to two groups of young normal individuals (N=9, and N=10 respectively), in which participants were asked to fill in the blanks at end of each statement (the Noun target) with the word that they "think should go there" (Please see *Appendix C* for the task instructions).

The inclusion criterion for the stimulus statementswas that cloze (probability of a given kind of answer) was at least 80% for trochaic (first syllable stressed) nouns. Cloze data were based on whether the answer was a two-syllable trochaic noun (first syllable stressed), not whether the answer was the exact intended Noun target. For example, the statement "You enjoyed the aroma when your friend from India burned some____" had as its intended target Noun "**IN**cense". One participant answered "**CAN**dles," which was also counted as correct, because "**CAN**dles" is a two-syllable trochaic noun.

Twenty-eight statements met this criterion and were included as final noun-predicting statements. Five statements with cloze values lower than the inclusion criterion (but still higher than 70%) were usedin practice trials (see *Section 4.4* for procedures for presenting practice and experimental stimuli).

The complete list of stimulus statements is in *Appendix C.1,* with cloze probabilities forboth the trochaic stress pattern match and an exact target word match. The demographic information for participants in the cloze task is in *Appendix C.2*,and the instructions and example format of the cloze task are in *Appendix C.3.*

Another set of 33 sentences were used to elicit Verb target words during stimuli recording. *Appendix C.1* provides a complete list of verb eliciting sentences. They were constructed to end with the Verb counterparts of the Noun targets of experimental and practice sentences. These sentences were merely for eliciting Verb target words and were not used otherwise in the study.

Twenty-three noun-predicting filler sentences were constructed as well. Each filler sentence could end with two different target words(or phrases): one with first syllable stress, and the other with second syllable stress.From these, three sentences were used in practice trials and 20 were used in the experimental trials, as specified in the following sections.

4.3.2 Stimulus recording and editing

4.3.2.1 Conditions (1)-(4)

The 28noun-predicting statements with highcloze (minimum 80% trochaic stress cloze), five practice statements, 33 verb-eliciting sentences and 46 filler sentences (23 with a first-syllable stressed target and 23 witha second-syllable stressed target) were recorded, in a sound- and electronically-shielded booth, by a practiced female native speaker of American English. Recordings were made into .wav file in Adobe Audition 3.0 (an acoustic recording and editing software by Adobe Corporation) at a sampling rate of 44,100 Hz. For all recordings, the speaker was instructed to produce the statements at a normal pace and without any undue emphasis, and her productions were monitored by the principal investigator and a native English speaker. The speaker spoke at a consistent distance of about 3cm away from an Audio-technica CARDIOID ATR20 microphone. The acoustic signal input to the computer was set to “line in” under the

Windows 7 operating system (Microsoft Corporation). Recording noise was reduced by 100% under Abode Audition 3.0, using a procedure described by Winters (2006).

For purposes of recording, the noun-predicting statements plus targets as well as the verb-eliciting sentences were padded to avoid end-of-sentence declination effects on the target words. Specifically, a short phrase was added to the sentence, after the target word. For example, the “INsult” stimulus above ends with “to her,” and the “INcense” stimulus ends with “after dinner.”

The 33 target Nouns for this experiment (28 experimental; 5 practice) were excised from the recorded statements, and the 33 target Verbs were similarly cut from their sentence contexts. Then all target words were low-pass filtered to create 66 target stress patterns (33 trochaic Noun Stress Patterns and 33 iambic Verb Stress Patterns). The cutoff frequency 900 Hz was chosen so as to make the speech unintelligible without distorting the prosodic information. The process for estimating this cutoff was performed by three native English listeners, and is described in *Appendix D.*

Finally, the 33 noun-predicting statements (experimental and practice) were cross-spliced with the four kinds of targets (Noun, Verb, filtered Noun Stress Pattern and filtered Verb Stress Pattern), generating 112 experimental stimuli (four conditions, 28 in each condition) and 20 practice stimuli (four conditions, five in each condition). The cross-splicing point in each statement was the point where the original target word began. Each cross-spliced statement-plus-target was saved as a separate .wav file. The silent portions at the beginning and end of each .wav file were removed.

4.3.2.2 Conditions (5)-(8)

A male version of the same set of stimuli was recorded in Adobe Audition 3.0 (Adobe Corporation) by a native speaker, using the same procedures.

The male version of the targets served as the deviant stimuli for the oddball paradigm. The female version served as the standard stimuli. In the oddball task, listeners heard the female version of the stimuli70% of the time, and 30% of the time they heard the male version of the same stimuli.

4.4 EXPERIMENTAL PROCEDURES AND EEG INSTRUMENTATION

Participants who passed all the screening procedures were presented with experimental stimuli while they wore a stretchy EEG Cap (electroencephalographycap) to record ongoing waveforms. The experimental procedures are described in *Section 4.4.1.* In *Section 4.4.2,* the instrumentation method for EEG recording and the recording procedures are specified.

4.4.1 Experimental procedures

There were two blocks of trials. Block 1 contained experimental sentences with filtered targets (Conditions (1) and (2)) and filtered targets for the oddball listening task (Conditions (5) and (6)). Block 2 contained experimental sentences with unfiltered targets (Conditions (3) and (4)) and unfiltered targets for the oddball listening task (Conditions (7) and (8)).

As indicated in *Section 4.3.1*, each filler sentence ended with two different target words. The target words for the filler sentences that were used for Block 1 differed from those used in Block 2. Half of the filler sentences ended with first-syllable-stressed targets in Block 1, and the same set of sentences ended with second-syllable-stressed targets in Block 2. The reverse was true for the other half of the filler sentences: they ended with second-syllable-stressed targets in Block 1 and first-syllable-stressed targets in Block 2. Within each block 10 filler sentences of each kind (first- or second-syllable-stressed targets) were used in the experimental block (specified below). The rest were used in the practice block. All sentences were pseudo-randomized within each block of trials, to make sure that 1) filler sentences were intermixed with experimental sentences at least every three trials; and 2) the block ended with a filler sentence.

All stimuli were presented at a level 40dB above subjects' pure tone average (threshold average for three frequencies: 500Hz, 1000Hz, and 2000Hz) for the worse ear to ensure that the acoustic input was clear. Stimuli were presented through TDH-49/50 earphones. Stimulus intensity level was at least 20dB above the threshold at 2000Hz.*

For the experimental conditions ((1)-(4)), participants were instructed to listen for the answer for one comprehension question, which they would be asked after the task block was complete. The purpose for this procedure was to keep the participants attentiveand processing the linguistic contexts (predicting statements) throughout the entire experiment. The question addressed an explicitly-stated fact that was supplied in the last third of the stimulus block, and the answer was "Yes" in one block of trials, and "No" in its corresponding block.

For control oddball paradigm, a total of 150 stimuli were presented in filtered and unfiltered conditions, respectively. The standard stimuli occurred 105 times and the deviant stimuli occurred 45 times. The experimental task for these conditions was passive listening.

Participants were given a break after completing each block of trials, or whenever they asked for one.

Note: Because the audiometric threshold is nonlinear above 2000Hz, it cannot be guaranteed that the stimuli were be 20dB above threshold at frequencies higher than 2000 Hz simply by making sure that the stimuli were 40 dB above the average threshold of the audiometric results.

4.4.2 EEG recording

Brain electrical activity was recorded from 64 silver-silverchlorides (Ag/AgCl) mounted on an elastic cap (Neuroscan Quick-Cap, Compumedics Neuroscan). These electrodes were arranged under the standard Quick-Cap setting in the SynAmps RTsystem (Compumedics Neuroscan), which link each electrode to a separate channel. After fitting the Quick-Cap to subjects' head sizes, about 5 grams of conductive EEG gel were applied to fill the center hole of each electrode.

Two separate electrodes were mounted above and below the left eye to monitor vertical electro-oculographic (VEOG) activity, Finally, two additional electrodes were mounted on the mastoid process (M1 as the left mastoid process and M2 as the right mastoid process), to serve as references. These electrodes were held with tape and filled with conductive gel as well.

Before the recording, each electrode's impedance was checked to make sure it was below 10kΩ. This was done in the NeuroScan SynAmps RT system, in which a user-customized interface shows the impedance of each electrode by color (low impedance in black or dark blue and high impedance in red and pink). If a specific electrode hada high impedance value, a stick was used to adjust the contact of the electrode by gently stirring the gel until the impedance changed to be 10 kΩ or lower (indicated by black or dark blue color).

The stimuli were presented to the participants through the Neuroscan system Stim^2(Compumedics Neuroscan) program. The pseudorandomization for each block of trials was programmed into the system. The inter-stimulus interval (ISI) between consecutive trials was 4s.

When the recording started, individual sweeps of electroencephalic (EEG) activity, time-locked to the onset of the targets, were recorded and stored in a continuous file (.cnt) for offline analysis. Raw EEG data were continuously recorded and digitized at 280Hz and the ongoing waves were bandpass filtered from 0.05Hz to 100Hz. Analog filter skirts were sloped at -12dB per octave. The amplified and filtered EEG activity was digitized through an acquisition interface system (Neuroscan Synamp) and routed to a computer for individual sweep storage, display, averaging and post hoc filtering (SCAN 4.0, Compumedics Neuroscan). Trials with artifacts were discarded offline if the amplitude of EEG signal exceeded ±50μV.

4.5 DATA ANALYSIS

This section is divided into five sub-sections. Section 4.5.1 specifies the offline pre-processing steps for continuous EEG files, performed before the actual data analysis. *Section 4.5.2* discusses measurement and computation of amplitude parameters. *Section 4.5.3* describes the main statistical tests to address the experimental hypotheses. Finally, in *Section 4.5.4*, the method is described for identifying the underlying source that generated the surface topography.

4.5.1 EEG offline preprocessing

EEG recordingswere pre-processed offline in four steps before being subjected to statistical analysis: cutting into epochs, correcting for baselines, linear detrending, and rejecting artifacts.

For cutting epochs, the time window was identified from -200ms (200ms before target onset; the point at which target begins is denoted as 0ms) to + 1000ms (1000ms after stimulus onset). This whole analysis window was defined as an epoch and saved as epoch file (.eeg) (Handy, 2004). Then, each epoch was baseline corrected using the segment from -200ms to 0ms, which means that the voltages from the pre-stimulus data points were averaged, and that value was subtracted from all data points in the post-stimulus interval (Neuroscan Edit Manual, Vol II, p. 146). Subsequently, linear detrending was done for the entire epoch to remove trend artifact (Tenke & Kayser, 2001).

For the final step of pre-processing, epochs were rejected whenever electrical activity in the eye channel (VEOG) exceeded ±50 µV. This was done manually for each baseline-corrected and linearly-detrended file. The alpha wave of EEG primarily was managed by minimizing the fatigue experienced by the subjects during recording. Because muscle activity and movement generally cause high amplitude non-periodic spikes, any epochs that had spike amplitudes larger than ±100 µV were rejected. Overall, less than 20% of the trials were rejected for this reason.

All remaining epochs were subjected to the standard averaging algorithm in the Neuroscan system and saved as average files for each condition. The averaged epochs were low-pass filtered at 30Hz to remove high frequency noise. The digital filter slope was set at -12dB per octave.

If the epoch rejection rate for a particular subject was higher than 30%, it has been suggested that the entire dataset should be rejected for that subject (Picton, Bentin, Berg, Donchin, Hillyard, Johnson, Miller, Ritter, Ruchkin, Rugg, & Taylor, 2000). None of the participant data met this rejection criterion.

4.5.2 Measurement of ERP amplitude

The dependent variables for the current study are peak-to-peak amplitudes and hemispheric Global Field Power (GFP) of ERP deflections: N400 and P350 for Conditions (1)-(4) and P300 for Conditions (5)-(8).

As indicated in Table *4-1*, peak-to-peak amplitudes of two selected electrodes were used to address Hypothesis A, whereas the hemispheric GFP was calculated to address Hypothesis B.

The following two sub-sections first re-state the specific predictions for ERP amplitudes generated from the current hypotheses. Then the specific method of measuring peak-to-peak amplitudes and GFP are elaborated.

4.5.2.1 Predictions about ERP amplitudes

Based on the hypotheses, the following predictions were made about ERP deflections:

(1) The Verb Target Stress Pattern conditions (Conditions (2) and (4)) will elicit larger P350 and N400 amplitudes than Noun Target Stress Pattern conditions (Conditions (1) and (3)), at Cz and Pz, because they violate the expectancy. (Hypothesis A)

(2) For Conditions (1)-(4), GFP results and peak-to-peak amplitudes of N400 and P350 will produce a main effect for Hemisphere and may reflect an interaction between Lexical

Stress Pattern and Hemisphere. Specifically, amplitudes may be larger for the left side than the right side. (Hypothesis B). In contrast, GFP results and peak-to-peak amplitudes of P300 will be larger in the right side than the left side.

4.5.2.2 Measurement of amplitudes

According to past studies, N400, P350 and P300 are all central-parietal distributed waveforms and usually maximized at Cz (central midline) and Pz (posterior midline) electrodes (Friedrich, Kotz, Friederici, & Alter, 2004; Kutas & Hillyard, 1980; Ji, Porjesz, Begleiter, & Chorlian, 1999). To address Hypothesis A, amplitudes were measured from both sites (Cz and Pz).

In order to obtain peak-to-peak amplitudes, the ERP indices of interest need to be manually labeled. For each experimental average file (.avg), three peaks* were labeled: the negativity at around 200ms (180-250ms), a positivity around 350ms (300-430ms) and the negativity around 400ms (390-570ms). The criteria for labeling were that: 1) only the peaks within the respective prescribed window were considered; 2) the absolute highest and lowest points were labeled; 2) if two peaks at around 350ms were similar in amplitude, the later one was labeled.

A second rater, naïve to condition, labeled 20% of the data and reached high overall reliability with the primarily rater: Pearson $r=0.988$, $p<0.001$; and Kappa=0.606, $p<0.001$.* *

Peak-to-peak amplitudes were computed as the amplitude difference between the highest peak and lowest valley for a given ERP deflection. Although there are several ways of computing amplitude, including mean amplitude measures and peak amplitude measures, peak-to-peak amplitude measures were used because they are more robust than other measurements to residual noise and other artifacts (Handy, 2004).

The descriptive statistics for the peak-to-peak amplitude parameter were calculated to inspect for outliers before conducting statistical tests, because parametric statistics on ERP data are very sensitive to outliers (Dien & Santuzzi, 2004). The existence of residual outliers even after visual inspection is due to the occasional bad channel that can escape human visual examination.

To exclude all possible outliers, for any given trial, if the peak-to-peak amplitude was outside two standard deviations from the mean under the same task condition for the same participant, that trial was discarded from the analysis as an outlier. There were no such outliers observed in this study. (Please see Chapter 5 for descriptive statistics).

**Note*: here, peaks are indicated as either maximal positive or negative values within a certain time window

***Note*: Kappa value greater than 0.6 indicates very strong agreement.

For testing hypothesis B, all electrodes on the Quick Cap (64 electrodes in total) were divided into two regions: Left and Right. Each region contained 26 electrodes (both regions excluded the midline electrodes). For each region, hemispheric global field power (GFP) was computed for the respective analysis time windows for each ERP component of interest. GFP is defined as the square root of the mean of the squared derivations of the voltage of each electrode from the common average voltage (Lehmann & Skrandies, 1980; also see <u>*Appendix E.*</u>1 for mathematical descriptions).

Under the Neuroscan system's automatic computation, the resultant GFP was a positive waveform plotted as a function of time across the entire epoch for each prescribed region (Left vs Right) for a given participant. Therefore, the GFP for a given ERP component could be segmented out directly according to its respective analysis time window. The highest peaks of the GFP waveform were manually labeled using the same manual labeling criteria listed above for peak-to-peak amplitudes. For experimental conditions, only the GFPs for N400 were labeled. Because all the GFP values were positive, it was very hard to distinguish the P350 GFP from the N400 GFP. In fact, in some files, these two peaks merged into one sole large peak. Therefore, the overall highest peaks between the interval 300ms and 500ms were defined as the N400, which actually represents the overall activity of P350-N400 complex.

4.5.3 Statistical procedures

To test Hypothesis A, within-subject *t*-tests on Lexical Stress Pattern (Noun vs. Verb) were applied to the peak-to-peak amplitude data from the two selected electrodes (Cz and Pz), separately for P350 and N400 (2 sets of 2 tests each).

To test Hypothesis B, three separate two-way ANOVAs were conducted for experimental conditions, one with GFP measures and one each with peak-to-peak amplitude at C3 vs C4and T7 vs T8. Each analysis compared the effects of Lexical Stress Pattern (Noun vs Verb), and Hemisphere (Left vs Right).

For the control conditions, two-way ANOVAs were conducted for P300 GFP measures and peak-to-peak amplitudes for C3vs C4 as well as for T7 vs T8. Each analysis compared the effects of Gender (female vs male) and Hemisphere (Left vs Right). It was predicted that there would be significant differences between Left and Right P300 GFPs in the lateralization control conditions (5)-(8), with larger results in the Right Hemisphere than in the Left. In addition, the amplitude of P300 induced by deviant stimuli was expected to be significantly larger at C4 than at C3.

Bonferroni corrections were applied for all the above analyses.

A supplemental exploratory 2-way ANOVA (Lexical Stress Pattern by Segmental Information (filtered vs. unfiltered)) was conducted to explore another effect, and potentially to shed light on the cascading inhibition model of lexical stress parsing. As indicated in Chapter 3, if there is no interaction between these two variables, or if there is an interaction and *post hoc* analysis indicates that unfiltered conditions have larger effects of Lexical Stress Pattern than filtered conditions, the results can be accommodated under that stress parsing model. An interpretation of the former result pattern could be that in both filtered and unfiltered conditions, the difference detected in ERP amplitudes can be attributed to lexical stress parsing. For the latter outcome part of the main effect in unfiltered conditions could be attributed to the vowel reduction at the phonetic level. However, if this *post hoc* analysis indicated that the unfiltered conditions have smaller effects for Lexical Stress Pattern than filtered conditions, the results could no longer be explained by the current CI model. Instead, this result might reflect a qualitative nonlinear change of lexical stress processing when segmental information is removed.

4.5.4 Source localization

Estimating the source that generates the recorded EEG poses many challenges in terms of which algorithm to use and how to interpret the results.

Among those challenges, the most fundamental one is the famous “inverse problem” itself: an infinite number of underlying source distributions could generate the same surface electromagnetic distribution (measured as topography in EEG). Because of these infinite possibilities, there has to be a “constraint” for the solution (Hämäläinen & Ilmoniemi, 1994;Pascual-Marqui, 1995, 1999).

Admittedly, the ideal situation for source estimation is to have a prescribed Region of Interest (ROI) to constrain the solution boundary. However, because of the exploratory nature of this study and lack of previous imaging results (such as fMRI) on the processing of lexical stress patterns, “hot spots” for determininga priori regions of interest are not available.

In this circumstance, the most often recommended method in the source estimation literature is MNE-based (minimum norm estimates) estimation. This is a method of finding the shortest vector in the Euclidean source-current space which can explain the surface measurements. Nothing is assumed about the source, except that it is confined within the brain (Hämäläinen & Ilmoniemi, 1994). Studies documented that the MNE method has high accuracy for locating simulated sources without ambient noise, simulated sources with ambient noise, and data from an experiment that involved observing a checkerboard in a visual paradigm (Hämäläinen & Ilmoniemi, 1994).

More importantly, as the authors claimed, because the estimation is based on the minimum norm, virtually no information from the surface electromagnetic field is lost. The surface topographic distribution is merely transformed into another from (Hämäläinen & Ilmoniemi, 1994).

Another important challenge for source estimation is the placement of the recording electrodes. Almost all pure mathematically-based algorithms assume perfectly perpendicularly placed electrodes (or magnetic channels) mounted on the head. In reality, there are usually tilts and loose placements for multiple channels. Unlike pure mathematical interpolation, MNE addresses this problem by correcting the algorithm with Maxwell equations that automatically take into account the off-diagonal electro-magnetic fields, apply physics properties of the electromagnetic field and correct for imperfect placement to the maximum, so that the result is free from off-diagonal artifacts (Hämäläinen & Ilmoniemi, 1994). Please refer to Appendix Ffor specific algorithm of MNE method.

However, it was reportedin later research that MNE is very poorat localizing deep sources and often misplaces them (Dale, Liu, Fischl, Buckner, Belliveau, Lewine, & Halgren, 2000). The solution for this problem is to change the MNE procedure from an absolute solution to a statistical one, by introducing some variance Pascual-Marqui, 1995, 1999, 2002).

The sLORETA (standardized Low Resolution brain Electromagnetic Tomography) procedure does so by generating variance from Bayesian inference and producing a pseudo-statistic that can map the activation pattern ontothe MNI (Montreal Neurological Institute) Colin-27 MRI image template (Holmes, Hoge,Collins, Woods,Toga, &Evans,1998;Pascual-Marqui, 1995, 1999, 2002). In applying sLORETA for the current study, three steps were taken. First, a forward head model was built based on the registered electrodes on the MRI image with the Talairach human brain atlas (Lancaster, Woldorff, Parsons, Liotti, Freitas, Rainey, Kochunov, Nickerson, Mikiten, & Fox, 2000). In the current study, this is a three-layer sphere. The registration between spherical and realistic head geometry employed EEG electrode coordinates reported by Towle, Bolanos, Suarez, Tan, Grzeszczuk, Levin, Cakmur, Frank, & Spire (1993). Second, the noise covariance matrix was computed from actual recordings by Bayesian inference. Finally, the source was estimated by MNE algorithm with Bayesian variance, producing roughly F-distributed pseudo-statistics. Then the pseudo-statistics were mapped onto 15,000 voxels from

64 electrodes using an unconstrained method. The unconstrained method specified that, in each voxel, there are three vectors representing three spatial orientations (x,y,z), as opposed to constrained method which only uses one vector in each voxel. The unconstrained method was used because it yields better results when no a priori ROI is prescribed (Pascual-Marqui, 2002).

A simulation study found that sLORETA is the optimal method of source localization (Pascual-Marqui, 2000). It achieved exact, zero error, localization of test dipoles with arbitrary orientation, located at arbitrary voxel positions, in the absence of noisy measurements. The author strongly claimed that “Localization error cannot be improved beyond the present result. It is zero. Up to the present, no other instantaneous, distributed, discrete, imaging method for EEG/MEG has been published (to the best of the author’s knowledge) that achieved perfect localization.” (Pascual-Marqui, 2002, p. 14).

Though Pascual-Marqui (2002) is clearly confident about the localization power of sLORETA, he did not recommend using the pseudo-statistic map for any formal experimental testing other than visualization.

5.0 RESULTS

In this chapter, results of preliminary analyses, including distributional tests of the data, inspection of the grand averages of ERP indices and their topographic distributions, as well as descriptive statistics are first presented.

Then, the results from the control conditions (i.e., P300) are presented, followed by the findings from the proposed main analyses for the two hypotheses. After that, a supplemental analysis to rule out an interaction between Filtering and Lexical Stress pattern is discussed. Finally, exploratory source estimation results are summarized and illustrated at the end.

For testing Hypothesis B, in addition to the proposed electrodes (C3 vs C4), another two electrodes were added (T7, temporal left vs T8 temporal right). The rationale for this addition is elaborated in *Section 5.2.1.* Distributional tests and descriptive statistics for these two electrode sites are also included in the preliminary analysis section.

5.1 PRELIMINARY ANALYSIS

5.1.1 Data exclusion

Based on the exclusion criteria for EEG data in *Section 4.5.1.*, one participant was excluded because of noisy channels for all analyses. Other exclusions from analysis due to specific bad/noisy channels are summarized in *Table G-1* and *Table G-2* respectively for experimental and control conditions in *Appendix G*.

Response to the post hoc written questionnaires about factors affecting ERP results (*Appendix A.2*) revealed no obvious patterns so no further data were excluded from analysis

5.1.2 Distributional tests of the data

The main dependent variables are the peak-to-peak amplitudes of P350 and N400 in experimental conditions and P300 in control conditions. Because the proposed statistical comparisons involve paired sample *t*-tests and ANOVAs, a test for data normality is necessary. Shapiro-Wilk normality tests were not significant, which indicates that the normality assumption was not violated. This was the case for all conditions and all electrodes. *Table G-3* and *G-4* in *Appendix G* show the p-values from the Shapiro-Wilk normality test.

5.1.3 Grand averages

Before formal statistical testing, inspection of the grand averages of the targeted waveforms is also important. The purposes of this step were to check 1) whether the unexpected Lexical Stress Pattern in experimental conditions and deviant Gender Shift in control conditions induced N400, P350 and P300 amplitude differences larger than those in the standard conditions and 2) whether the topographic distributions showed the predicted lateralization pattern.

For these two purposes, the grand average waveforms at Cz for control conditions and at Cz and Pz for the experimental conditions were inspected. These waveforms, and their topographic distributions, are shown below. Please note that these grand averages are only for visual inspection and demonstration, and the apparent differences may not necessarily bear statistical significance.

5.1.3.1 Control conditions

For the filtered control conditions, the grand-averaged waveform seems to have a larger and more delayed positivity around 300ms after stimulus onset (P300) for deviant (male) stimuli than for standard (female) stimuli (see *Figure 5-1*). The pattern is the same in the unfiltered conditions but the effect induced by unfiltered deviant stimuli seems to be more pronounced than that induced by the filtered stimuli (*Figure 5-2*).

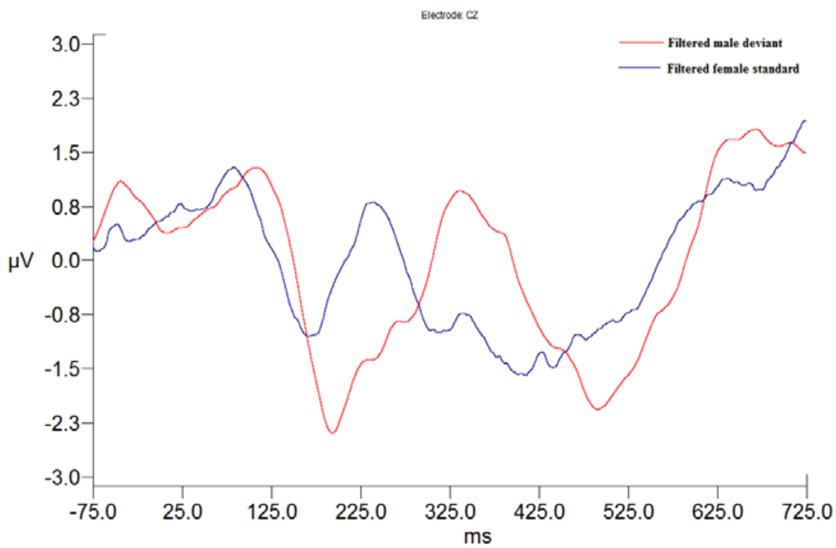

Figure 5-1. The grand average of P300 in filtered oddball control conditions at Cz. The red line represents the filtered deviant stimuli produced by a male speaker, while the blue line represents the filtered standard stimuli produced by a female speaker.

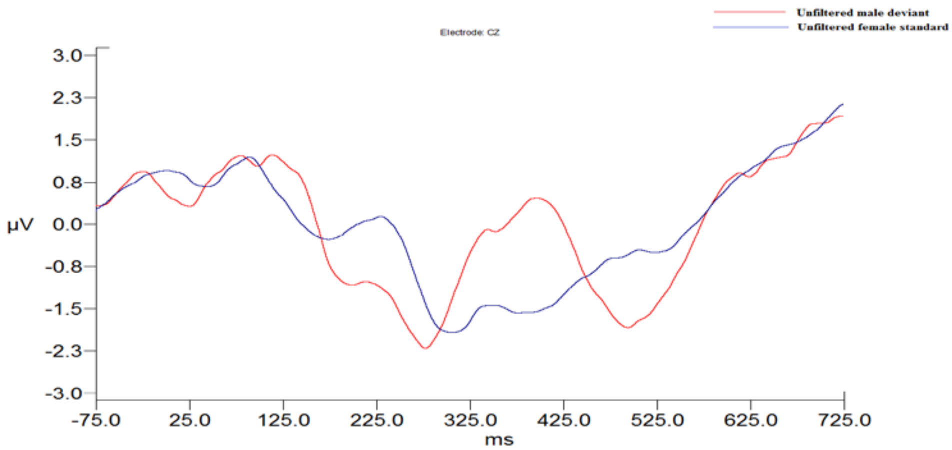

Figure 5-2. The grand average of P300 in unfiltered oddball control conditions. The red line represents the unfiltered deviant stimuli produced by a male speaker while the blue like represents the unfiltered standard stimuli produced by a female speaker. Each stimulus starts at 0ms.

Topographic distribution shows that the P300 induced by deviant (male) stimuli was distributed bilaterally in filtered conditions but to the right in the unfiltered conditions (*Figure 5-3* and *5-4*, respectively).

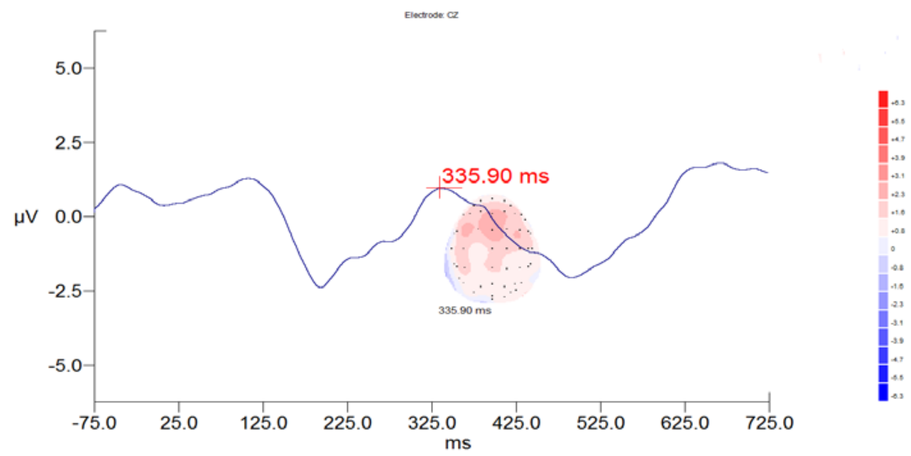

Figure 5-3. The topographic distribution of P300 induced by filtered deviant stimuli

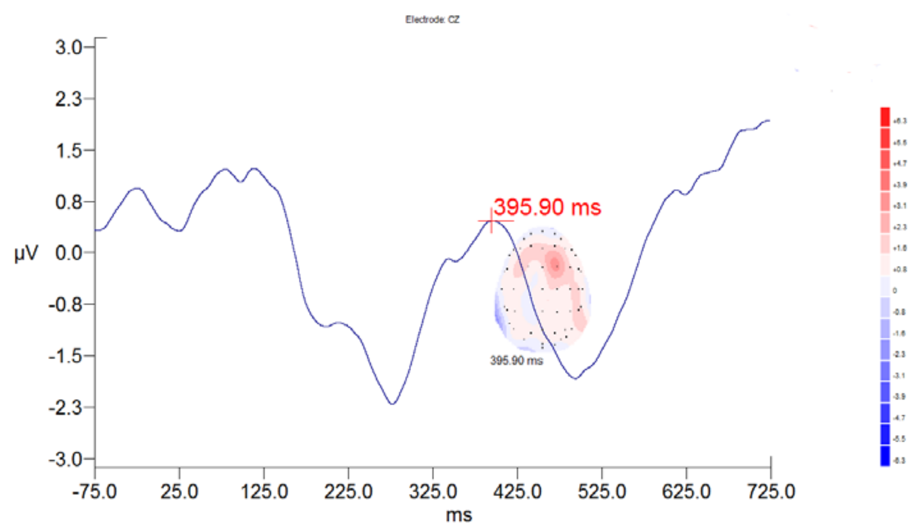

Figure 5-4. The topographic distribution of P300 induced by unfiltered deviant stimuli

5.1.3.2 Experimental conditions

As shown in *Figure 5-5*, the grand averages at Cz of filtered Verb Lexical Stress Pattern targets following a Noun-predicting sentence seem to have a larger negativity at 200ms following stimulus onset (N200), a smaller positivity at around 350ms following stimulus onset (P350) and a larger negativity at around 400ms following stimulus onset (N400) than the filtered Noun Lexical Stress Pattern targets. The same pattern was found at Pz, as shown in *Figure 5-6*.

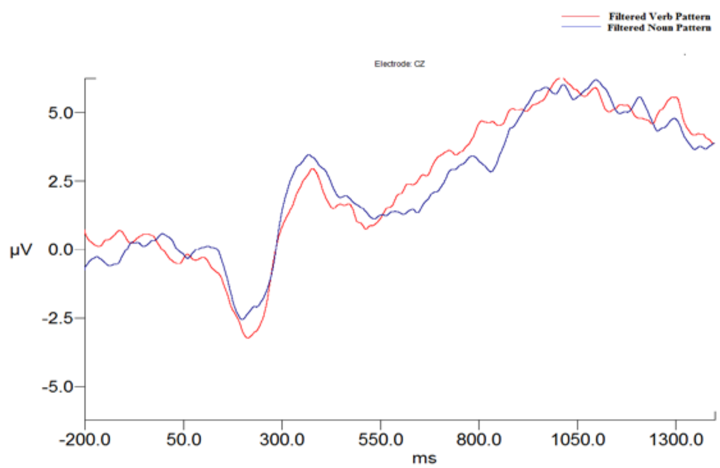

Figure 5-5. Grand averages of filtered Verb and Noun Lexical Stress Pattern targets following a Noun-predicting sentence at Cz. The red line represents the waveform from unexpected filtered Verb Lexical Stress Pattern targets while the blue line represents the filtered Verb Lexical Stress Pattern targets while the blue line represents the filtered Noun Lexical Stress Pattern targets.

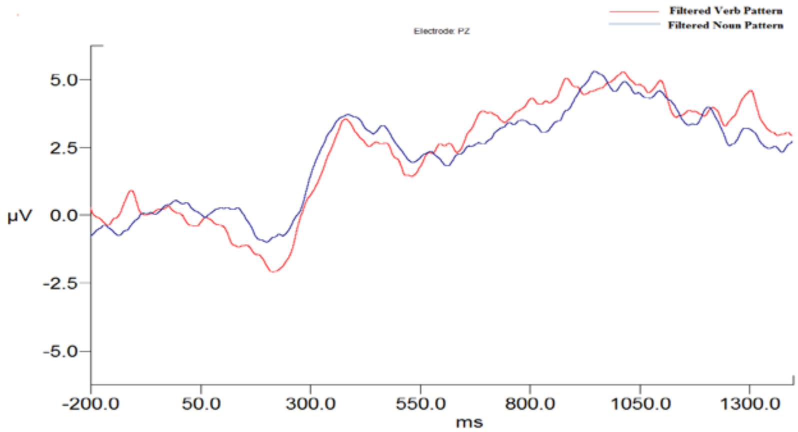

Figure 5-6. Grand averages of filtered Verb and Noun Lexical Stress Pattern targets following a Noun-predicting sentence at Pz. The red line represents the waveform from unexpected filtered Verb Lexical Stress Pattern target while the blue line represents thefiltered Verb Lexical Stress Pattern target while the blue line represents the filtered Noun Lexical Stress Pattern target.

For unfiltered conditions, the oscillations of the waveform were bigger and the difference between Verb targets and Noun targets seem less clear than that in the filtered conditions. The most obvious difference is that Verb targets seem to induce a larger N400 than Noun targets. This was the case for both Cz and Pz, which appears to due to expectancy violation, shown in *Figure 5-7* and *5-8* respectively.

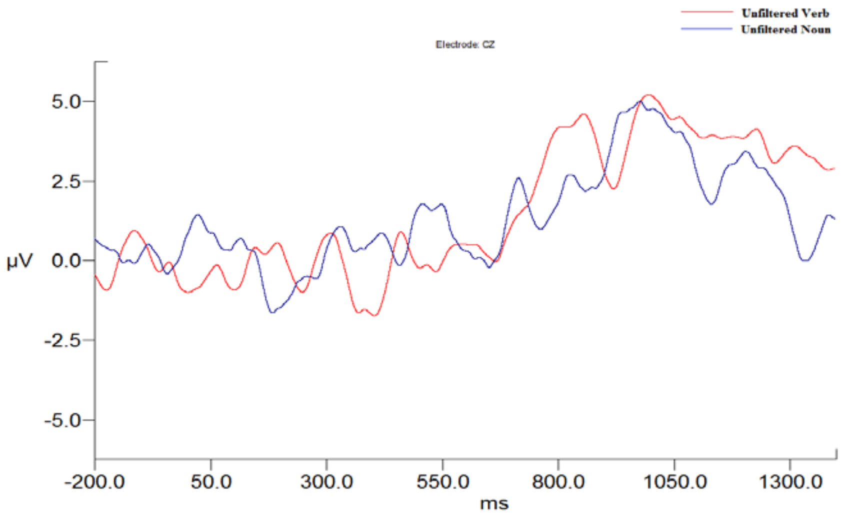

Figure 5-7. Grand averages of unfiltered Verb and Noun targets following a Noun-predicting sentence at Cz. The red line represents the waveform from unexpected unfiltered Verb target while the blue line represents the unfiltered Noun target.

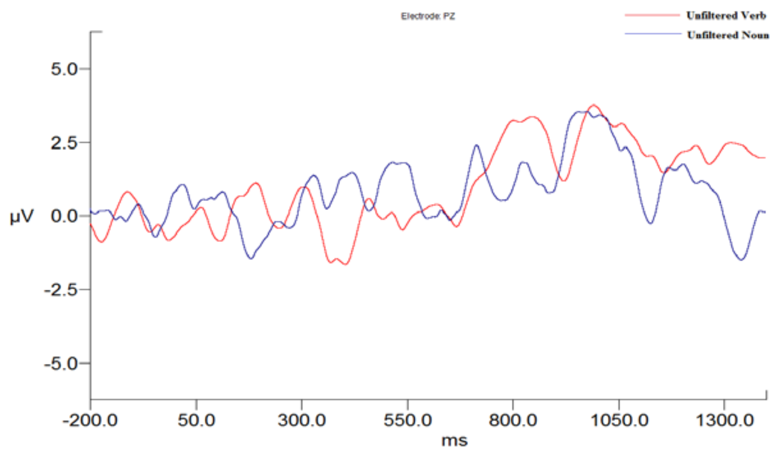

Figure 5-8. Grand averages of unfiltered Verb and Noun targets following a Noun-predicting sentence at Pz. The red line represents the waveform from unexpected unfiltered Verb target while the blue line represents the unfiltered Noun target.

Topographic distributions for the filtered Verb Lexical Stress Pattern condition show a right-lateralized positivity around 350ms and a left lateralized and delayed negativity for N400, as indicated in *Figure 5-9*.

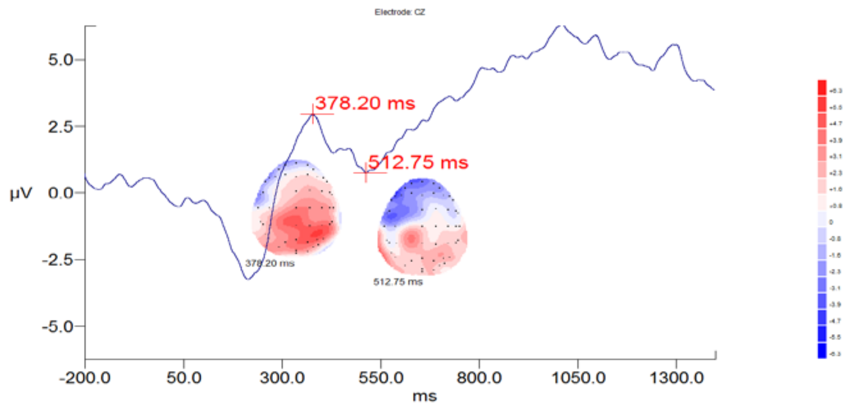

Figure 5-9. The topographic distribution of P350 and N400 induced by filtered Verb Lexical Stress Pattern targets.

On the other hand, topographic distributions do not show observable lateralization patterns for P350 and N400 in unfiltered conditions, as evident in *Figure 5-10*.

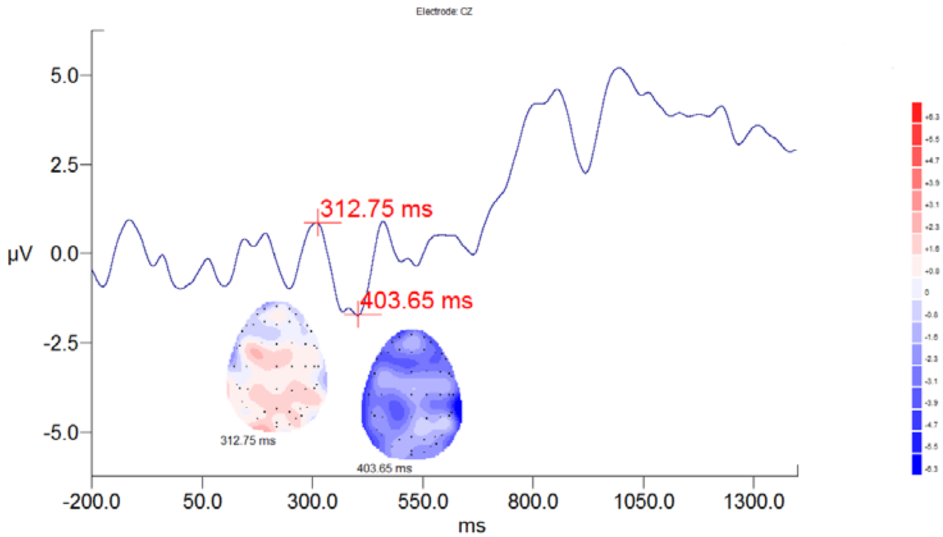

Figure 5-10. The topographic distributions of P350 and N400 induced by filtered Verb Lexical Stress Pattern targets.

5.1.4 Descriptive statistics

The descriptive statistics are presented here for all the variables, including P300 amplitudes for testing Gender Shift in the control conditions and N400 and P350 for testing the two main experimental hypotheses.

5.1.4.1 Variables in statistical testing for control conditions

Descriptive statistics for P300 induced by filtered and unfiltered stimuli are presented in *Table 5-1* and *5-2*, respectively, including peak-to-peak amplitudes at C3, C4, T7, and T8, as well as GFP from left and right electrodes. From inspection of individual data, there were no outliers observed.

Table 5-1. Descriptive statistics for P300 induced by filtered stimuli. (C3: central left; C4: central right; T7: temporal left; T8: temporal right, LGFP: left Global Field Power; RGFP: right Global Field Power)

	Mean	Std. Deviation	Std. Error Mean
C3 Filtered (female) standard	3.317	3.861	0.626
C3 Filtered (male) deviant	6.726	3.746	0.624
C4 Filtered (female) standard	3.301	3.880	0.629
C4 Filtered (male) deviant	6.882	3.757	0.626
T7 Filtered (female) standard	1.360	0.815	0.151
T7 Filtered (male) deviant	3.363	2.629	0.488
T8 Filtered (female) standard	2.285	1.430	0.266
T8 Filtered (male) deviant	5.134	3.735	0.693
LGFP Filtered (female) standard	1.168	0.475	0.080
LGFP Filtered (male) deviant	1.770	0.724	0.122
RGFP Filtered (female) standard	1.237	0.459	0.078
RGFP Filtered (male) deviant	2.271	1.364	0.230

Table 5-2. Descriptive statistics for P300 induced by unfiltered stimuli. (C3: central left; C4: central right; T7: temporal left; T8: temporal right, LGFP: left Global Field Power; RGFP: right Global Field Power)

	Mean	Std. Deviation	Std. Error Mean
C3 Unfiltered Female standard	2.151	1.098	1.882
C3 Unfiltered Male deviant	5.198	2.270	0.389
C4 Unfiltered Female standard	2.251	1.599	0.274
C4 Unfiltered Male deviant	5.257	2.634	0.452
T7 Unfiltered Female standard	1.378	0.812	0.156
T7 Unfiltered Male deviant	3.222	1.496	0.287
T8 Unfiltered Female standard	2.163	1.254	0.241
T8 Unfiltered Male deviant	3.751	1.698	0.327

Table 5-2. (Continued)

LGFP Unfiltered Female standard	1.194	0.462	0.079
LGFP Unfiltered Male deviant	1.499	0.640	0.110
RGFP Unfiltered Female standard	1.293	0.522	0.090
RGFP Unfiltered Male deviant	1.843	0.598	0.102

5.1.4.2 Variables for testing Hypothesis A

For testing Hypothesis A, the primary dependent variables were N400 and P350 peak-to-peak amplitudes for filtered and unfiltered Verb and Noun Targets following Noun-predicting sentences at Cz and Pz. The descriptive statistics for these variables are shown in *Table 5-3.*

Before generating the descriptive statistics, the data were inspected for the existence of outliers. Because all the distributions were normal, outliers were defined as data values outside two standard errors. Under this definition, no outliers were observed.

Table 5-3. Descriptive statistics of peak-to-peak amplitudes of N400 and P350 at Cz and Pz for experimental conditions. (Cz: midline central; Pz: midline parietal)

	Mean	Std. Deviation	Std. Error Mean
Filtered noun N400 Cz	-4.536	3.037	0.537
Filtered verb N400 Cz	-6.489	3.193	0.564
Filtered noun P350 Cz	10.889	6.956	1.230
Filtered verb P350 Cz	9.066	3.441	0.608

Table 5-3. (Continued)

Filtered noun N400 Pz	-4.568	3.254	0.575
Filtered verb N400 Pz	-4.286	2.162	0.382
Filtered noun P350 Pz	8.544	4.890	0.864
Filtered verb P350 Pz	8.251	3.866	0.684
Unfiltered noun N400 Cz	-4.726	2.250	0.404
Unfiltered verb N400 Cz	-3.344	2.305	0.414
Unfiiltered noun P350 Cz	8.079	3.107	0.558
Unfiltered verb P350 Cz	4.115	2.796	0.502
Unfiltered noun N400 Pz	-3.859	2.882	0.518
Unfiltered verb N400 Pz	-4.151	3.542	0.636
Unfiltered noun P350 Pz	4.799	3.095	0.556
Unfiltered verb P350 Pz	5.224	3.391	0.609

5.1.4.3 Variables for testing Hypothesis B

For testing Hypothesis B, the variables of interest were N400 and P350 peak-to-peak amplitudes for filtered and unfiltered Verb and Noun Targets following Noun-predicting sentences at C3, C4, T7 and T8, as well as the left and right GFP for N400. The descriptive statistics for these variables are listed in *Table 5-4., 5-5, 5-6, 5-7*, respectively. No outliers were observed.

Table 5-4. Descriptive statistics of peak-to-peak amplitudes of N400 at C3, C4, T7, and T8 as well as left and right GFPs for filtered experimental conditions. C3: central left; C4: central right; T7: temporal left; T8: temporal right, LGFP: left Global Field Power; RGFP: right Global Field Power)

	Mean	Std. Deviation	Std. Error Mean
Filtered Noun N400 C3	-1.389	3.176	0.561
Filtered Verb N400 C3	-3.156	4.130	0.730
Filtered Noun N400 C4	0.562	3.460	0.612
Filtered Verb N400 C4	-1.268	4.831	0.854
Filtered Noun N400 T7	-3.047	3.517	0.677
Filtered Verb N400 T7	-2.740	5.354	1.030
Filtered Noun N400 T8	-1.346	4.746	0.913
Filtered Verb N400 T8	-1.039	4.710	0.906
Filtered Noun N400 LGFP	3.311	1.305	0.227
Filtered Verb N400 LGFP	4.156	1.638	0.285
Filtered Noun N400 RGFP	2.736	1.177	0.205
Filtered Verb N400 RGFP	3.246	1.309	0.227

Table 5-5. Descriptive statistics of peak-to-peak amplitudes of N400 at C3, C4, T7, and T8 as well as left and right GFPs for unfiltered experimental conditions. (C3: central left; C4: central right; T7: temporal left; T8: temporal right, LGFP: left Global Field Power; RGFP: right Global Field Power)

	Mean	Std. Deviation	Std. Error Mean
Unfiltered Noun N400 C3	-0.712	3.213	0.577
Unfiltered Verb N400 C3	-4.233	5.120	0.919
Unfiltered Noun N400 C4	-0.617	4.303	0.773
Unfiltered Verb N400 C4	-2.520	4.595	0.825
Unfiltered Noun N400 T7	-1.951	2.947	0.602
Unfiltered Verb N400 T7	-2.976	4.863	0.993
Unfiltered Noun N400 T8	-0.887	4.838	0.988
Unfiltered Verb N400 T8	-1.971	3.099	0.633

Table 5-5. (Continued)

Unfiltered Noun N400 LGFP	2.906	1.299	0.230
Unfiltered Verb N400 LGFP	3.768	1.886	0.333
Unfiltered Noun N400 RGFP	2.587	0.887	0.157
Unfiltered Verb N400 RGFP	2.940	1.482	0.262

Table 5-6. Descriptive statistics of peak-to-peak amplitudes of P350 at C3, C4, T7, and T8 for unfiltered experimental conditions. (C3: central left; C4: central right; T7: temporal left; T8: temporal right, LGFP: left Global Field Power; RGFP: right Global Field Power)

	Mean	Std. Deviation	Std. Error Mean
Filtered Noun P350 C3	3.628	3.338	0.590
Filtered Verb P350 C3	1.594	4.984	0.881
Filtered Noun P350 C4	5.200	4.264	0.754
Filtered Verb P350 C4	3.256	4.815	0.851
Filtered Noun P350 T7	1.207	4.000	0.770
Filtered Verb P350 T7	1.659	4.977	0.958
Filtered Noun P350 T8	2.346	4.958	0.954
Filtered Verb P350 T8	3.289	3.892	0.749

Table 5-7. Descriptive statistics of peak-to-peak amplitudes of P350 at C3, C4, T7, and T8 for filtered experimental conditions. (C3: central left; C4: central right; T7: temporal left; T8: temporal right, LGFP: left Global Field Power; RGFP: right Global Field Power)

	Mean	Std. Deviation	Std. Error Mean
Unfiltered Noun P350 C3	1.946	2.802	0.503
Unfiltered Verb P350 C3	-0.238	5.282	0.949
Unfiltered Noun P350 C4	2.501	3.952	0.710
Unfiltered Verb P350 C4	1.560	4.360	0.783

Table 5-7. (Continued)

Unfiltered Noun P350 T7	1.257	2.789	0.569
Unfiltered Verb N400 T7	0.795	5.031	1.027
Unfiltered Noun N400 T8	2.039	4.091	0.835
Unfiltered Verb N400 T8	1.904	3.180	0.649

5.2 RESULTS FROM CONTROL CONDITIONS

5.2.1 Two-way ANOVA of Hemisphere and Gender Shift on peak-to-peak P300 amplitudes

For the control conditions, an auditory oddball paradigm was used. It was expected that the deviant (infrequent) stimulus would induce a larger positivity at around 300ms post stimulus onset than the standard (frequent) stimulus. The standard stimulus was a female voice uttering a single word and the oddball stimulus was a male voice uttering the same word. This independent variable is denoted as “Gender Shift” in the statistical analysis. Two side electrodes were selected to test the lateralization pattern: C3 (central left) and C4 (central right). This variable is denoted as “Hemisphere.”

For the control conditions, six two-way ANOVA comparisons were conducted, analyzing peak-to-peak amplitudes of P300 at C3 vs C4 and T7 vs T8, as well as left and right GFP, separately for filtered and unfiltered conditions. Therefore, the alpha level after Bonferroni correction (.05/6) is 0.008.

In the following texts and tables, "*" indicates that the *p*-value obtained was significant after Bonferroni correction. The results of all ANOVAs are summarized in *Table 5-8.*

For both filtered and unfiltered conditions, main effects of Gender Shift were found. There were no significant main effects of Hemisphere or significant interactions between Hemisphere and Gender Shift.

The expected right lateralization pattern was not observed in these results. After examining the literature further, it was found that the right lateralization pattern for P300 induced by gender shift occurs at more peripheral electrodes than C3 and C4, though the maximum of the waveform itself is a centrally distributed (Jerger et al., 1995).

In this regard, the absence of hemispheric difference may be due to electrode selection. Therefore, two peripheral electrodes, T7 (temporal left) and T8 (temporal right), were selected and the same ANOVA procedure was repeated for peak-to-peak P300 data from these two electrodes. Because the peripheral channels were noisier, eight participants were excluded from analysis in the filtered conditions and five were excluded from unfiltered conditions.

For both filtered and unfiltered conditions, significant main effects of Gender Shift were found. In addition, significant main effects of Hemisphere were found for unfiltered conditions.

Left and right GFP (Global Field Power) of P300 were computed by including data from all the electrodes on each side of the head, and excluding the midline electrodes. ANOVA on left vs. right GFP data showed significant main effects of Gender Shift and Hemisphere in filtered conditions and significant main effects for Gender shift in unfiltered conditions, seen from p-values after Bonferroni correction.

Overall, the results of the control conditions showed that, for all the electrodes analyzed, the oddball stimuli (male) induced significantly larger P300 amplitudes than the standard stimuli (female). The P300 was larger on the right than on the left for peripheral electrodes (T7 vs T8) but not for more central electrodes (C3 vs C4), and the GFP computed from right hemisphere electrodes was generally larger than that from left hemisphere electrodes.

Bar graphs were plotted for comparisons that showed significant results for the "Hemisphere" effect. T7 vs T8, and left vs right GFP for both filtered and unfiltered stimuli are plotted in *Figure 5-11* and *5-12*, respectively. It can be seen that in both plots, the right side response was larger than the left for both filtered and unfiltered conditions. There was no interaction between Lexical Stress Pattern and Hemisphere lateralization.

Table 5-8. Statistical results for control experiments. (*significant before but not after Bonferroni correction, **significant before and after Bonferroni correction)

	Main effect of Gender Shift	Main effect of Hemisphere	Interaction
C3 vs C4 (filtered)	F(1,135)=78.552, *p*<0.001**	F(1,135)=0.054, *p*=0.816	F(1,135)=0.004, *p*=0.951
C3 vs C4 (unfiltered)	F(1,147)=31.061, *p*<0.001 **	F(1,147)=0.012, *p*=0.912	F(1,147)=0.019, *p*=0.890
T7 vs T8 (filtered)	F(1,107)=43.226, *p*<0.001 **	F(1,107)=6.336, *p*=0.013*	F(1,107)=0.243, *p*=0.623
T7 vs T8 (unfiltered)	F(1,115)=28.965, *p*<0.001**	F(1,115)=8.945, *p*=0.003**	F(1,115)=0.882, *p*=0.350
LGFP vs RGFP (filtered)	F(1,131)=8.103 , *p*=0.005**	F(1,131)=9.730, *p*=0.002**	F(1,131)=0.493, *p*=0.484
LGFP vs RGFP (unfiltered)	F(1,139)=33.240, *p*<0.001 **	F(1,139)=4.019, *p*=0.047*	F(1,139)=2.319, *p*=0.130

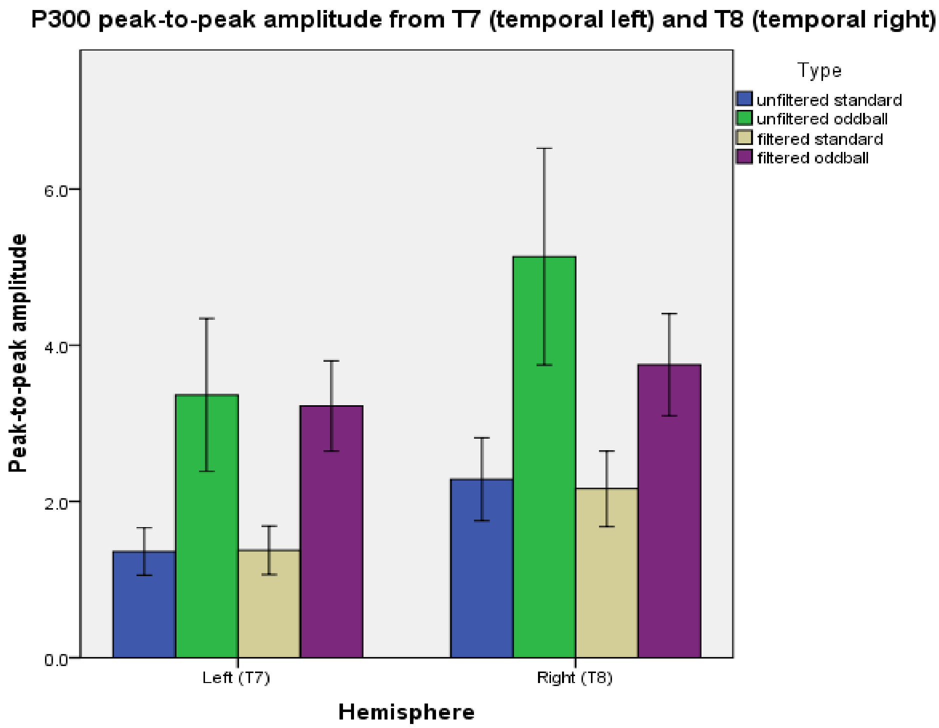

Figure 5-11. P300 amplitudes at left and right temporal electrodes (T7 and T8) in control conditions.

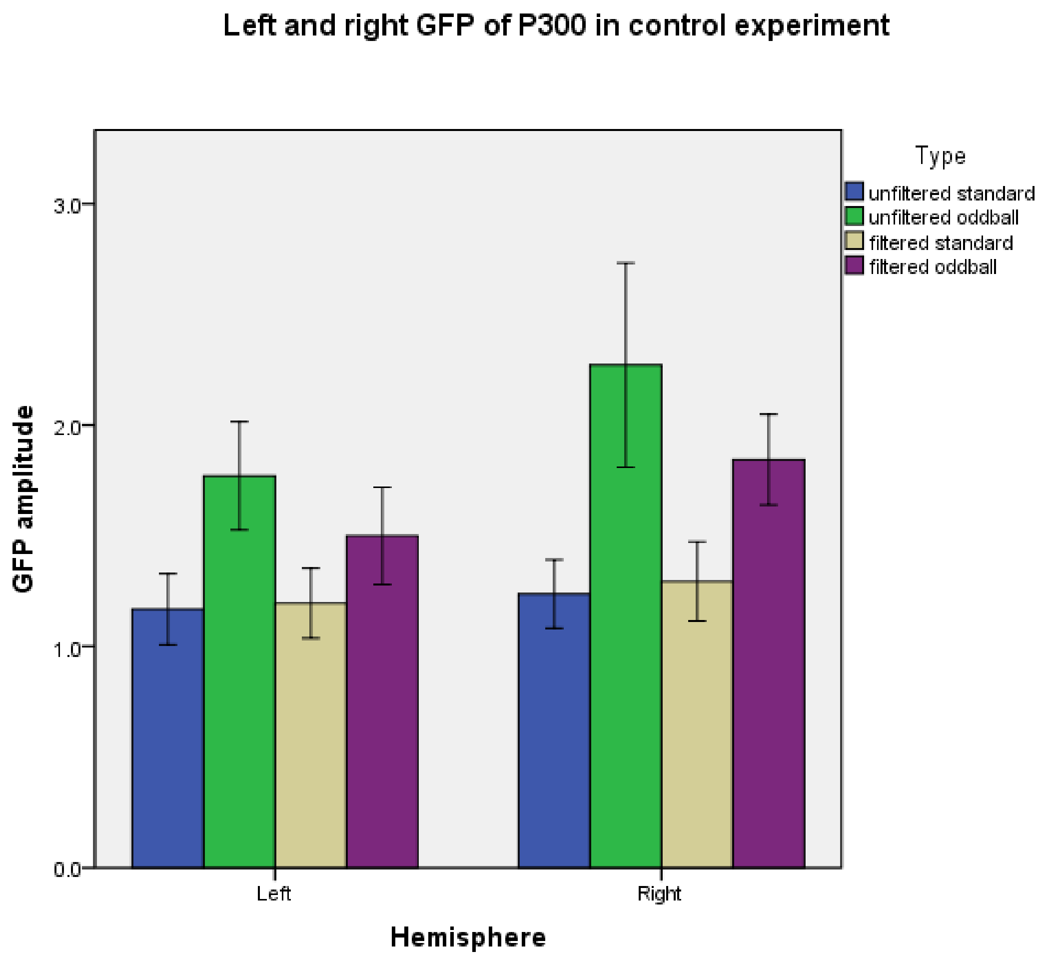

Figure 5-12. P300 left and right GFP amplitudes in control conditions.

5.3 PAIRED SAMPLE T-TESTS FOR HYPOTHESIS A

The first hypothesis (Hypothesis A) of this study is that lexical stress parsing can modulate lexical selection without the presence of segmental information. This hypothesis was tested using peak-to-peak amplitude of N400 and P350 There are eight comparisons in total, testing N400 and P350 separately for filtered and unfiltered conditions, at Cz and Pz. Therefore, the alpha level after Bonferroni correction (0.5/8) is 0.00625. For each comparison, a *t*-test is conducted to compare Verb Lexical Stress Pattern and Noun Lexical Stress Pattern.

Table 5-9 summarizes the results of paired sample *t*-tests. For filtered conditions, both the N400 and P350 results were significantly different between experimental targets (Filtered Verb Lexical Stress Pattern) and control targets (Filtered Noun Lexical Stress Pattern) at Cz. However, neither the N400 nor the P350 results were significantly different between experimental (Filtered Verb Pattern) and control targets (Filtered Noun Pattern) at Pz.

For unfiltered conditions, P350 was significantly different between experimental (Verb) and control (Noun) at Cz. Like filtered conditions, both the N400 and P350 results were not significantly different between unfiltered experimental (Verb) and control (Noun) conditions at Pz.

Overall, the results indicated that the N400 and P350 were significantly different when participants are processing unexpected Verb Lexical Stress Pattern than when they were processing the expected Noun Lexical Stress pattern. However, the effects were restricted to more frontal and central electrodes rather than posterior electrodes.

Table 5-9. Results of paired sample t-test on peak-to-peak amplitudes of N400 and P350 at Cz and Pz for experimental conditions. (* denotes significance before Bonferroni correction and ** denotes significance after Bonferroni correction)

	N400 (filtered conditions)	P350 (filtered conditions)	N400 (unfiltered conditions)	P350 (unfiltered conditions)
Cz	$t(32)=4.165$, $p<0.001$**	$t(32)=3.263$, $p=0.003$**	$t(31)=2.398$, $p=0.023$**	$t(31)=4.948$, $p<0.001$**
Pz	$t(32)=-0.476$, $p=0.638$	$t(32)=0.321$, $p=0.750$	$t(31)=0.379$ $p=0.708$	$t(31)=-0.530$, $p=0.600$

5.4 ANOVA TESTING FOR HYPOTHESIS B

Hypothesis B states that lexical stress parsing is lateralized to the left hemisphere. To test this hypothesis, 10 two-way ANOVAs were conducted. Eight of the comparisons tested the effects of Hemisphere and Lexical Stress Pattern on peak-to-peak amplitudes of P350 and N400 separately for filtered and unfiltered conditions, at C3 vs C4 (central left electrode vs central right electrode) or at T7 vs T8 (temporal left electrode vs temporal right electrode). Another two two-way ANOVAs were conducted to test the effects of Hemisphere and Lexical Stress Pattern on the Global Field Power (GFP) of N400 from left and right hemispheres. Thus, alpha level after Bonferroni correction is 0.005. All effects of ANOVA tests for Hypothesis B are summarized in *Table 5-10.*

C3 (left Central) and C4 (right Central) electrodes were selected as the sites for testing peak-to-peak amplitudes of N400 and P350. Significant main effects were found for both Hemisphere and Lexical Stress Pattern for N400 in filtered conditions. For unfiltered conditions, only Lexical Stress Pattern produced a significant main effect. No other significant effects were found.

For P350, significant main effects were found for both Lexical Stress Pattern and Hemisphere in filtered conditions. No significant interaction was found. In unfiltered conditions, only Lexical Stress Pattern produced a significant main effect. No other significant effects were found.

When T7 vs T8 peak-to-peak amplitudes were tested, there was no significant effect for any of the contrasts.

On the other hand, GFP analysis showed a significant main effect for both Lexical Stress Pattern and Hemisphere for filtered conditions, but not unfiltered conditions. No significant interaction was found.

Table 5-10. Summary of ANOVA test results for Lexical Stress Pattern and Hemisphere

	Main effect of Lexical Stress Pattern	Main effect of Hemisphere	Interaction
C3 vs C4 (filtered) N400	F(1,127)=7.002, *p*=0.009*	F(1,127)=7.161, *p*=0.008*	F(1,127)=0.014, *p*=0.907
C3 vs C4 (filtered) P350	F(1,127)=6.546, *p*=0.012*	F(1,127)=4.325, *p*=0.040*	F(1,127)=0.003, *p*=0.954
C3 vs C4 (unfiltered) N400	F(1,123)=11.978, *p*=0.001**	F(1,123)=1.332, *p*=0.251	F(1,123)=1.065, *p*=0.304
C3 vs C4 (unfiltered) P350	F(1,123)=4.300, *p*=0.040*	F(1,123)=2.441, *p*=0.121	F(1,123)=0.681, *p*=0.441
T7 vs T8 (filtered) N400	F(1,107)=0.119, *p*=0.731	F(1,107)=3.67, *p*=0.059	F(1,107)<0.001, *p*>0.999
T7 vs T8 (filtered) P350	F(1,107)=0.651, *p*=0.442	F(1,107)=2.571, *p*=0.112	F (1,107) =0.081. *p*=0.776
T7 vs T8 (unfiltered) N400	F(1,95)=1.633, *p*=0.213	F(1,95)=1.572, *p*=0.204	F(1,95)=0.001, *p*=0.972
T7 vs T8 (unfiltered) P350	F(1,95)=0.143, *p*=0.706	F(1,95)=1.432, *p*=0.235	F(1,95)=0.043, *p*=0.836
LGFP vs RGFP (filtered)N400	F(1,131)=8.103, *p*=0.005**	F(1,131)=9.730, *p*=0.002**	F(1,131)=0.493, *p*=0.484
LGFP vs RGFP (unfiltered) N400	F(1,127)=5.741, *p*=0.018*	F(1,127)=5.101, *p*=0.026*	F(1,127)=1.009, *p*=0.317

Overall, the results indicated that the N400 induced by the unexpected Verb Lexical Stress Pattern was larger in the left hemisphere than in the right hemisphere, while the reverse near-significant trend was shown for P350. The lateralization pattern effect was larger in the filtered than in the unfiltered conditions. Bar graphs were plotted for those comparisons that showed significant results for hemispheric lateralization. Therefore, C3 vs C4 peak-to-peak amplitudes for N400 and P350, as well as the GFP are plotted for both filtered and unfiltered targets, in *Figure 5-13*, *5-14*, and *5-15*, respectively.

It can be seen that N400 was larger on the left side than on the right, for both filtered and unfiltered conditions (*Figure 5-13*), while the reverse was true for P350 (*Figure 5-14*).

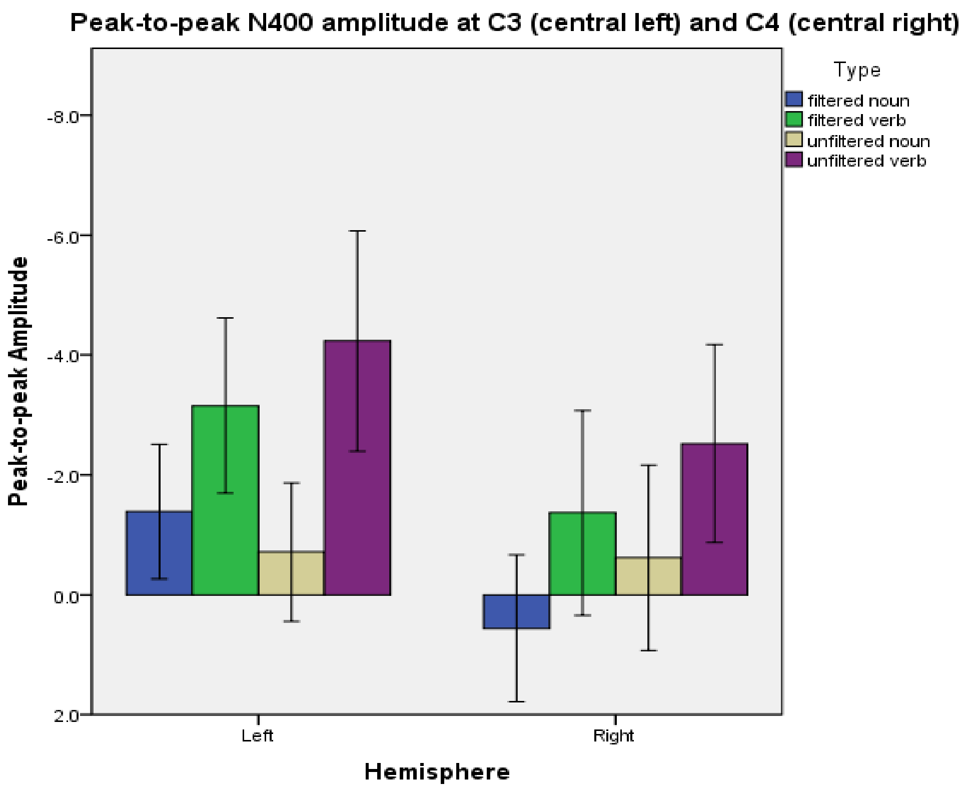

Figure 5-13. The peak-to-peak amplitudes of N400 at C3 (central left) and C4 (central right) electrodes, for both filtered and unfiltered Noun and Verb targets. (Please notice that the amplitude axis was reversed for the purpose of illustration)

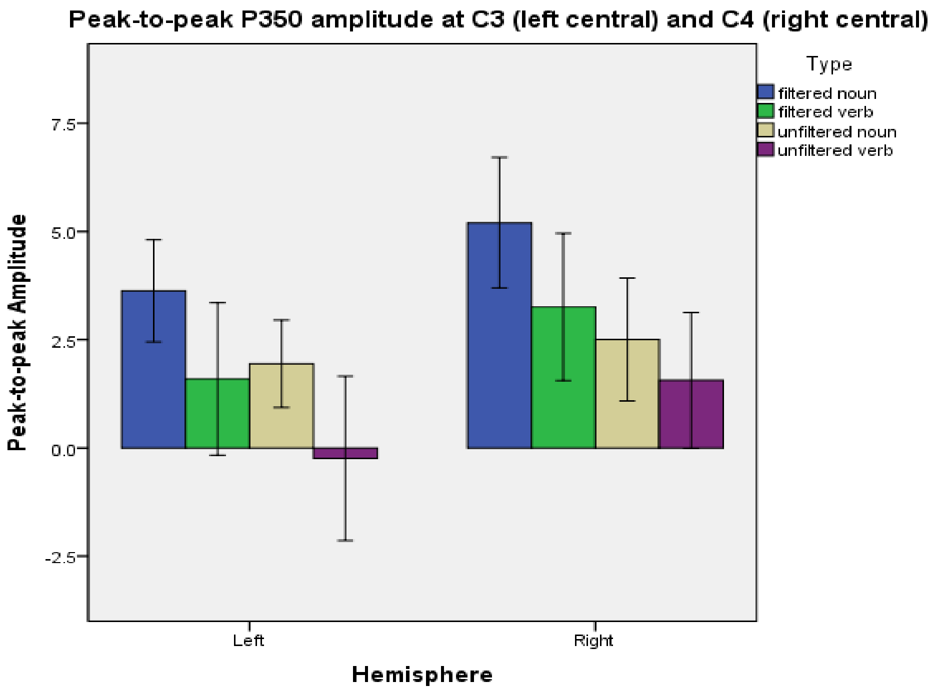

Figure 5-14. The peak-to-peak amplitudes of P350 at C3 (central left) and C4 (central right) for both filtered and unfiltered Noun and Verb targets.

The overall GFP was larger in the left hemisphere than in the right for N400, for both filtered targets and unfiltered targets.

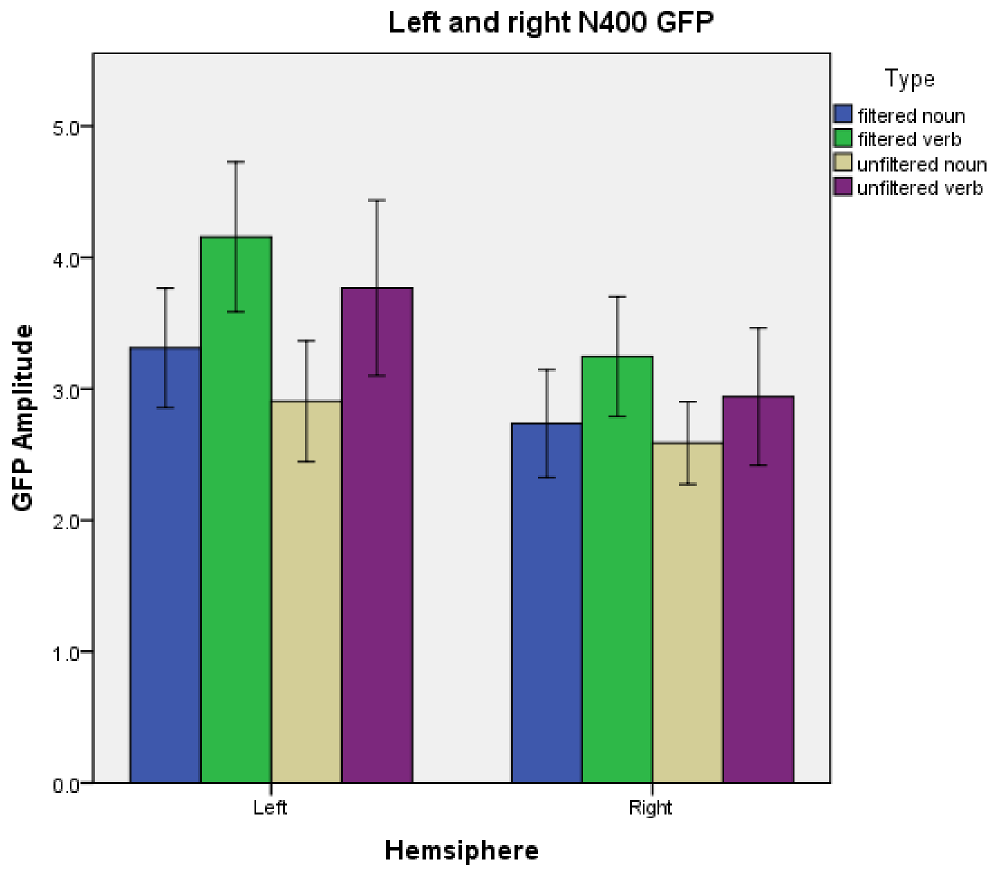

Figure 5-15. Left and right hemisphere GFP amplitudes for both filtered and unfiltered Noun and Verb targets.

5.5 SUPPLEMENTAL TESTS AND SOURCE ANALYSIS

5.5.1 Supplemental test

In order to ensure that Filtering did not interact with Lexical Stress Pattern, two supplemental two-way ANOVAs were conducted (Lexical Stress Pattern and Filtering). Alpha level after Bonferroni Correction (.05/2) is 0.025.

For N400, there was no main effect for either Lexical Stress Pattern or Filtering: F (1,125) =3.287, *p*=0.072 and F (1,125) =5.032, *p*=0.027. There was no significant interaction between Filtering and Lexical Stress Pattern: F (1,125) =2.064, *p*=0.153. For P350, none of the effects was found to be significant (main effect of Filtering, F (1,125) =0.397, *p*=0.530; main effect of Lexical Stress Patten F (1,125) =0.538, *p*=0.465; interaction, F (1,125) = 0.271, *p*=0.603).

The fact that there was a main effect of Filtering on N400 corresponds to the finding that the N400 induced by unfiltered stimuli was larger than the N400 induced by filtered stimuli. What is critical about these supplemental analyses was the absence of interaction between Filtering and Lexical Stress Pattern, indicating that the Filtering manipulation did not affect the Lexical Stress Pattern processing qualitatively.

5.5.2 Source estimation results

Because there were numerous graphs and videos generated to account for the four dimensional data in source estimation (three-dimensional space change in a time series) at different angles and there is limited space here to include them, only the coronal slices for time sequences and volume sequences are presented in this Chapter to illustrate the main area activations and dynamic processes. For more figures and video links, please refer to *Appendix H*.

In the following section and in *Appendix H*, the volume sequences represent the slices dissected in coronal (front to back), sagittal (left to right) and axial (top to bottom), at the exact peak of a given ERP waveform, whereas time sequences represent the activation pattern changes at one slice (midline coronal, sagittal or axial).

5.5.2.1 The control conditions

For filtered conditions, the time sequence change from 250ms to 325ms was plotted at 3.75ms interval in *Figure 5-16*, at the middle section coronal slices (MNI coordinates, x=-0.71, y=-22.91, and z=21.20). The yellow-orange-red spectrum indicates the activated areas. The time sequence starts from the upper left corner, and first goes to the right and then goes down and ends at lower right corner.

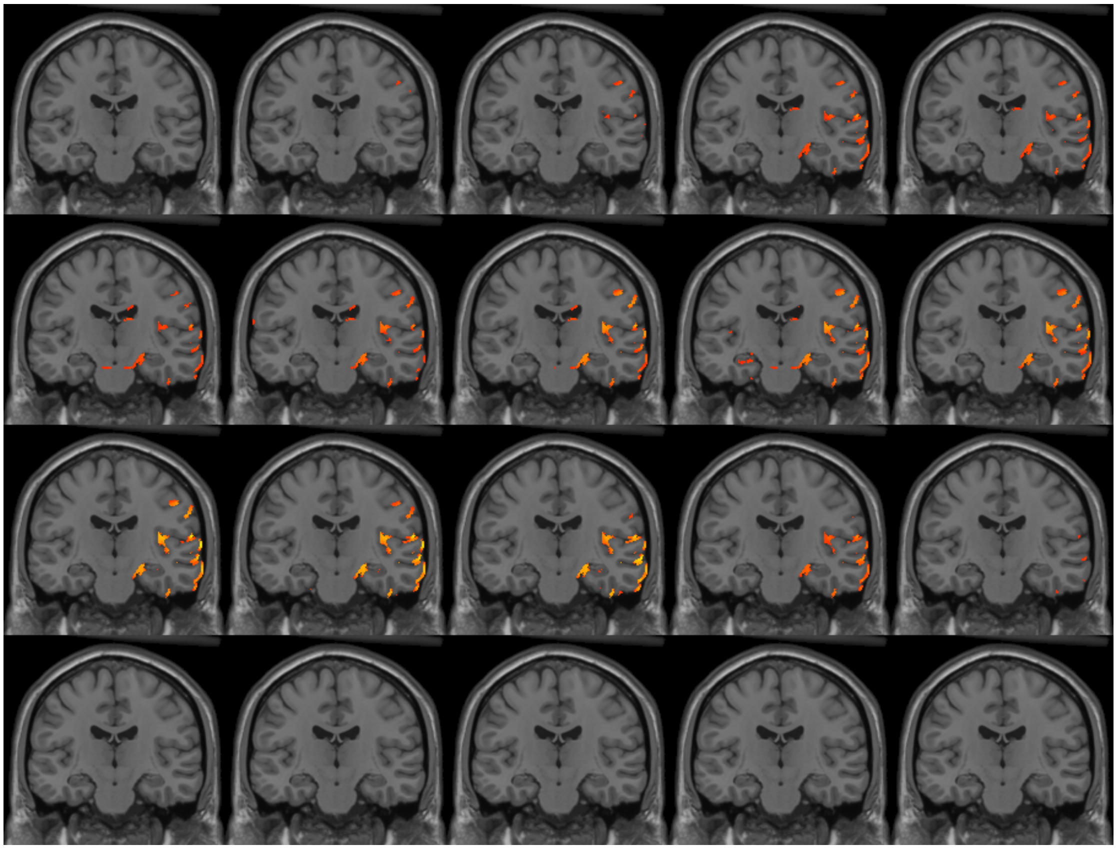

Figure 5-16. Time sequence plot for P300 in filtered conditions.

It can be seen that around the P300 peak, the activation was mostly lateralized to the right, especially to the right temporal lobe. The volume sequences of coronal sections are shown in

Figure 5-17. In plotting these slices, the brain volume was represented in 20 slices and the inter-slice interval loss was 10% of the total volume. All the following volume sequences followed the same convention.

From the volume sequence, it can be seen that the activation was very central in the anterior-to-posterior plane. The activation was rarely seen at anterior or posterior slices.

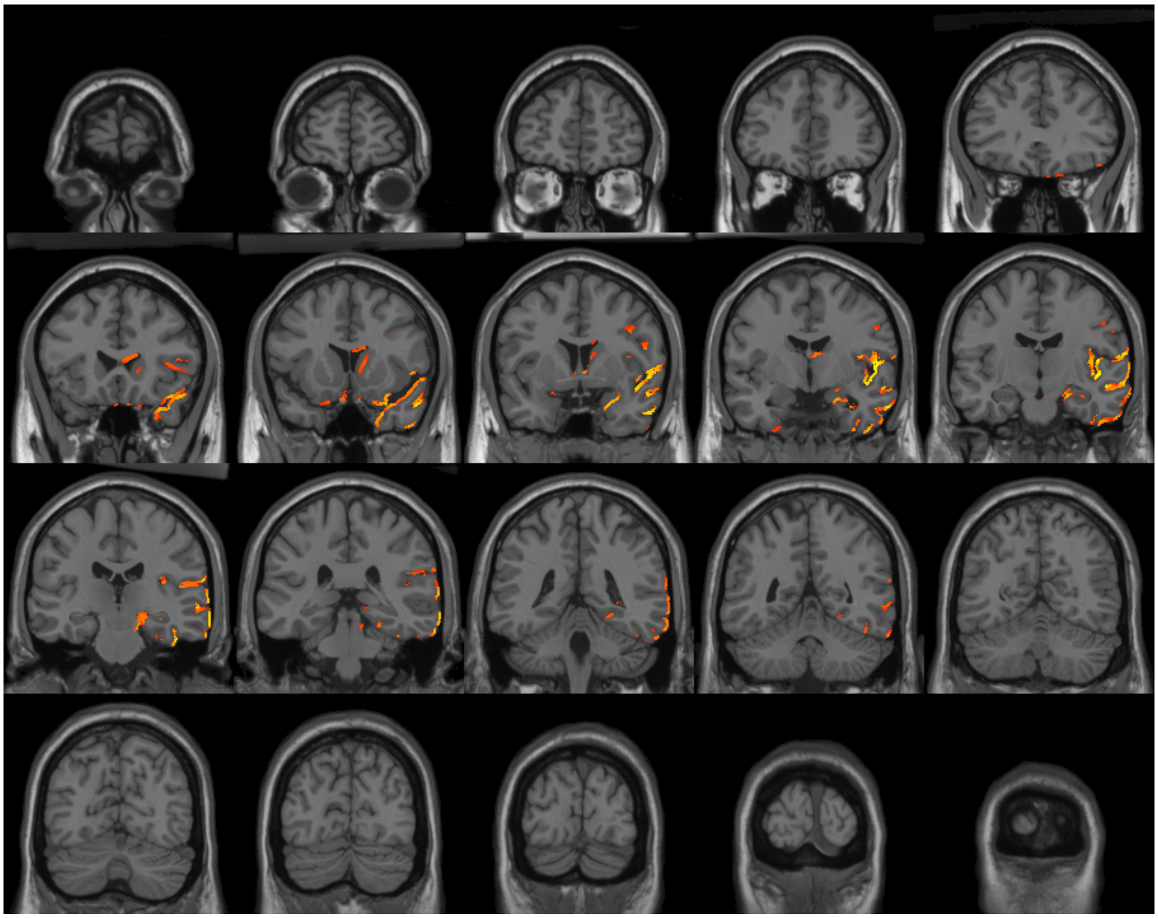

Figure 5-17. The volume sequence that shows activations at P300 peak for filtered conditions from 20 coronal slices.

The time sequence at middle-section coronal slices for unfiltered stimuli from 250ms to 325ms at 3.75ms interval are shown in *Figure 5-18*. It can be seen that around 250ms, the activations were mostly in the left. Upon approaching the peak of P300, the activations shifted to the right, and became bilateral.

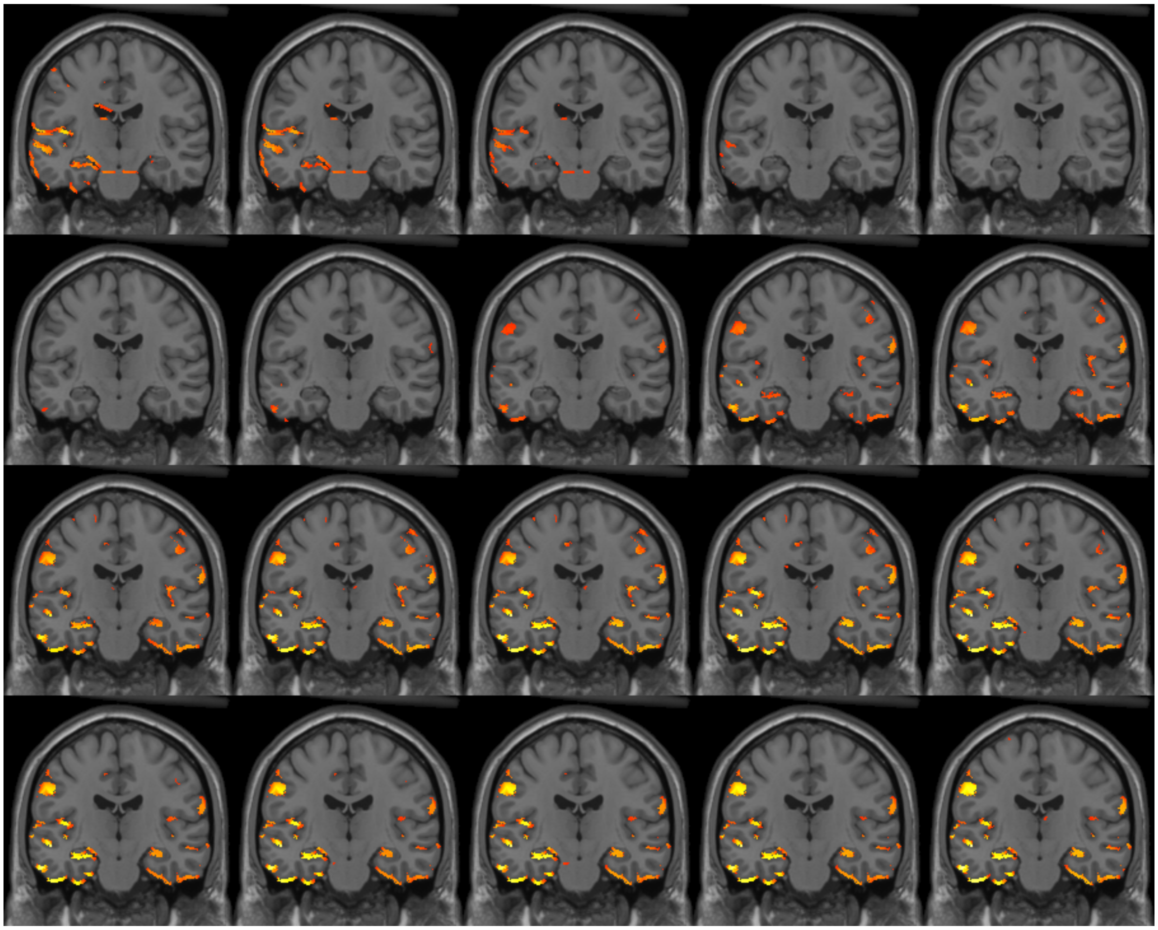

Figure 5-18 Time sequence plot for P300 in unfiltered conditions.

The volume sequences at P300 peak for unfiltered stimuli are plotted in *Figure 5-19*. This figure shows that at P300 peak, the activations were centrally distributed in the anterior-to-posterior plane. There were rarely activations at anterior and posterior slices. The activations were left-lateralized at frontal areas and gradually shifted to the right as the volume sequence approached the central areas.

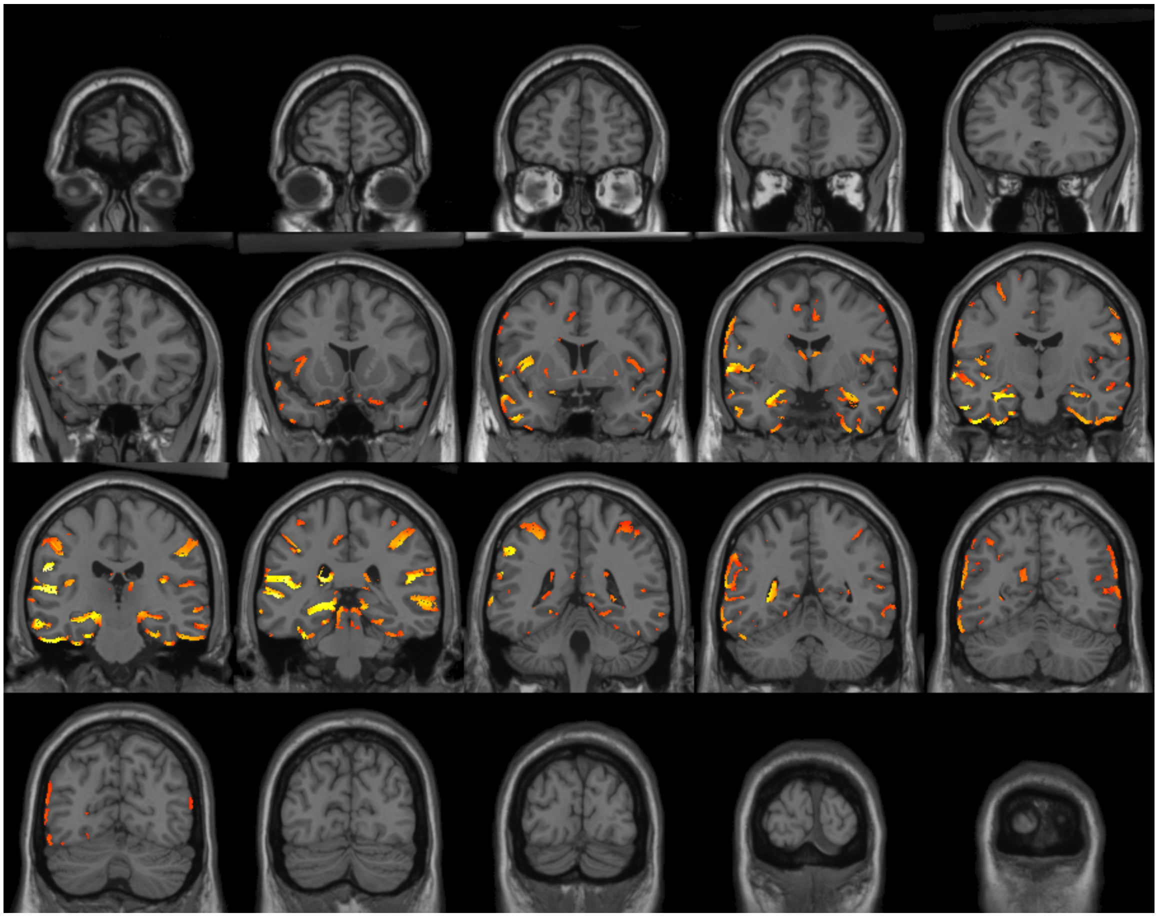

Figure 5-19. The volume sequence that shows activations at P300 peak for unfiltered conditions from 20 coronal slices.

5.5.2.2 Experimental conditions

For filtered Verb Lexical Stress Pattern conditions, in the time sequence from 300ms to 500ms, activations are plotted at coronal middle section slice at 10ms interval in *Figure 5-20*.

From this sequence, it appears that areas of neural networks that usually process unfiltered linguistic information were activated for filtered Lexical Stress Pattern violation, including left temporal area and left inferior frontal gyrus (IFG). Other activations can be observed in the right middle frontal gyrus (MFG), superior and middle temporal gyri (more to the left, less so in the right) and bilateral middle frontal gyri.

The most robust area throughout the time sequence was left IFG. The overallactivation pattern migrated from more bilateral to left-lateralized.

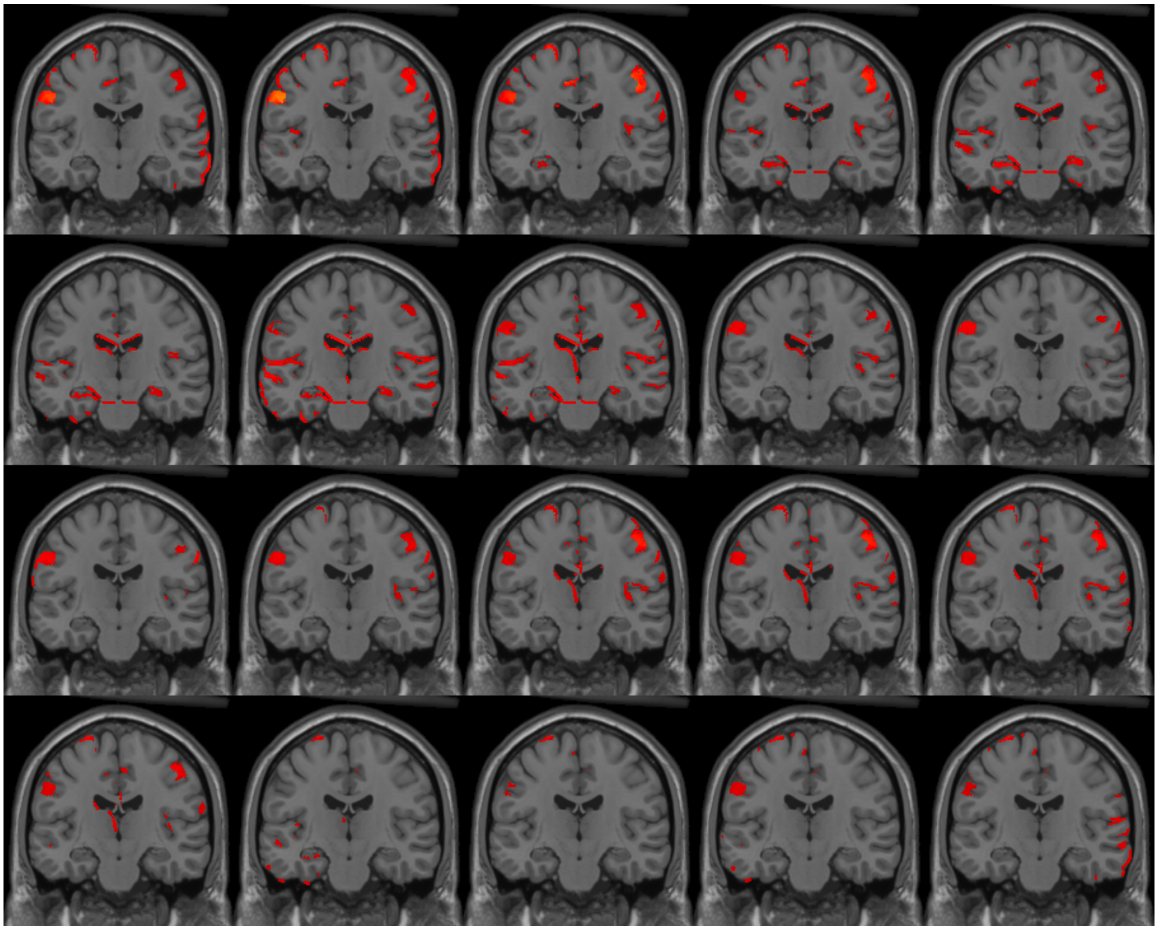

Figure 5-20. The time sequence at middle coronal section from 300ms to 500ms in filtered verb Lexical Stress Pattern condition.

The volume sequence at N400 peak was plotted as 20 coronal slices with 10% inter-slice volume loss at *Figure 5-21*. There is a clear trend shift for activation: as the slices move from anterior to posterior, the activation shifted from the left to the right. The left lateralization was most seen in frontal areas whereas right activations were located in posterior areas.

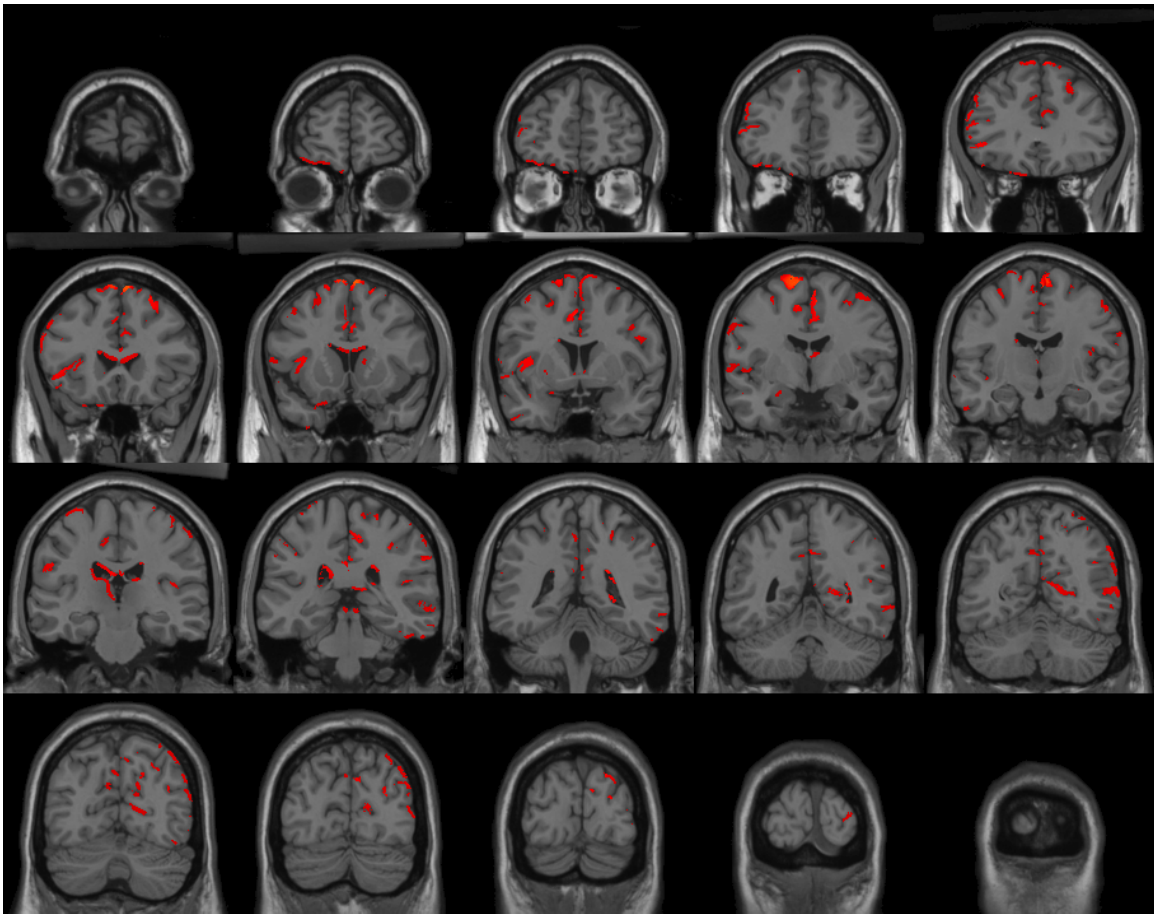

Figure 5-21. The volume sequence that shows activations at N400 peak for filtered Verb Lexical Stress Pattern from 20 coronal slices.

For the unfiltered Verb Lexical Stress Pattern conditions, the time sequence is plotted in *Figure 5-22*. There were two episodes of activation, separated by an empty slice located in the rightmost column of the second row, which represents the interval from 390ms to 400ms. Therefore, the first episode was likely to reflect P350 and the second episode to reflect N400. In both episodes, shifts from right to left can be observed. The most robust area is still the left inferior frontal gyrus. Other activated areas include right frontal middle gyrus, bilateral superior temporal gyri and bilateral superior parietal areas. The overall activation pattern is more distributed than the filtered conditions.

The volume sequence at N400 peak for unfiltered conditions showed a more bilateral distributed pattern as well, as plotted in *Figure 5-23*. Moreover, the activation pattern was more posterior than that in the filtered condition.

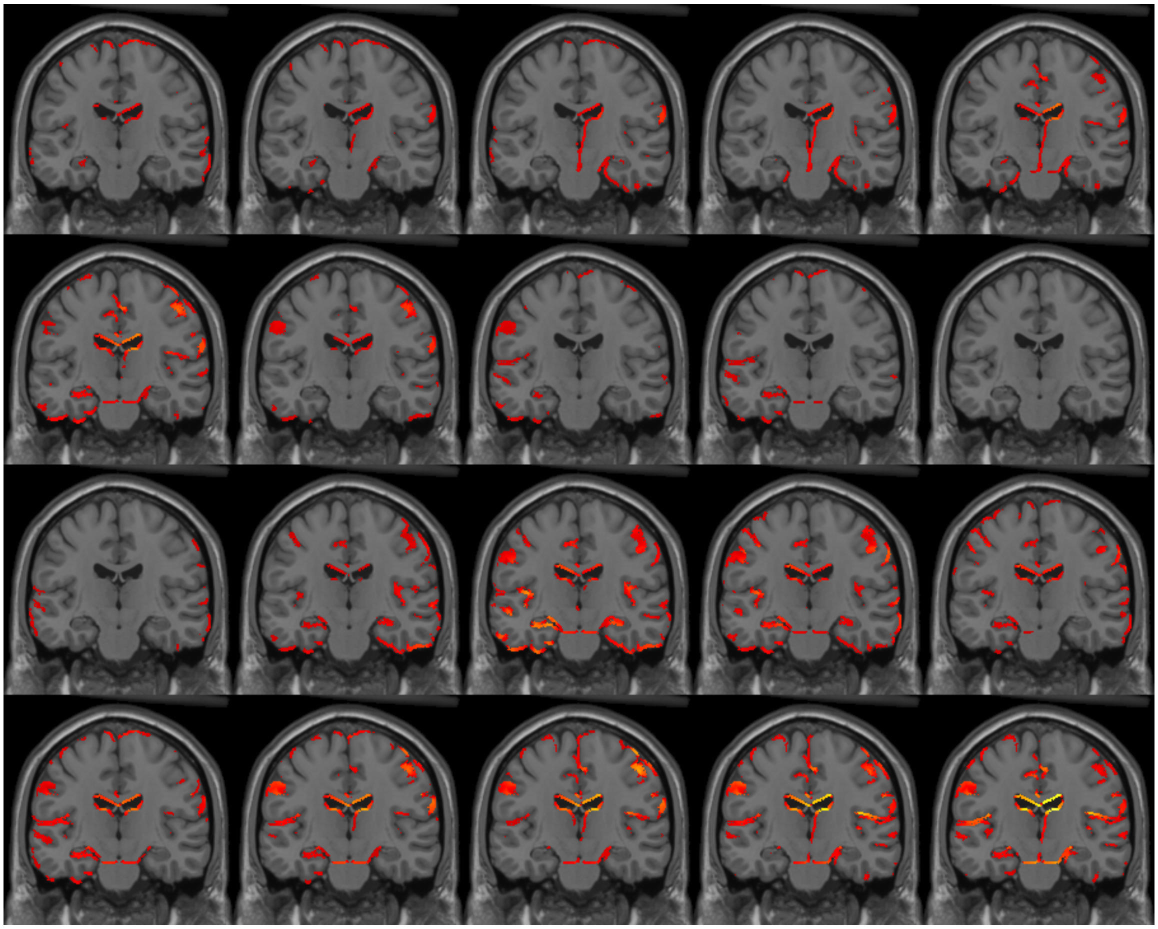

Figure 5-22. The time sequence at middle coronal section from 300ms to 500ms in unfiltered Verb Lexical Stress Pattern condition.

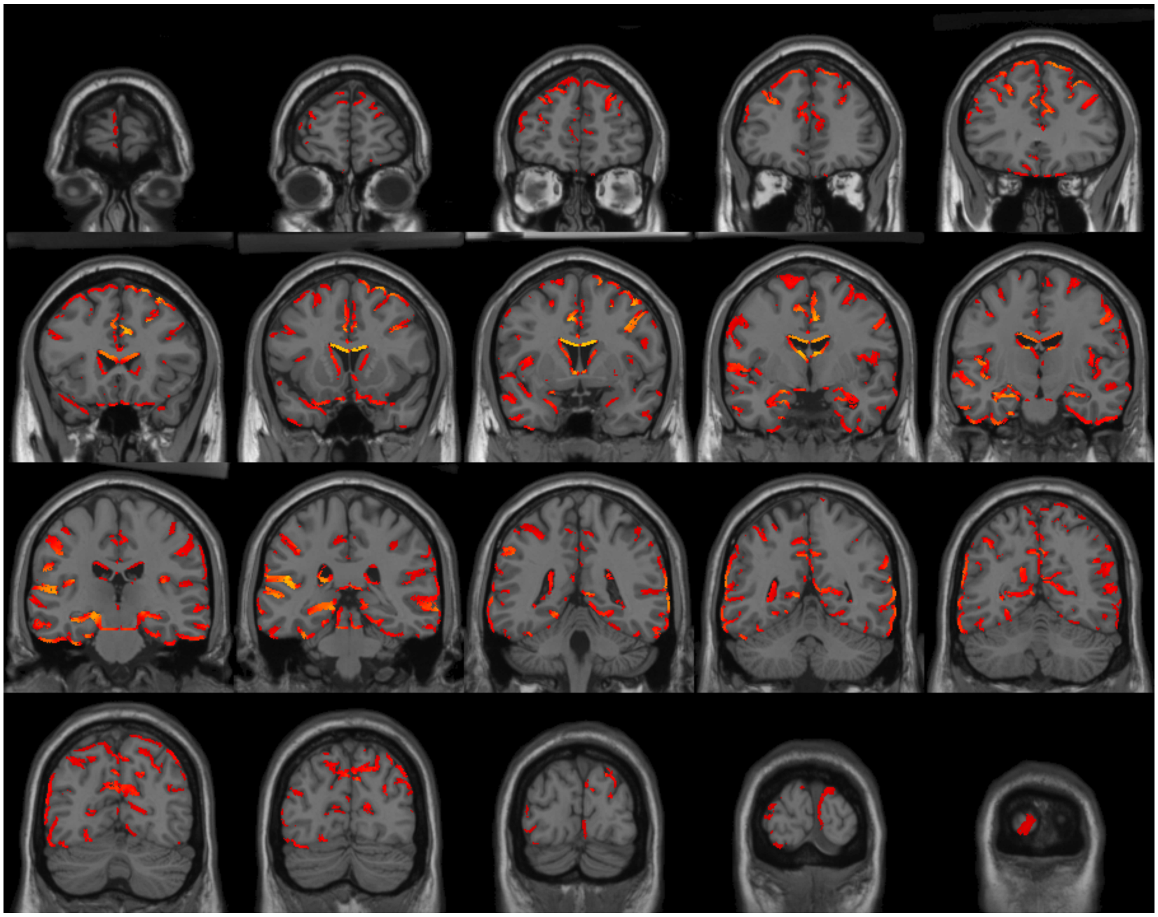

Figure 5-23. The volume sequence that shows activations at N400 peak for unfiltered Verb Lexical Stress Pattern from 20 coronal slices.

6.0 DISCUSSION

In this chapter, current study results are discussed and compared with past empirical evidence, in an effort to direct the revision and advancement of the CI model (*Section 1.2*) as well as to offer implications for future study design. Four sections are included. Results from testing ***Hypothesis A***: lexical stress parsing can modulate lexical selection without the presence of segmental information, are discussed first, in *Section 6.1*. In *Section 6.2,* the scalp distributions of ERP components are analyzed to address ***Hypothesis B***: lexical stress parsing is lateralized to the left hemisphere. An attempt is also made to interpret the underlying neural generators for the N400 component by explaining the possible neural dynamic pathways. In *Section 6.3*, a revised CI model is first proposed based on the in-depth analysis from the previous two sections, incorporating the new findings of this study and integrating past theories on lexical access. Then, limitations of the study, possible alternative explanations, and future directions are given. Finally, in *Section 6.4*, results from the control conditions, involving Gender Shift induced P300, are laid out with a brief discussion of the source analysis and theoretical aspects of this component.

6.1 HYPOTHESIS A: LEXICAL STRESS PARSING CAN INFLUENCE LEXICAL SELECTION WITHOUT SEGMENTAL INFORMATION

In this section, theories on the underlying neural mechanisms and interpretations of N400 are first given to offer a recent perspective on the processes it indexes. Then the current results on ***Hypothesis A*** testing are reviewed in this context, followed by integration with past empirical studies on lexical stress. This subsection ends with the implication of the current results on revision of the CI model and other models of lexical stress processing.

6.1.1 N400 theories and the blurred boundary between "pre-lexical activation" and "post-lexical selection"

N400 has a long history of being used as an index for investigating semantic memory, lexical integration, and expectancy violation under various cognitive and language study paradigms (for reviews, see Federmeier & Laszlo 2009; Lau, Phillips & Poeppel, 2008; van Petten, 1993). Numerous theories have been developed to explain the mechanism of this negativity. On one end of the theoretical spectrum, N400 has been proposed to a reflect relatively late stage of lexical processing: the integration of lexical meaning of the current word with other sources of information from higher levels of semantic hierarchy, i.e. sentence and discourse level context, message-level representations (Brown & Hagoort, 1993). This view is explicitly discussed in Hagoort, Baggio and Willems (2009), as the notion that N400 indexes semantic "unification," defined as "the integration of lexically retrieved information into a representation of multi-word utterances, as well as the integration of meaning extracted from nonlinguistic modalities" (p. 823). This view puts great emphasis on the constructive nature of the meaning integration, in which the N400 reflects late-stage integration difficulty encountered when a current stimulus violates expectations generated by top-down knowledge. However, this interpretation is in contradiction with some empirical results, in which N400 is induced by pseudo-words and some illegal strings. Such stimuli do not have lexical representations and therefore it is hard to fit these results under the view that N400 reflects late-stage lexical integration (Deacon, Dynowska, Ritter & Grose-Fifer, 2004; Hagoort et al., 2009).

On the other end of the theoretical spectrum, because pseudo-words and some illegal strings have induced N400, it has been proposed that N400 reflects perceptual processing stages prior to word recognition and lexical representation, such as orthographic and phonological analysis (Deacon, et al. 2004). However, this theory cannot explain the modulation effect on N400 from discourse level influences, pragmatics, and top-down world knowledge (Chwilla & Kolk, 2005; van Berkum, 2009).

To reconcile this broad spectrum of N400 theories, Kutas and Federmeier (2011) propose a view that embraces the features of both accounts, in which N400 is characterized as a "temporal interval in which uni-modal sensory analysis gives way to multi-modal associations in a manner that makes use of and has consequences for long-term memory"(p. 639). In this account, N400 sits at the intersection between perceptual influence and lexical processing. Further, the cumulative data from 30 years of research on this component points to a comprehension system that is interactive and dynamic in nature, open to both linguistic and nonlinguistic influences at this time window. The modulation from multi-modal sources of information also indicates that the processing of this comprehension system is partially incremental, context-dependent, and statistical in nature and may be subject to revision. In this sense, the boundaries between several theoretical dichotomies are blurred by this account as well, among them the boundary between pre-lexical and post-lexical processing.

Kutas and Federmeier (2011) argue that there is no "magic moment" for lexical recognition and no clear boundary between pre-lexical activation and post-lexical selection (p. 630). N400 represents a time interval during which meaning interpretation is initiated by accessing lexical representations.

Further, the incremental and interactive nature of N400 is reflected by the P350 modulation effect as well. P350 (P3b) is proposed to index a transition between perceptual processing and lexical processing, the latency of which can be modulated systematically by perceptual factors, such as familiarity and complexity (Kutas, McCarthy & Donchin, 1977). P350 also modulates the amplitude of N400 (see review in Federmeier & Laszlo, 2009). This indicates that perceptual recognition and access to multi-modal long-term lexical representations influence each other and there is no abrupt transition between these two.

By using P350 and N400 as indices for testing the influence from the prosody level in the CI model, a degree of interaction between perceptual processing and lexical identification could be observed. Therefore, the interactive modulatory nature of N400 and P350 was exploited to reflect the interactive nature of different levels of the CI model, proposed earlier in this document.

6.1.2 Result pattern and interpretations

The Lexical Stress Pattern violation of the unexpected Verb targets induced significantly larger N400 at Cz than did expected Noun targets, in both filtered and unfiltered conditions. Thus, lexical stress indeed influenced lexical activation and selection. As indicated in the previous section, N400 indexes a process of accessing lexical representations rather than a discrete processing point or stage. Thus, it is concluded that lexical stress information at the prosodic level does have an influence in some period between initial lexical activation and final integration.

Further, the fact that N400 difference between expected Noun and unexpected Verb Lexical Stress Patterns was still significant under filtered conditions is consistent with ***Hypothesis A***: lexical stress parsing influence the access to lexical representations even without segmental information. Hence, lexical stress might be a separate source for accessing multi-modal lexical representations as indexed by N400. As conceptualized in the CI model, this information is situated at a different level from the segmental information.

Different Lexical Stress Patterns also induced significantly different P350 results. In contrast to N400 results, P350 amplitude was larger in the Noun target condition than in Verb target filtered condition. The same trend was shown in the unfiltered condition, though not significant after Bonferroni correction. This result is not surprising, given the interactive nature of P350 and N400. By the end of the high-cloze Noun-predicting sentence, listeners had built a high expectancy of the Lexical Stress Pattern of the Noun target. P350, sitting between the boundary of perceptual and lexical processing, reflects modulation of the information that gets access to long-term lexical representations. In the Noun target conditions, the Lexical Stress Pattern was more expected perceptually than it was in the Verb target conditions, and this was reflected in the increased P350 peak and decreased N400 in the Noun target conditions (Kutas et al., 1977; Kutas & Federmeier, 2011). On the other hand, in the Verb target conditions, the Lexical Stress Pattern was perceptually recognized to a much lower degree before access to long-term lexical representations because of the unresolved expectancy violation, resulting in lower P350 peak and higher N400 peak than in the Noun target conditions.

Overall, interactive P350 and N400 modulation may reflect a process in which the expected Lexical Stress Pattern was better recognized perceptually than the unexpected Lexical Stress Pattern before access to multi-modal lexical representations. The perceptual recognition component of the process was reflected by a cortical positivity towards the end of the time window for stimulus perception at around 350ms (Besson & Macar, 1997; please see Hillyard & Kutas, 1983 for review). Following that, the negativity at around 400ms reflected the perturbation of overall cortical neural activity caused by feeding different sources of perceptual information and top-down information into long-term lexical access processes. The greater the discrepancies among different information sources and the more difficult it was to resolve them, the larger N400 would be. In other words, as Kutas and Federmeier (2009) point out, N400 reflects a comprehension system that "makes use of all the information it can, as soon as it can in order to deal with a rapid, noisy input stream" (p. 634). Thus, greater difficulty dealing with all the information input in this process will result in a larger N400.

The failure to find significant differences at posterior electrode Pz suggests that the components were fronto-centrally distributed. As indicated in later discussion (*Section 6.2.3*), the source analysis of N400 suggested that the neural generators were most likely to be located at left inferior frontal gyrus and superior and middle temporal gyrus. The electromagnetic field generated by these sources may not able to propagate to the posterior sites on the scalp, because what EEG electrodes measure as the surface electrical activity is mainly spatial summation of post-synaptic potentiation of local columns of neurons in parallel orientations (Bagic, 2007; Parkkonen, 2011). Therefore, it is highly improbable for postsynaptic potentiation sources to affect distant surface locations other than the surface immediate perpendicular to the source.

The supplemental analysis results (*Section 5.5* in Chapter 5) showed that Filtering (filtered vs unfiltered) did not interact with Lexical Stress Pattern (Noun vs Verb) for peak-to-peak amplitudes at Cz. This suggests that the processing of suprasegmental information may be parallel and additive to segmental information, as elaborated in the following section (*Section 6.1.3.4*).

6.1.3 Integration with past studies on lexical stress

6.1.3.1 Task-dependent lexical stress

As stated in Chapter 1, in reviewing the past literature on lexical stress processing, a pattern emerged. That is, **studies involving tasks directly activating phonological representations found significant effects of lexical stress**. These tasks include fragment priming (Cooper et al., 2002; Friedrich et al., 2004; Soto-Faraco et al., 2001; van Donselaar et al., 2005), onset gating (Arciuli & Cupples, 2004; Lindfield, Wingfield, & Goodglass, 1999; Wingfield, Lindfield, & Goodglass, 2000), word shadowing (Slowiaczek, 1990), and phoneme migration (Mattys & Samuel, 2000).

In contrast, **studies that have tasks involving "activation of lexical concepts" did not find significant results of lexical stress**. These tasks include associative priming (Cutler, 1986; van Donselaar et al., 2005), lexical decision for isolated words (Cutler & Clifton,1984), and monitoring of a phoneme target after the word of interest (Small, et al., 1988).

This pattern was explained by the CI model, as elaborated in Chapter 1 and Chapter 3 (*Section 1.2.1* and Chapter 3). Results of the current study combined with the above N400 interpretation proposed by Kutas and Federmeier (2009) could also account for this pattern. That is, if a given task only probed, or the measurement of the dependent variable was only initiated at, a stage after multi-modal information converges to the lexical representation, the influence of lexical stress might not be observed with that task. The former kind of studies as well as current study used tasks that probed stages prior to final integration of lexical representations, and therefore found effects of Lexical Stress Pattern. Meanwhile, because the latter kind of studies either probed stages after lexical integration or measured the influence at this late stage, influences of lexical stress pattern were not found.

6.1.3.2 The discrepancy of P350 results with a previous study

The P350 results contradicted Friedrich, Kotz et al. (2004)'s ERP study with German lexical stress violations. As noted in *Section 1.3.2*, two mismatch conditions were created in the Friedrich et al. study, segmental mismatch and lexical stress mismatch. The lexical stress mismatch condition induced P350 but not N400. The segmental mismatch condition induced both P350 and N400. Moreover, the P350 from segmental mismatch was larger and different in topographic distribution than the P350 from lexical stress mismatch.

There are two major discrepancies between current study and Friedrich et al. (2004). First of all, in our study, N400 was observed for lexical stress mismatch. Second, in the current study, the standard condition with appropriate lexical stress induced a larger P350 than the lexical stress mismatch condition.

These discrepancies may arise from several contributing factors: (1) In Friedrich et al. (2004) study, no sentential context was involved and therefore no previous lexical stress expectancy was built upon perceiving the target; (2) a lexical decision task was used in Friedrich et al. (2004), which may create some task-related factors that contributed to the result difference. For example, this task does not require meaning integration; (3) there was no filtered condition in Friedrich et al. (2004) study, and therefore participants were not forced to use the lexical stress alone to make judgments; (4) the lexical stress violations in Friedrich et al. (2004) study were created by pitch modulation while in the current study they were from natural stimuli splicing; (5) there might be inherent language- dependent differences between English and German.

6.1.3.3 The lexical frequency issue

For the Noun-Verb homonym targets in the stimulus set, one member of the pair may have different lexical frequency in everyday communication than the other. If the frequencies between the Noun and the Verb in the stimulus set were overall significantly different, then there might be a systematic confound involved in the stimulus set.

In order to check this possibility, overall frequencies from the CELEX database for all the targets were entered for *post hoc* paired sample *t*-test between Noun and Verb conditions (Baayen, Piepenbrock & Gulikers, 1995). No significant difference was found: t (27) =-0.40, p=0.968. Thus, lexical frequency might not be a contributing factor for effects obtained in the current study.

6.1.3.4 Parallel processing of segmental and suprasegmental information

The findings from the supplemental statistical test (no interaction between Filtering and Lexical Stress Pattern) can be accounted for by the CI model. Specifically, it could be explained that lexical stress, which is situated at a different level distinct from the phonetic level, influences the access to long-term lexical representations in a qualitatively similar way as segmental information situated at the phonetic level. Therefore, the Lexical Stress violation is proposed to cause a quantitative difference that might be additive and parallel to other sources of influence, such as segmental information, to guide lexical representation access.

At least one past study reported similar effects when it came to the additive parallel N400 induced by lexical level prosody violations. Li, Yang and Hagoort (2008) did an ERP study on accentuation pitch and lexical tones in Mandarin Chinese at the discourse level, by creating these two kinds of anomalies.

One of the most striking findings of the Li et al. study is that both inconsistent accentuation and inappropriate lexical tone yielded N400 effects, and interestingly there was no interaction between them. The waveform evoked by inconsistent pitch accentuation had a similar topography to that evoked by lexical tone violation, with a maximum over central-parietal electrodes. Furthermore, the effect for the combined violations was the linear sum of the effects from these two individual sources.

This suggests that lexical level prosody might be parsed in a parallel manner with other sources of information for accessing long-term lexical representation. Further studies are needed to test the validity of this hypothesis.

6.2 HYPOTHESIS B: LEXICAL STRESS PARSING IS LATERALIZED TO THE LEFT HEMISPHERE

In the material below, peak-to-peak amplitude data, Global Field Power (GFP) and source estimation of N400 between left and right hemispheres are discussed in three sub-sections in relation to ***Hypothesis B***.

6.2.1 The peak-to-peak amplitudes at selected electrodes

The peak-to-peak amplitude of N400 was significantly larger at C3 (left central) than at C4 (right central), in filtered conditions but not in unfiltered conditions. This lack of effect in unfiltered conditions may be due to the fact that the listeners still rely partially on segmental cues such as schwa reduction to make lexical selections (Cutler, 1986). When and only when the segmental information was removed, the processing entirely relied on suprasegmental features.

Alternatively, the bilateral pattern in unfiltered conditions might arise from parallel processing of segmental and suprasegmental features of the target, i.e. when both kinds of features were available, both hemispheres were recruited for processing.

The peak-to-peak amplitudes of N400 and P350 were not significantly different between T7 (temporal left) and T8 (temporal right). This indicates that N400 induced by lexical stress parsing induced is a more centrally distributed component, consistent with general N400 distribution (Kutas & Federmeier, 2011) and past studies with similar stimuli. For instance, Lee & Federmeier (2009) found that Noun-Verb homonym ambiguity (such as “park” in different contexts) induced a fronto-centrally distributed N400. Though the disambiguation process of Lee & Federmeier (2009) did not rely on the lexical stress pattern, the access process for lexical representations still holds relevance for the current study. That is, disregarding the different sources of information available, the selection process of Noun-Verb homonym from lexical representation was similar. Therefore, it is not surprising that the N400 distribution was fronto-centrally distributed in current study as well.

6.2.2 GFP distribution and possible underlying mechanisms

The topographic map for Global Field Power (GFP) of N400 indicates that the parsing of lexical stress pattern without segmental information (i.e., filtered stimuli) is an overall left-lateralized fronto-centrally distributed process. Further, ANOVA indicated that the Hemisphere factor did not interact with Lexical Stress Pattern, which was the same as the pattern obtained from C3 and C4 electrodes for filtered stimuli. This not only supports the inference that the analysis from C3 vs C4 is representative of the global surface electromagnetic field distribution, but also indicates that the absence of interaction may represent an important feature of lexical stress parsing: the processing of the mismatched Lexical Stress Pattern may not be qualitatively different from the processing of the matched Lexical Stress Pattern. That is, the fact that none of the statistical tests yields a significant interaction suggests that matched and mismatched lexical stress targets were computed under a qualitatively similar mechanism. These targets triggered similar neural networks to fire, and this similarity in neural generator networks resulted in proportional changes in surface ERP amplitudes and similar morphology.

6.2.3 Source estimation analysis of N400

For the filtered conditions, the source activations were mostly observed at left inferior frontal gyrus, left superior and middle temporal gyri and bilateral middle frontal gyri (please see *Figure 5-20* and *5-21* in Chapter 5, as well as *Figure H-5* and *H-6* in *Appendix H*). This suggests that Lexical Stress Patterns were detected and processed with the same neural network for segmental information processing, as indicated by numerous past fMRI and MEG studies (Friederici, 2002; Friederici & Alter, 2004; Maess, Herrmann, Hahne, Nakamura & Friederici, 2006; Poldrack, Temple, Protopapas, Nagarajan, Tallal, Merzenich & Gabrieli, 2001).

For the unfiltered conditions, similar areas were activated. The most robust activation for both conditions was in the left inferior frontal gyrus, which has been associated with both phonological and semantic processing in past neuroimaging studies (for reviews see Costafreda, Fu, Lee, Everitt, Brammer, & David, 2006 and Fiez, 1997). Other activated areas included right middle frontal gyrus, and bilateral superior temporal gyri. Overall, the activation for unfiltered conditions was more distributed. This is not surprising, given that unfiltered conditions rendered more information to process than filtered conditions.

This apparent overlap between lexical stress parsing and the common processing neural networks for segmental information may explain the absence of interaction between Filtering and Lexical Stress Pattern in the supplemental test as well (as discussed in *Section 6.1.3.4*) . Similar networks of underlying generators produced similar surface amplitude and morphology.

However, evidence from source analysis based on sLORETA should not be taken as conclusive. First of all, this experiment was not designed for spatial localization and had an inherent exploratory nature. Second, the electromagnetic field was inevitably distorted by both endogenous and exogenous noise, which could cause spatial localization errors that cannot be readily estimated for the current study. Future fMRI or MEG studies could offer better tests of the localization of lexical parsing processes than the current approach (Menon & Kim, 1999; Sekihara, Sahani & Nagarajan, 2005).

6.3 IMPLICATION TO THEORETICAL DEVELOPMENT, LIMITATIONS AND ALTERNATIVES

In this section, the findings of the current study that cannot fit the Cascading Inhibition (CI) model are first discussed, after which a revision of the CI model is proposed. Following that, implications of the results for other theoretical models of lexical stress are presented. Then, directions for future theoretical model development are given. Finally, alternative views and limitations of the study are provided.

6.3.1 The implications for the proposed CI model and the theories of other investigators

6.3.1.1 The implications for the CI model

Four result patterns were not predicted by the CI model as originally proposed (see *Figure 1-2*). First, there was no interaction between Lexical Stress Pattern and Hemispheric distribution of the any ERP components. Second, the effects of Lexical Stress Pattern did not interact with segmental information filtering, as indicated by the supplemental test (please see *Section 5.5.1* in Chapter 5). Thirdly, filtering did influence the hemispheric distribution of N400. Contrary to expectation, N400 for the filtered conditions was left lateralized in topographic distribution whereas N400 from the unfiltered conditions was bilaterally distributed. Finally, the source analysis suggests that the neural networks recruited by suprasegmental and segmental information were not dissimilar.

These results call for two revisions of the CI model in describing the lexical stress parsing process.

First, it was originally hypothesized in the CI model that, since the lexical stress is situated at a different level from segmental information, it is processed fundamentally differently from segmental information. However, the current results didn't support this prediction. Rather, they indicate that though segmental information and suprasegmental information may situated at different levels, the computation rule applied to process them may not necessarily be different and may recruit the same neural network.

Second, it was proposed that lexical stress parsing influences the lexical identification level only through the mediation of the two intermediate levels. This was not supported by the current dataset either. The fact that filtering out segmental information pushed the hemispheric distribution of N400 to the left suggests that lexical stress information may have direct access to the lexical identification level. When the intermediate levels were removed and meaning integration with global context was imposed on the comprehension system, Lexical Stress Pattern was used for direct lexical identification. However, there is an alternative task-demand explanation for the leftward shift in the filtered conditions, which is elaborated in *Section 6.3.4.*

Taken together, these results suggest that minor computation rule changes between the levels in the hierarchical structure are required. Specifically, (1) the fundamental computation of processing each input level does not have to be qualitatively different; (2) the access to the lexical identification level might be shared by different levels in the CI model, though the connection strengths of each level to the lexical identification might be different, with the phonetic level having the strongest connection; (3) the access to the lexical identification level by upper levels of the hierarchy might be statistical in nature: e.g., the unavailability of information from the phonetic level may shift the processing focus to the prosodic level. Therefore, in the filtered conditions, the prosodic level would be able to influence the lexical identification level directly.

In *Figure 6-1*, the second and third computation rule changes are illustrated. This figure is very similar to *Figure 1-2*; the only difference is the added purple line that represents the influence the prosodic level exerts on the lexical identification level. The strength of this influence may statistically increase when phonetic information is not available.

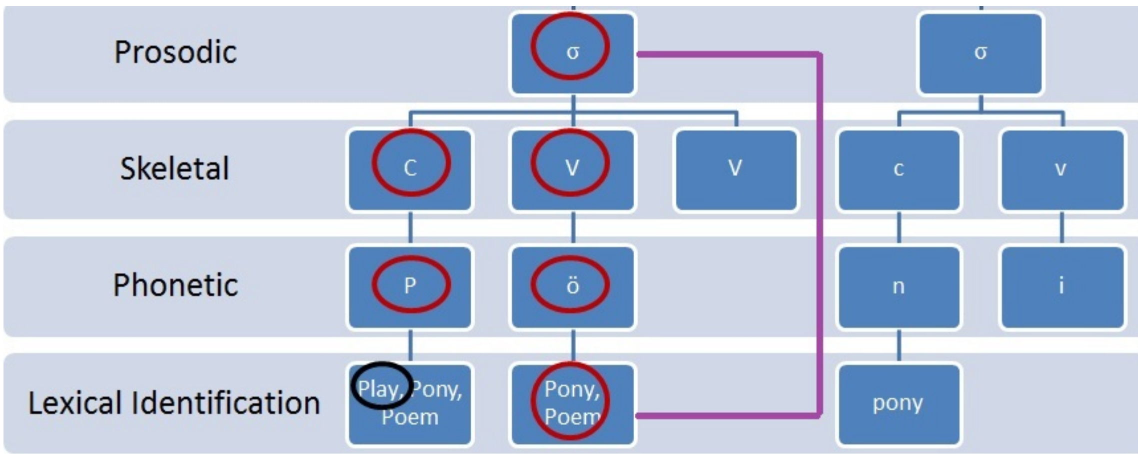

Figure 6-1.The revised Cascading Inhibition model. The purple line indicates the direct influence from the prosodic level to the lexical identification level, the strength of which may increase statistically when information from either of the two intermediate levels is not available.

One theoretical question ensuing from the above rule changes is that if there is no qualitative difference in computation rules between the levels, how does the processor distinguish them? One possible mechanism is that the separation of information streams may depend on different input channels, such as modulation frequencies. For example, auditory inputs with quick modulation frequencies may get the highest priority in accessing lexical representation information. This conjecture is in accordance with Poeppel's (2003) "asymmetrical sampling in time" hypothesis of speech analysis, in which two time scales were proposed, one "commensurate with processing formant transitions" and the other one "commensurate with syllabicity and intonation contours" (p. 245).

6.3.1.2 The implications for other theoretical models

Results of the current study also offer direct implications for Cutler (1986)'s "functional homophonous" proposal, Packard's (1986) Lexicalization Hypothesis, and Dickey's (1995) Limiting Domain Hypothesis.

Cutler (1986) drew two conclusions in her “functional homophonous” proposal. One was that lexical stress could not influence lexical access. The other was that lexical stress information was not accessed initially for lexical activation and only exploited later when the selection was made. The results of the current study, however, are incompatible with both of these conclusions. Lexical Stress Pattern was exploited at the earliest opportunity (as indicated by the dynamic modulation between P350 and N400) for access lexical representation, even when segmental information was not available. This was also consistent with results from past gating studies, in which lexical stress information was used immediately, and held advantage from very early on (Arciuli & Cupples, 2004; Lindfield et al., 1999; Wingfield et al.,2000)

Further and contradictory to the predictions of the current study, one proposal from Packard’s (1986) Lexicalization Hypothesis was supported: There was no qualitative computational difference between segmental and suprasegmental information processing, as elaborated in the above section. However, this result does not support the entire Lexicalization Hypothesis. The core claim of the Lexicalization Hypothesis is that the exploitation of lexical level prosody is as obligatory as the exploitation of segmental features. This is not the case for English, because lexical stress does not contrast meanings for the majority of the English lexicon and is therefore processed qualitatively differently from other obligatory lexical level prosody in tone languages and pitch accent languages (Gandour, Wong, Hsieh, Weinzapfel, Van Lancker, & Hutchins, 2000; Xu, 2006). Rather, the implication of the results from the current study should be to construct an interactive and statistically-based model, as introduced in the previous section and elaborated in the next section.

Finally, effects from the current study were not restricted by the “syllable” constraint, as set forward in the Dickey (1995) Limiting Domain Hypothesis. The current results indicate that linguistic prosody defined over a unit larger than one syllable provided access to lexical activation and selection processes.

6.3.2 Future model development

Summarizing the above two sections, at least three points are critical when it comes to future theoretical model development. First, the inputs need to be interactive and multi-modal. As stated in Chapter 3, the influences on the activated cohort of lexical items need to be statistical in nature and need to be able to be revised, modulated or even overwritten by multiple sources of information. Kutas and Federmeier (2011) also attribute the cumulative ERP data in years of cognitive and language research to a "distributed, multimodal, bihemispheric comprehension system" (p. 642). Second, the computations for different input sources need to be parallel, incremental and context-dependent. Thirdly, future theoretical models for lexical identification should consider blurring the dichotomy between "pre-lexical activation" and "post-lexical selection" processes (Cutler, 1986; Soto-Faraco et al., 2001). Considering these factors, in the revised CI model, the direct influence of information from the prosodic level to the lexical identification level was added. The claim in the CI model that the whole process is parallel, incremental and statistical in nature was maintained.

Another important caution is that, the adoption of hierarchical structure of the CI model follows the convention of speech processing models in the literature on prosody. Some indirect evidence suggests that lexical stress influences the perception of segmental information, per the categorical perception studies or phoneme migration studies discussed in Chapter 1 (Please see *Section 1.1*, Connine et al., 1987; Mattys & Samuel, 2000)

However, there is not sufficient evidence to suggest that this hierarchical structure has to be the only possible operational structure for processing lexical stress. It is quite possible that the processing of lexical stress and segmental information is completely parallel or that this information is operationally represented in two separate structures. The hierarchical structure in the CI model is only one possibility, which needs further testing.

6.3.3 Alternative views of the lexical stress paring mechanism and possible future studies

A debate that could be raised by the testing of ***Hypothesis A*** concerns the possible "pre-activation" of the lexical stress pattern before the onset of the target. The fact that the contextual sentence itself was not filtered, and by the end of it, high expectancy of the target word had been built (reflected by high cloze value) suggests that part of the obtained effect could have been driven by lexical expectancy violation instead of Lexical Stress violation. Simply put, the resulting N400 may reflect the possibility that the phonological representation of the "then already activated" word was violated, and therefore may not be attributable to an active lexical stress parsing process.

This possibility, however, can only be explained under "early-stage" theoretical models of N400 (Kutas & Federmeier, 2011). Specifically, if N400 reflects simple phonological representation violation, then it is possible that the obtained N400 could result from simple phonological violation instead of lexical stress parsing.

This alternative can be tested using the same target Noun-Verb homonym pairs and modifying the context to be syntactically but not semantically constraining. Under a syntactic constraint, if N400 reflects lexical representation access and not phonological processing, it will not be induced by unexpected Verb targets. Instead, P600, which is interpreted as reflecting violations between linguistic prosody and syntactic structures, should be observed (Steinhauer et al., 1999). On the other hand, if N400 reflects early phonological processing, it will be triggered by unexpected Lexical Stress Patterns under syntactic-constraining contexts.

Another alternative view involves the "stress typicality issue". Evidence from gating studies reviewed in Chapter 1 (Arciuli & Cupples, 2004; Lindfield et al., 1999) suggests that stress typicality may serve as a confounding factor. Typically stressed words hold an advantage over atypically stressed words in the selection process, and have earlier isolation points (i.e., the point at which listeners isolate the target word from the activated cohort). In English, the typically stressed pattern for two syllable words is the first syllable stress pattern, which is the "Noun Pattern" in the current study. Therefore, it is possible that the smaller N400 in the matched condition could partly be attributed to the advantage for processing stress typicality instead of the satisfaction of lexical expectancy. This possibility needs further investigation.

6.3.4 The problem of task demand differences between filtered and unfiltered conditions

The left lateralization of the lexical stress parsing process in the filtered conditions might have other explanations as well. One of them relates to processing demands. Upon hearing the filtered target, it is likely that efforts made by listeners to figure out the identity of word caused or at least contributed to the left lateralization by increasing task demand (Meyer, Friederici & von Cramon, 2000)

Given this possibility, one may argue that passive listening or phoneme monitoring serve as better task choices for controlling task demand than the comprehension task used in the current study. However, one practical matter is that during the ERP recording in the dark, passive listening could bore participants easily and cause background EEG change due to fatigue (Klimesch, 1999). Phoneme monitoring, on the other hand, would not ensure that listeners paid attention to the semantic content of the stimuli. Instead, listeners might divert their attention to the phonological representation of the words, resulting in disruption of the targeted neural activity for lexical activation and selection.

6.3.5 Cautions for interpreting GFP results

GFP is computed as the standard variance distribution of the prescribed amplitude for each given ERP waveform (Skrandies, 1990; for algorithm of GFP see *Appendix E.1*). It reflects the overall deviance from the averaged electrophysiological response. That is to say, the greater the GFP value, the more deviant the overall electrical field distribution.

In the current study, left and right hemisphere GFP was computed separately from the overall averaged amplitudes. By the functional definition of GFP, these two measures reflect overall variance in terms of surface electrical field distribution for the two hemispheres.

High variance is usually correlated with high amplitude and high overall activity. However, since variance is not a direct measure of amplitude, it should be interpreted with caution. Larger left GFP than right GFP should be interpreted as the electrodes on the left side of brain produced electrophysiological responses that were more deviant from the overall average than electrophysiological responses from the electrodes on the right side of the brain.

6.3.6 Cautions for interpreting source estimation

The source estimation results should be taken with caution as well. As stated by Pascual-Marqui (2000) and specified in Chapter 4, sLORETA source analysis is the optimal method when a prior ROI (region of interest) is prescribed.

However, the source estimation in this study was exploratory in nature: the activated voxels and regions could not be interpreted as results from formal hypothesis-driven comparisons. Instead, these activated areas should serve as starting points for prescribing ROIs in future hypothesis testing.

6.3.7 The problem of subject sex imbalance

In this study, the vast majority of participants were females (29 females and 3 males). In order to see whether this sex imbalance had any effect on ERP components, the descriptive statistics were computed for females and males separately for each component in each condition. All the male data fell within the interquartile range of female data (i.e. the range between 25 percentile and 75 percentile of the data distribution). Thus, data collected from males and females seemed not to differ.

6.4 SUBSTANTIATION OF GENDER SHIFT INDUCED P300 RIGHT LATERALIZATION IN CONTROL CONDITIONS

6.4.1 Challenges of selecting electrodes for Gender Shift effect analysis

Prosodic changes in Gender Shift conditions have been found to be processed in the right hemisphere rather than the left hemisphere, in dichotic listening and fMRI studies (Belin, Zatorre, Lafaille, Ahad, & Pike, 2000; Lattner, Meyer, & Friederici, 2005; Moncrieff et al., 2004). The same processing effect has been found using an auditory oddball paradigm: a positivity at around 300ms post stimulus onset (P300) has been induced by infrequent gender (oddball) stimuli that were equated on other acoustic parameters (i.e. duration and intensity: Jerger et al., 1995; Lattner & Friederici, 2003).

Theoretically, it has been proposed that P300 indicates perceptual difference detection by systematic perturbation of neural activity to "update working memory" (p. 5, Mehta, Jerger, Jerger & Martin, 2009; Donchin & Coles, 1988). In the context of the current study, P300 is proposed to reflect working memory updating given the perceptual change of gender in voice. This change is nonlinguistic, and as such serves as a good candidate for controlling prosody change that bears linguistic significance.

However, although numerous dichotic listening and fMRI studies indicate that the processing of nonlinguistic prosody change is right lateralized, Gender Shift induced P300 has rarely been replicated in the auditory oddball paradigm. Therefore, for the purposes of the current study, it was largely unknown whether the right lateralized neural generator(s) of the P300 component would have the same topographical distribution as evidenced in the dichotic listening and fMRI studies. Thus, the specific optimal electrode sites for analysis were not clear.

In Jerger et al. (1995), the right lateralization of Gender Shift processing was identified by computing an index by selecting four electrodes at different locations on the scalp. Amplitude differences between these electrodes were converted to a lateralization index. In this way, no matter which electrode induced the maximal right lateralization effect, the dynamic change was captured. Therefore, the problem of selecting electrodes for analysis was circumvented.

In the current study, the 64-electrode cap provided enough data coverage density to compute the Global Field Power (GFP) of P300 for left and right hemispheres separately, to monitor the dynamic change. In addition, it enables us to explore underlying activated source by sLORETA method. Because both approaches could back up analyses from electrodes, the electrode selection problem was not circumvented in the current study. A lateralization index was not used. Instead, statistical analysis from selected electrodes at either the left or right side of the scalp was compared *post hoc* with GFP analysis to validate the electrode selection.

In the following sections, the general statistical results of P300 effect are first discussed, followed by electrode selection approach, surface analysis and source activation analysis.

6.4.2 General result pattern for P300

Overall, from all the electrodes selected for analysis (C3, C4, T7, T8) and from the central electrode (Cz) the infrequent oddball male stimuli indeed triggered much stronger P300 than the frequent standard female stimuli.

First and foremost, this demonstrates that the experimental setup was effective (valid/free of artifacts) for eliciting cortical neural electrophysiological responses to auditory inputs. That is to say, if there is an endogenous cortical response, the current experimental setup should be able to capture it.

Further, the results are consistent with the long-established hypothesis that Gender Shift in voice induces working memory updates, which triggers cortical P300 responses. Admittedly, updating working memory is not the only proposed mechanism for P300 in the literature. Other theories include Event-Related Desynchronization (ERD) of attention resource allocation. It has been proposed that attention allocation for cognitive tasks desynchronizes the background EEG alpha wave and contributes to the P300 component (Pfurtscheller, 1977, 1992; Pfurtscheller &Aranibar, 1977; Klimesch, Pfurtscheller, & Schimke, 1992). In addition, delta responses that are involved in signal matching, decision making and surprise, and theta responses that are involved in focused attention and signal detection have also been proposed as possible mechanisms for P300 generation (Polich, 1997).

The main effect of Gender Shift was smaller in filtered conditions than in unfiltered conditions, though in both cases statistical significance was achieved. This may due to the fact that people discriminate gender not only from low-frequency suprasegmental features such as fundamental frequency (Fo), but also from higher frequency information related to voice quality. For example, levels of aspiration noise located around the third formant are important for gender perception, giving a female voice a more “breathy” quality than a male voice (Mendoza, Valencia, Munoz, & Trujillo, 1996). Because these high frequency features influence perception of gender, low-pass filtering of the stimuli inevitably reduced the effect size of P300.

6.4.3 Electrode selection problem and resolution

For the initial electrode selection, central left (C3) and central right (C4) electrodes were analyzed. This selection was made for two design purposes: 1) C3 and C4 already had been selected for N400, because N400 is centrally distributed and usually peaks at central electrodes. It is general convention that the same set of electrodes should be selected in the control conditions as in the experimental condition; 2) because maximal P300 is usually located around the central line, it was hypothesized that maximal P300 difference in the current study could be detected around central areas as well.

However, no significant effect of lateralization was obtained at C3 and C4: the peak-to-peak amplitude of P300 was not significantly different between C3 (central left) and C4 (central right) electrodes. There was no significant interaction between Hemisphere and Gender Shift, either. This suggests that the P300 difference in hemispheric distribution induced by Gender Shift might be a more peripherally distributed component. Indeed, in Jerger et al. (1995), more peripheral sites than C3 and C4 were selected, the lateralization index captured activity from these sites and the statistical inferences that Gender Shift induced right lateralization of P300 were based on this index. Therefore, these comparisons characterized differences between the peripheral and central sites combined, instead of raw amplitudes at electrodes around center line.

Given this, follow-up analyses were conducted in the current study, under the hypothesis that a hemispheric difference might be detected at peripheral electrodes. Accordingly, T7 (right temporal) and T8 (left temporal) were selected as sites for analysis. In this analysis, significant main effects were found for both Gender Shift and Hemisphere. Peak-to-peak amplitudes of P300 were larger at T8 (right temporal) than at T7 (left temporal), supporting the prediction that P300 would be distributed to the right. There was no significant interaction between Hemisphere and Gender Shift, which suggests that the P300 increase induced by deviant stimuli was proportional for both T7 and T8.

6.4.4 Comparison between Global Field Power and source analyses

The Global Field Power analysis produced a result pattern similar to the T7/T8 analysis: there were significant main effects for both Hemisphere and Gender, but no significant interaction. This indicates that overall, 1) P300 was lateralized to the right; 2) the Gender Shift in the deviant stimuli produced a proportional P300 increase on the left and the right side; 3) the statistical result obtained from analysis of T7 and T8 sites was not a coincidental event that could potentially reflect artifacts other than overall surface distribution. Instead, the difference between T7 and T8 was representative of the general topographical distribution change.

The source localization of P300 showed different patterns for filtered and unfiltered conditions. For filtered conditions, strong activation at P300 was seen at right inferior frontal gyrus (IFG), superior and middle temporal gyri, and right inferior parietal lobe. This is consistent with the Left Ear Advantage for nonlinguistic prosody patterns found in dichotic listening studies and with the localization areas reported in fMRI studies (Belin et al., 2000; Lattner et al., 2005; Moncrieff et al., 2004).

For the unfiltered conditions, on the other hand, the estimated source was located in the left hemisphere. This is likely due to the fact that, the unfiltered target stimuli were real words, and the early left lateralization for phonological processing of real words is largely automatic (Näätänen, 1990; Shaffer& LaBerge, 1979). However, a dynamic shift towards the right was still observed as the P300 gradually developed and peaked. Around 200ms, the source was lateralized largely to the left frontal lobe. Around 300ms, the activated sources began to shift towards the right. When the P300 component peaked, the most activated areas were located at interhemispheric areas, i.e. bilateral middle frontal gyri and bilateral superior parietal lobes (Please see *Appendix H* for illustration of this dynamic change). This pattern may correspond to a dynamic change in perception: the perception of unfiltered oddball word stimuli was lateralized and processed in the left hemisphere early on for phonological processing (Näätänen, 1990), and it was only later that Gender Shift was detected at around 300ms post stimulus onset. At this point, the processing of nonlinguistic prosody differences began to shift to the right side. This dynamic right shift should be the subject of further investigation.

7.0 CONCLUSION

In reviewing the past empirical studies on lexical stress processing, a task-dependent pattern was evident: studies involving tasks directly activating phonological representations reported significant effects of lexical stress, while studies that have tasks involving "activation of lexical concepts" did not find significant results of lexical stress in English, though there was influence found in other languages (such as Mandarin Chinese).

This suggested that suprasegmental information does influence lexical identification in English, but differently from segmental information. Cutler (1986) argued that lexical stress cannot access lexical representations at the initial activation stage and only influences later-stage lexical selection, while Dickey (1995) argued that whether suprasegmental information can access lexical representations at the activation stage depends on whether it is limited by syllable boundary. Based on data from Mandarin Chinese, Packard (1986) proposed that the processing of lexical level prosody is not fundamentally different from segmental information.

Incorporating features from different theoretical perspectives and empirical results, a Cascading Inhibition model was proposed for this study, implementing both hierarchical structure and parallel information flow. The hierarchical structure has four levels: prosody level, skeletal level, and phonetic level, and finally, the level of lexical identification. This structure specifies the direction of influence, which is from top to bottom. The lowest level is the lexical identification level, which is the ultimate outcome of the whole process. The parallel information processing is realized by simultaneous processing of multiple levels. That is to say, each level can initiate processing before any higher level completes processing for the whole word.

Further, the whole process was proposed to be statistical in real-life language comprehension: identification of any given word not only depends on the degree to which available information is consistent with this word, but also depends on the extent to which it is not consistent with other words. That is to say, if any information in the incoming signal is not consistent with stored phonology at any level above lexical identification (i.e. prosodic, skeletal or phonetic level) for a given competitor in the lexical cohort, that competitor will be inhibited.

The CI model is able to account for and reconcile most of the past empirical results. Because phonetic processing and lexical concept activation are both under the influence of lexical stress parsing in the CI model, and because it is known that both processes are lateralized to the left hemisphere (Alho et al.,1998; Barry, 1981; Frost et al., 1999; Jordan et al., 2000; Zahnet al., 2000; Zatorre et al., 1996), two hypotheses were generated: *Hypothesis A*: lexical stress parsing can influence lexical identification even without segmental information; and *Hypothesis B:* lexical stress parsing is lateralized to the left hemisphere.

In the current study, both hypotheses were supported. When a (mismatched) Verb Lexical Stress Pattern occurred in the final position of a Noun-predicting sentence, a significantly larger N400 was induced at central electrodes than when the sentenced ended with a (matched) Noun Lexical Stress Pattern. Given that N400 is taken to index the process of accessing long-term lexical representations (Kutas & Federmeier, 2011; Lau et al., 2008), this result strongly supports *Hypothesis A*. To test *Hypothesis B*, the distributional pattern of N400 was investigated. In comparing peak-to-peak amplitudes from selected electrodes and Global Field Power from left and right sides of the brain, a left lateralization pattern was found for filtered conditions, but not for unfiltered conditions. Source estimation confirmed the left lateralized pattern of neurogenerators in the filtered conditions and the bilateral distributed pattern for the unfiltered conditions. These results partially supported *Hypothesis B*, with one condition: if there is no segmental information available. Moreover, the absence of interaction between Hemisphere and Lexical Stress Pattern suggested that the processing of segmental information and suprasegmental information may not be fundamentally different and is very likely to be in parallel.

To integrate these results, a revision of the original Cascading Inhibition model is proposed. The revision adds a direct influence from the prosody level to the lexical identification level. This influence is proposed to be weaker than the influence from the phonetic level, because the overall computation in CI model is statistical in nature and lexical stress information carries less statistical discriminability than phonetic level information for the activated cohort

For the P300 induced by Gender Shift in the control conditions, a right lateralization was produced. This supports what has been reported in much of the literature about nonlinguistic prosody (e.g., Belin et al., 2000;Blonder, Bowers, & Heilman, 1991; Heilman et al., 1984; Ivry & Robertson, 1998; Jerger et al., 1995; Kotz et al., 2003; Lattner & Friederici, 2003; Lattner et al., 2005), suggesting a separate mechanism for processing nonlinguistic prosody from lexical-level prosody.

Further investigation is needed to address some unresolved issues in the current study, for example, controlling the task demand increase in the filtered condition, as well as improving the localization of neurogenerators using a neuroimaging method with high spatial resolution. In addition, there are other predictions generated from the CI model that could advance results in this area of investigation. Two of them are of particular clinical relevance. One is that lexical stress may serve as an independent contributing factor in disordered language processing and the other is that it may be affected in left hemisphere damaged patients. Testing these predictions not only could provide a better understanding of neural mechanisms for processing lexical level prosody, but also more insight into how lexical prosody processing might be disrupted in the disordered brain.

APPENDIX A

VERBAL INTERVIEW SCRIPT AND WRITTEN QUESTIONNAIRE FOR SCREENING

A.1 VERBAL SCREENING QUESTION SCRIPT (SPOKEN QUESTIONS ARE PUT IN QUOTATION MARKS)

"Would you give us verbal permission to ask a few screening questions"? Y / N

If yes, proceed; If no, stop here and express gratitude for making contact.

Personal information:

(1) "Could you please tell us your age"?

____

(2) "How many years of education do you have? "

____

(3) "What is your native language? " (What language(s) did you learn when you were learning to speak as a child)?

____

(4) "Do you have more than minimal understanding of other languages than English?" If yes, "could you please describe your proficiency level?"

____

Neurological Status:

(1) "Have you had any of the following conditions?"

"Stroke? Hemorrhage? Brain tumor? Seizures? Schizophrenia? A head injury for which you were hospitalized? Any other neurological diseases? "

If no, proceed. If yes, ask for description.

(2) "Have you had a brain scan, such as a CT or MRI of the brain?"

If yes: "What was the result?"

(3) "Have you ever had concussion or general anesthesia? Other neurological conditions?" If yes, "Please indicate the year it happened."

____

Hearing and auditory processing:

(1) "Have you ever used hearing aids?"

____

(2) "Have you ever been diagnosed with any kind of auditory processing disorders, including attention deficit hyperactivity disorder (ADHD)?"

____

(3) "Have you ever experienced any hearing difficulties?"

If yes, "Could you please describe what kind of hearing difficulty you have? In what situations or conditions?" ____

A.2 WRITTEN QUESTIONNAIRE

Name: _______________________

Gender (circle): F M

Age: ________________________

Do you have any chronic illnesses? If yes, please indicate type.

____

Are you on regular medication? If yes, please indicate type.

____

Are you a smoker? If yes, how much do you smoke per day?

____

Do you exercise regularly? If yes, how often do you exercise?

____

Have you ever experienced any difficulties understanding language, or learning? If so, please describe.

____

APPENDIX B

SCREENING PROCEDURES

B.1 AUDIOMETRY

Air-conduction pure-tone thresholds will be obtained for each ear at 500, 1000, 2000, and 4000Hz (using a two-channel audiometer, Grason Stadler, Model 16 or Maico, Model 52). Three-frequency pure-tone average (PTA) will also be calculated (at 500Hz, 1000Hz and 2000Hz). The hearing inclusion criteria are: (1) pure tone thresholds <25 dB HL at 500, 1000, 2000, and 4000 Hz (American National Standards Institute, 2004) and (2) PTA difference between ears no greater than 10 dB. This is to ensure that participants will receive the stimulus signal at relatively equal intensity levels for both ears, providing better control for Hypothesis B.

B.2 RANDOMIZED DICHOTIC DIGIT TEST

The Randomized Dichotic Digit Test (RDDT) will be administered to all potential participants to minimize the possibility of central auditory processing problems (Strouse &Wilson, 1999). In the RDDT, participants are presented with digit pairs, one to each ear, and their task is to repeat each pair. There is no requirement to identify which ear the digits come from.

The digit pair list for this study is recorded on track 7 of the VA CD Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 2.0 (Department of Veterans Affairs, 1998). It contains 18 randomized presentations for one-, two-, and three-pair digits for a total of 54 presentations, spoken by a male. All digits were aligned at onset for the dichotic presentation. The inter-trial interval varies from 4 sec for one-digit pairs, to 5 sec for two-digit pairs and 6 sec for three-digit pairs, allowing more time for participants to repeat a greater number of digits.

The RDDT will be administered at 50dB SL related to each participant's PTA in each ear, rounded to the nearest 5dB HL step. The dichotic material will be played through a two-channel audiometer (Grason Stadler, Model 16 or Maico, Model 52) and presented to each participant through TDH-49/50 earphones. The testing will be conducted in a quiet room. Participants will be excluded if their performance falls out of the 99.7% confidence interval (±3SD) of theperformance average of his/her corresponding age group for two out of three digit tests at either ear (Moncrieff & Wilson, 2009; Strouse &Wilson, 1999).

Please see the *Table B-1* for the digit table.

Table B-1. The randomized dichotic digit test

Randomized Dichotic Digits Test - Free Recall Mode

Track 6 Calibration Tone
Track 7 Test

#	One Pair		Two Pairs		Three Pairs		Response
	L R	L R	L R	L R	L R	L R	
1					6,2,4	8,5,9	
2			2,10	3,9			
3	5	6					
4	10	6					
5					5,9,6	1,3,10	
6	6	4					
7			4,8	1,9			
8			4,8	5,6			
9					8,3,6	10,4,9	
10			10,3	9,8			
11					2,1,10	6,3,9	
12	5	2					
13					4,1,3	9,6,10	
14					1,6,5	8,3,4	
15					10,6,9	8,5,4	
16					9,10,8	4,5,3	
17					3,1,2	10,4,8	
18					4,5,9	3,2,1	
19	5	10					
20					3,4,10	9,8,5	
21	5	4					
22			2,8	9,10			
23			5,9	1,3			
24			3,9	8,4			
25	1	5					
26			4,1	9,6			
27					6,8,4	2,5,3	
	L R	L R	L R	L R	L R	L R	

#	One Pair		Two Pairs		Three Pairs		Response
	L R	L R	L R	L R	L R	L R	
28			10,4	6,9			
29			10,6	3,4			
30					6,4,5	1,10,8	
31					10,4,2	6,9,5	
32	1	2					
33	8	5					
34					6,10,4	3,1,2	
35					4,1,3	2,8,9	
36			1,2	9,4			
37			2,10	1,8			
38	10	9					
39	10	2					
40					10,6,8	4,1,2	
41	8	9					
42			10,6	4,1			
43	4	10					
44	3	10					
45					2,5,10	8,3,4	
46	1	3					
47	6	8					
48			8,4	9,6			
49	2	8					
50			1,9	3,2			
51			8,2	5,10			
52			9,10	4,5			
53	10	1					
54			6,3	4,2			
	L R	L R	L R	L R	L R	L R	

TOTALS One Pair Two Pairs Three Pairs

Right Ear ____ ____ ____ CODE ____ TEST # ____

Left Ear ____ ____ ____

Ear Adv ____ ____ ____ DOB ____ DATE ____

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B.3 HANDEDNESS TEST

A handedness scale will be administered, consisting of the six most discriminating items from the Chapman & Chapman (1987) questionnaire. To be included in the study, potential participants will have to answer all six as “right-handed.” The handedness of first-degree relatives will also be established, by asking potential subjects to report on the questionnaire items for parents, siblings, and/or children.Participants who have left-handed first-degree relatives will also be excluded from the study. Knowing the handedness of subjects and their first-degree relatives is necessary for a better account of the laterality data (Knecht, Dräger, Deppe, Bobe, Lohmann, Flöel, Ringelstein& Henningsen, 2000)

Table B-2. Chapman & Chapman Handedness Questionnaire* (*Note**: only the 6 most discriminating questions of the Chapman &Chapman handedness test will be included).

Subject ID:_________________________		**Date:**______________________________	
Please indicate below which hand you ordinarily use for each activity:			
With which hand do you …	**1.Right**	**2. Left**	**3. Either**
1. Write?			
2. Throw a snowball to hit a tree?			
3. Use a hammer?			
4. Use a toothbrush?			
5. Use a tennis racket?			
6. Hold a match when striking it?			

APPENDIX C

THE CONSTRUCTION OF STIMULUS SENTENCES AND THE CLOZE TASK

C.1 THE COMPLETE LIST OF FINAL STIMULUS AND PRACTICE SENTENCES WITH CLOZE

C.1.1 Experimental trials with cloze

For the following noun-predicting statements, the intended target word is indicated in**bold**. Obtained cloze values are in parentheses, with the three numbers representing: cloze probability for exact word match/cloze for trochaic noun stress pattern match/cloze for iambic noun stress pattern match. For example, a number sequence 0.67/1/0 means that 67% of the answers in the cloze task were the intended word, 100% of the answers have trochaic stress pattern, and 0% of the answers have iambic stress pattern.

(1) You don't know where he lives, so you need to look up his exact **address**. (1/1 /0)
(2) The type of place where the hippies lived in the 60s was called a**commune**. (0.5/0.8/0)
(3) You heard that his fracture wasn't simple; instead, it was **compound**. (0.67/1/0)
(4) You want to check your hair (make-up) so you look in your purse for your **compact**. (0.22/1/0)
(5) You were told that you could not leave the area; you have to stay within its **confines**.(0/ 0.9/0)
(6) A binding legal document is called a **contract**.(1/1/0)
(7) You read an article about a law-breaking soldier who got a dishonorable **discharge.**(0.89/0.89/0.11)
(8) To finish his routine on the parallel bars, the gymnast stuck a perfect **dismount.**(0/0.8/0)

(9) You saw the president’s limousine drive past, with a police **escort.**(0.89/0.89/0)
(10)You help your firm do business in other countries, but getting the products ready for **export.**(0.33/1/0)
(11)You made a delicious cake,that was flavored with vanilla **extract.**(0.67/0.89/0)
(12)You and your friends didn't feel the minor earthquake; it didn't make much of an **impact**. (1/1/0)
(13)You enjoyed the aroma when your friend from India burned some **incense**. (0.89/1/0)
(14)He told her she looked old and dowdy and she thought his remark was quite an **insult**. (0.9/0.9/0.1)
(15)As she moved toward her goal, she made slow but steady **progress**. (0.9/0.9/0)
(16)To hold a protest in front of the city hall, the group had to obtain a **permit**. (1/1/0)
(17)The section of the supermarket that has fruits and vegetables is called **produce**.(1/ 1/0)
(18)The student put a lot of work into his science fair **project.** (1/1/0)
(19)You were against the war, so you decided to join the crowd at a **protest**. (0.56/1/0)
(20)You heard that, because of a malfunction, the automaker had issued a **recall**.(1/1/0)
(21)The schoolchildren took a break from class and went outside for **recess**. (1/ 1/0)
(22)You love your parent's old music albums, especially the first Beatle's **record.**(0.56/1/0)
(23)You finally recovered from a long illness but then you did too much too soon, and had a **relapse**. (1/1/0)
(24)To find new medicines and other treatments, medical scientists have to do **research**.(0.9/ 1/0)
(25)You think you will like the speech, because it is on an interesting subject. (0.33/0.89/0)
(26)You read that the police arrested someone for the robbery, so they already have a **suspect.**(1/1/0)
(27)The property lines need to be exact, so we hired a professional to go to the land to do a **survey.**(0.9/0.9/0.1)
(28)When a weak sports team beats a stronger opponent, the win is considered an **upset.** (0.8/ 0.8/0)

C.1.2 Practice trials

(1) The girl liked her smile, and considered it her best **attribute.**
(2) You need to weigh the two options by comparison and **contrast.**
(3) She wanted to go to the 7:00 movie, but she had a **conflict.**
(4) You told your son that in the Civil War, a Confederate soldier was also called a **rebel.**
(5) Too much tax was withheld from your paycheck, so you filed a form to get your **refund.**

C.1.3 Filler sentences

(1) You received a wedding invitation and immediately sent back your reply.
(2) Your little girl will only eat pasta, and her favorite is spaghetti.
(3) You discovered that your house had been robbed, so you called the police.

(4) You heard the forecast for rain so you made sure to carry an umbrella.
(5) You want a garage that is not separate from your house; you want one that is attached.
(6) You went to a steakhouse and ordered a t-bone steak and a baked potato.
(7) You were offered admission to your top choice for college, and you were delighted to accept.
(8) You and your best friend feel the same way about most things, so you almost always agree.
(9) You made a good dinner but the best part was the cake that you served for dessert.
(10)Your children were making too much noise playing in the house, so you sent them outside.
(11)You need an operation but cannot afford it unless it is covered by your insurance.
(12)You want to take a history course but you're worried about the amount of work the professor would require.
(13)You know that it is a very difficult task and that doing it will be next to impossible.
(14)You had some tests at the doctor's office, and you are waiting for the results.
(15)You smelled some fish that had gone bad, and it made you cringe in disgust.
(16)Your teacher assigned you to read the book and then write a report.
(17)You bought a fish tank and several exotic fish so you could set up a home aquarium.
(18)You were asked to give feedback so you decided to make a suggestion.
(19)You heard some music that almost put you in a trance, it was so hypnotic.
(20)You bought some new software so now you have to install it on your computer.
(21)You can't finish the assignment today, but you're sure you can by tomorrow.

C.1.4 Verb eliciting sentences for experimental stimuli

(1) The governor used a microphone for his talk, because he had a large crowd to address.
(2) When you go somewhere special to experience a deep connection with nature, you go there to commune.
(3) You invest as much as you can in your savings so the interest can compound.
(4) You have too much garbage so you start to crush and compact (it).
(5) Your sick child keeps getting out of bed, and is very hard to confine. Your new puppy won't stay in his kennel, and is very hard to confine.
(6) You were told that the colors were different, but you could not see the contrast.
(7) The muscles expand and then contract.
(8) You tried to fire your gun but it failed to discharge. You finished your hospital stay and you're ready to discharge.
(9) When you get off your horse, you dismount.
(10)Your son wanted to bring a date to a wedding, and he was deciding who to escort.
(11)Your business sends products overseas, and you check to make sure the products are ready to export.
(12)Your dentist tells you that you have a bad tooth, and it's one that he's going to extract.
(13)Your company changed its policies on vacation days, and there are many people those changes will impact.

(14)The politician saw that the audience was already very angry, and he worried how many people his speech would further incense.

(15)The comedian always said rude things in his act, because his style of comedy was to insult.

(16)Your doctor will tell you when you can get your cast removed once he sees how quickly things progress.

(17)Your professor is pretty relaxed in class, but a ringing cellphone is one thing she will not permit. Your mother lets you do a lot of things, but staying out all night is one thing she will not permit.

(18)You drove by an orchard, and you wondered how much fruit the trees produce.

(19)When you have to plan a budget for a 10-year period, the later years are especially hard to project.

(20)You want to take your son to get a haircut, but you know he will protest.

(21)You think the library is open on Sundays, but you can't recall.

(22)It's a holiday, so the trial judge decided to recess. The trial had been going on all morning, so the judged decided to recess.

(23)You don't want to miss your favorite television program, so you set your DVR to record.

(24)If you don't continue your treatment, you could relapse.

(25)The big concert got rained out, so there was a lot of money to refund.

(26)Before you can decide which colleges to apply for, you need to research.

(27)In the murder mystery, there are many characters to suspect. In the kidnapping, the husband is the one that the police suspect.

(28)To complete the opinion poll, there are many people you will need to survey.

(29)Your very sensitive friend can take things too personally, and be too easy to upset.

C.2 DEMOGRAPHIC INFORMATION FOR PARTICIPANTS IN THE CLOZE TASK

The sentences in *C.1* were divided into two lists and presented to two groups of participants. The demographic information for these two groups is provided in *Table C-1* and *Table C-2*, respectively.

There was no significant difference between these two groups in age (t=0.960, df=17, p=0.351) or in years of education (t=-1.448, df=16, p=0.167). The gender ratios of these two groups are 6F:3M and 5F:5M, respectively.

Table C-1. The demographic information of first cloze task

	Age	Years of education	Gender	Ethnicity	Handedness	languages
1	21	16	F	White	R	English
2	22	16	M	White	R	English
3	27	17	F	White	R	English
4	35	13	M	White	R	English
5	33	19	F	White	Both	English
6	29	blank	F	White	R	English
7	36	8	M	Mexican/Irish	R	English
8	21	16	F	Hispanic	R	English
9	25	18	F	Jewish/Romanian/Ukranian	Both	English

Table C-2. The demographic information for the second cloze task

	Age	Years of education	Gender	Ethnicity	Handedness	Languages
1	29	17	M	White	R	English
2	28	19.5	F	White	R	English
3	25	19	M	White	R	English
4	23	18	F	White	R	English
5	26	15	M	White	R	English
6	25	18	F	White	R	English
7	30	15	F	Hispanic	R	Spanish & English
8	23	16	M	White	R	English
9	24	16	M	White	L	English
10	24	18	F	White	R	English

C.3 THE INSTRUCTION FOR THE CLOZE TASK AND AN EXAMPLE

The participants received a paper and pencil task in which they were first asked to provide their personal information. Then they were asked to fill in the target word.

Filler sentences were also included in this task so as to disguise possible target pattern.

A sample from the task is listed below:

Please provide your personal information below.

Age: ______________ Gender: Female Male

Handedness: Mostly right Mostly left

Education (in years): ______________________________

In the following table, some words have been erased and replaced with blanks. In each blank, please fill in the word that you think should go there.

1	You read that the police arrested someone for robbing the bank, so they already have a ______.
2	You paid too much in taxes, so you filed your tax return and waited for your ______.
3	You want to check your hair (make-up) so you look in your purse for your______.
4	You are renting an apartment, and you need to sign a legal ______.

APPENDIX D

ESTIMATING THE CUTOFF FREQUENCY FOR FILTERED STIMULI

Twenty target words (10 nouns and 10 verbs) will be selected to estimate the cutoff frequency for filtering. This set of words will represent all phonemes in the experimental stimuli.

These words will be filtered at cutoff frequencies from 700Hz to 800Hz in 10Hz increment (i.e. 700Hz, 710Hz, 720Hz….to 900Hz), because preliminary data indicates that native English speakers can distinguish segmental information above 800Hz and cannot recognize words below 700Hz.

Five young native English speakers will listen to all the filtered words. The threshold will be defined as the first frequency at which each individual participant can recognize the word. The threshold for each word from all the participants will be averaged. Then the lowest threshold of all words (i.e. the minimum value in Hz) will be selected as the final filtering cutoff frequency.

APPENDIX E

MATHEMATICAL PROCEDURES AND DESCRIPTIONS FOR EEG

E.1 MATHEMATICAL DESCRIPTION OF GLOBAL FIELD POWER (GFP)

Global Field Power (GFP) is denoted as G. The common average of all the electrodes is denoted as A. For all the electrodes (i=1, 2, 3,…..N)

$$G = \sqrt{\frac{(Ei - A)^2}{N}}$$

(i=1, 2, 3, 4, …… N)

The common average A is defined as

$$A = \frac{\sum Ei}{N}$$

(i=1, 2, 3, 4, …… N)

For example, if the amplitude readings are those numbers listed in the matrix below, in a given scalp distribution:

3	8	3	9
4	5	6	5
7	6	4	2

4	5	2	7

Then the common average A is the arithmetic mean of those numbers

$$A = \frac{3+8+3+9+4+7\ldots.+7}{16} = \frac{80}{16} = 5$$

Then the amplitude differences between individual electrodes and the common average are listed in the matrix below:

-2	+3	-2	+4
-1	0	+1	0
+2	+1	-1	-3
-1	0	-3	+2

Then the GFP is computed as

$$G = \sqrt{\frac{(4+9+4+16\ldots.+0+9+4)}{16}} = \sqrt{\frac{64}{16}} = 2$$

E.2 THEORIES OF FORWARD AND BACKWARD SOLUTIONS OF SOURCE ESTIMATION

E.2.1 Forward model matrix

First of all, an initial dipole is modeled by two vectors, its location, r and Moment M. “r” is a Cartesian coordinate (x,y,z) and M is (m, Θ,Φ), where m describes dipole magnitude, and Θ and

Φ (which are angles between x and y axis and x and z axis, respectively), describe dipole orientation.

Then a weighting matrix W is given by

$$W(e,r) = \frac{e + \frac{2(e-r)}{d.d} + \frac{e(e.r)-r}{d+1-e.r}}{d},\ where\ d = |r-e|$$

Where e represents a matrix specified surface electrode location

Thus, the surface voltage at each electrode from the initial dipole source is given by

$$Vmodel\ (e) = W(e,r).M$$

E.2.2 The inverse solution

A nonlinear model-fitting algorithm iteratively modifies the input parameters in such a way as to minimize the sum of squares between the real topographic voltage matrix and the above model matrix.

E.3 POWER ANALYSIS FOR EEG DATA

E.3.1 For Hypothesis A

Because there are six potential comparisons for the *t*-tests to address Hypothesis A (three selected electrodes for both N400 and P350), the corrected alpha level for planned (a priori) contrast would be 0.05/6= 0.0083.

G*power 3.1.3 for Windows 7 was used to estimate power (Baguley, 2004; Buchner, Erdfelder & Faul, 1996; Cunningham, & McCrum-Gardner, 2007). The comparisons were treated as a priori contrasts with one-tailed distributions.

The effect size estimated from the P350 mean and standard deviation of the Friedrich, Kotz, Friederici, & Alter (2004) study, as elicited by pitch-modulated conditions (which is the smallest effect size of that study) was 2.08. To be on the conservative side, we will use 0.8 (a medium effect size) in this sample estimation. The estimated sample size, for this effect size setting, is 33. The output parameters of the power analysis are listed in *Table E-1*

Table E-1. The power analysis output for matched t tests for Hypothesis A

t tests - Means: Difference between two dependent means (matched pairs)		
Analysis:	A priori: Compute required sample size	
Input:	Tail(s)	One
	Effect size dz	0.6
	α err prob	0.0083
	Power (1-β err prob)	0.8
Output:	Noncentrality parameter δ	3.4467376
	Critical t	2.5281224
	Df	32
	Total sample size	33
	Actual power	0.8146362

E.3.2 For Hypothesis B

Because there are four separate two-way ANOVAs to test Hypothesis B for both the main effects of and interactions between Lexical Stress Pattern (Noun vs Verb) and Hemisphere (Left vs Right), the corrected alpha level for planned (a priori) contrast would be 0.05/4= 0.0125. To be on the conservative side, the effect size was assumed to be 0.8, which is much smaller than the effect size estimated from Friedrich et al. (2004) study (effect size=1.44).

The power analysis was again conducted using G*power 3.1.3. The output is listed in *Table E-2*. The sample size was estimated to be 44 for this analysis.

Table E-2. The power analysis output for two-way ANOVA for Hypothesis B

F tests - ANOVA: Fixed effects, special, main effects and interactions		
Analysis:	A priori: Compute required sample size	
Input:	Effect size f	0.6
	α err prob	0.0125
	Power (1-β err prob)	0.8
	Number of groups	2
Output:	Noncentrality parameter λ	28.1600000
	Critical F	2.6769270
	Denominator df	42
	Total sample size	44
	Actual power	0.8109993

APPENDIX F

THE SOURCE ESTIMATION ALGORITHMS IN SLORETA

For a matrix Φ that contains electric potentials recording from Ne cephalic channels (Ne=64), that is linked to an arbitrary common reference channel C, the relationship between the topographic distribution and the underlying electric density is:

$$\Phi = \mathrm{KJ} + \mathrm{Cl}\ (1),$$

In which J is a matrix that denotes the underlying current density distribution, that contains 3*Nv rows. Nv is number of voxels, and in which voxel, three unknown dipole moments were specified, denoting three directions (x,y,z) in the space.

K is the "lead field" matrix that connects the EEG recordings with the underlying electric density distribution that has Ne rows and 3*Nv columns. This means that for each electrode on the scalp and each voxel in the brain, three filed parameters were specified, giving weight to each direction (x,y,z) in three-dimensional space.

To give out the harmonic inverse solution of J by minimum norm estimate (MNE), the Laplacian of the current density is zero.

$$\nabla^2 J(r) \equiv 0\ (2)$$

This MNE solution is standardized and the localization inference is based on the following function:

$$F = \|\emptyset - KJ - Cl\|^2 + \propto \|J\|^2 \ (3)$$

Where α>0 is the regularization parameter. The function is minimized every time with respect to J and C (underlying current density given the reference) for any set of K, Φ and α.

The explicit solution of this equation is that

$$\hat{J} = T\emptyset \ (4)$$

Where,

$$T = K^T H[HKK^T H + \propto H]^+ (5)$$

In which H is a Ne-by-Ne centering matrix, defined by

$$H = I - \frac{1l^T}{l^T 1} (6)$$

I denotes identity matrix (all the elements are 1) in (6), and the + sigh denotes Moore-Penrose pseudoinverse in (5)

From Bayesian point of view, the electric potential variance is due to

$$S_{\emptyset}^{noise} = \alpha H \ (7)$$

By assuming that the actual source and the noise is uncorrelated, the electrical potential variance is given by

$$S_{\emptyset} = KS_J K^T + S_{\emptyset}^{noise} = KK^T + \propto H \ (8)$$

Thus the estimated density is

$S_J = TS_{\emptyset} \ T^T$ (9)

With the noise variance, (9) is

$$S_{\hat{J}} = TS_{\emptyset}^{noise}T^{T} \quad (10)$$

Finally, the density power estimated by sLORETA is

$$\hat{J}_l^T \left\{ \left[S_{\hat{J}} \right]_{ll} \right\}^{-1} \hat{J}_l \quad (11)$$

APPENDIX G

SUPPLEMENTAL DATA TABLES

Table G-1. The inclusion/exclusion numbers and reasons for participant exclusions in experimental conditions

Electrodes	Total participant numbers before analysis	Inclusion	Exclusion	Reason for exclusion
Cz in filtered condition	34	33	1	noisy electrodes
Pz in filtered condition	34	33	1	noisy electrodes
C3/C4 in filtered condition	34	33	1	noisy electrodes
T7/T8 in filtered condition	34	26	8	noisy electrodes
Cz in unfiltered condition	34	32	2	one blink artifact; one noisy electrodes
Pz in unfiltered condition	34	32	2	one blink artifact; one noisy electrodes

Table G-2. (Continued)

C3/C4 in unfiltered condition	34	32	2	one blink artifact; one noisy electrodes
T7/T8 in unfiltered condition	34	24	10	one blink artifact; others noisy electrodes

Table G-2. The inclusion/exclusion numbers and reasons for participant exclusions in control conditions

Electrodes	Total participant numbers before analysis	Inclusion	Exclusion	Reason for exclusion
Cz in filtered condition	38	35	3	Too much blinking
C3/C4 in filtered condition	38	35	3	Too much blinking
T7/T8 in filtered condition	38	27	11	Three too much blinking; others noisy electrodes
Cz in unfiltered condition	38	36	2	Noisy electrodes
C3/C4 in unfiltered condition	38	35	3	Noisy electrodes
T7/T8 in unfiltered condition	38	30	8	Noisy electrodes

Table G-3. *p*-values for Shapiro-Wilk normality tests for experimental conditions. (FN: filtered noun stress pattern target; FV: filtered verb stress pattern target; UN: unfiltered noun target; UV: unfiltered verb target; Cz: midline central electrode; Pz, midline parietal electrode; C3: left central; C4: right central;T7: left temporal, T8:right temporal)

	P350 FN	N400 FN	P350 FV	N400 FV	P350 UN	N400 UN	P350 UV	N400 UV
Cz	0.200	0.176	0.964	0.200	0.270	0.085	0.726	0.210
Pz	0.331	0.342	0.740	0.118	0.420	0.693	0.115	0.613
C3	0.363	0.099	0.347	0.776	0.185	0.390	0.320	0.360
C4	0.121	0.272	0.178	0.102	0.280	0.112	0.150	0.122
T7	0.090	0.084	0.236	0.355	0.895	0.410	0.103	0.139
T8	0.190	0.301	0.215	0.271	0.198	0.606	0.330	0.169

Table G-4. *p*-values for Shapiro-Wilk normality tests for control conditions. (FS: filtered standard stimuli; FO: filtered oddball stimuli; US: unfiltered standard stimuli; UO: unfiltered oddball stimuli; Cz: midline central electrode; Pz, midline parietal electrode; C3: left central; C4: right central; T7: left temporal, T8: right temporal)

	P300 FS	P300 FO	P300 US	P300 UO
Cz	0.977	0.368	0.230	0.095
C3	0.145	0.860	0.238	0.117
C4	0.178	0.909	0.679	0.296
T7	0.223	0.440	0.533	0.071
T8	0.664	0.908	0.909	0.196

APPENDIX H

SUPPLEMENTAL RESULTS FROM SOURCE ESTIMATION

In Chapter 5, the time and volume sequences in the coronal view for both control conditions and experimental conditions are presented. Here the volume sequences in the other two views (sagittal and axial) for both conditions are first presented.

H.1 VOLUME SEQUENCES FOR P300 IN CONTROL CONDITIONS

H.1.1 P300 in filtered conditions

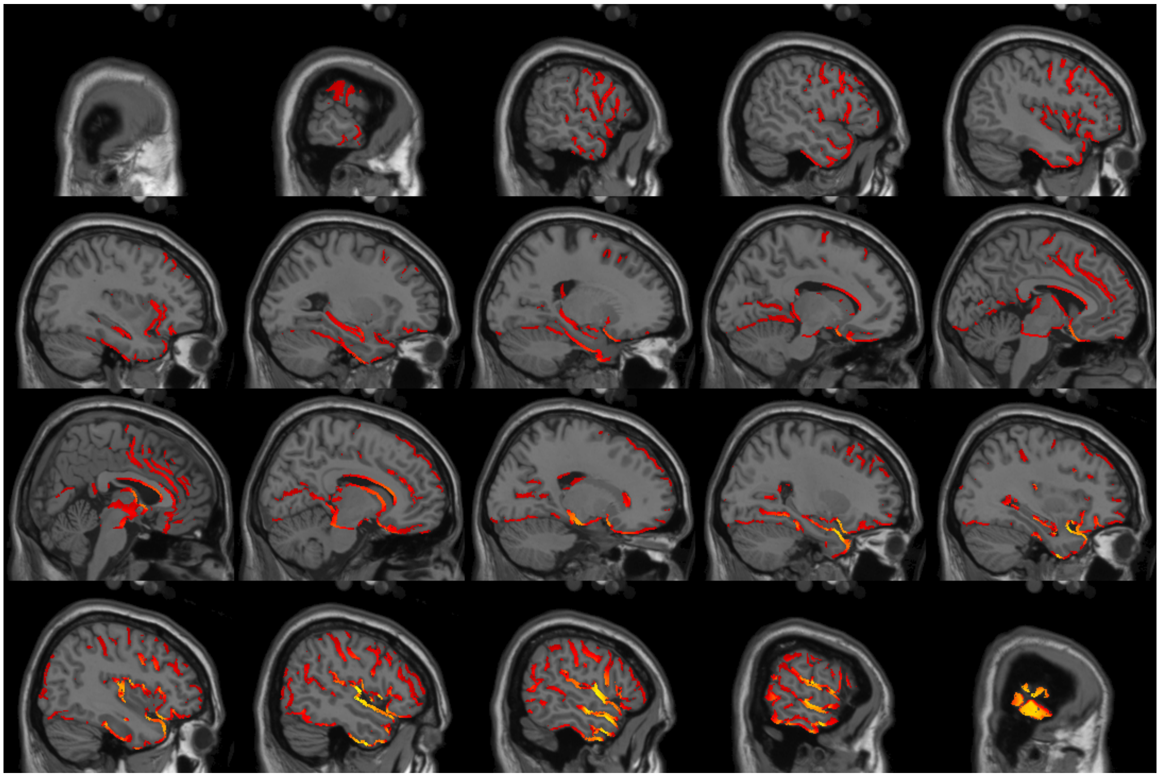

Figure H-1. The sagittal view of P300 in filtered conditions: 20 slices from left to right.

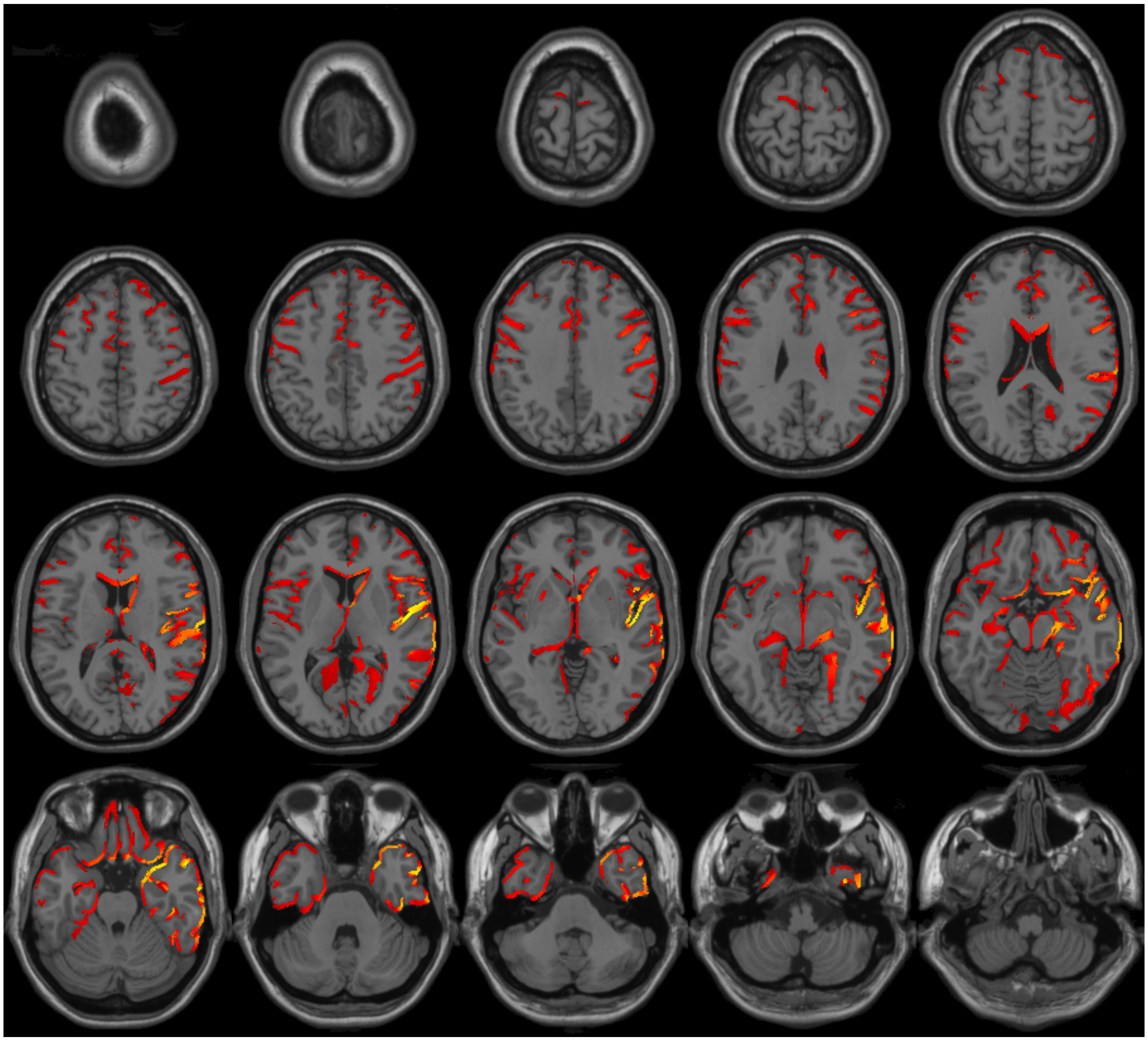

Figure H-2. The axial view of P300 in filtered conditions: 20 slices from top to bottom.

H.1.2 P300 in unfiltered conditions

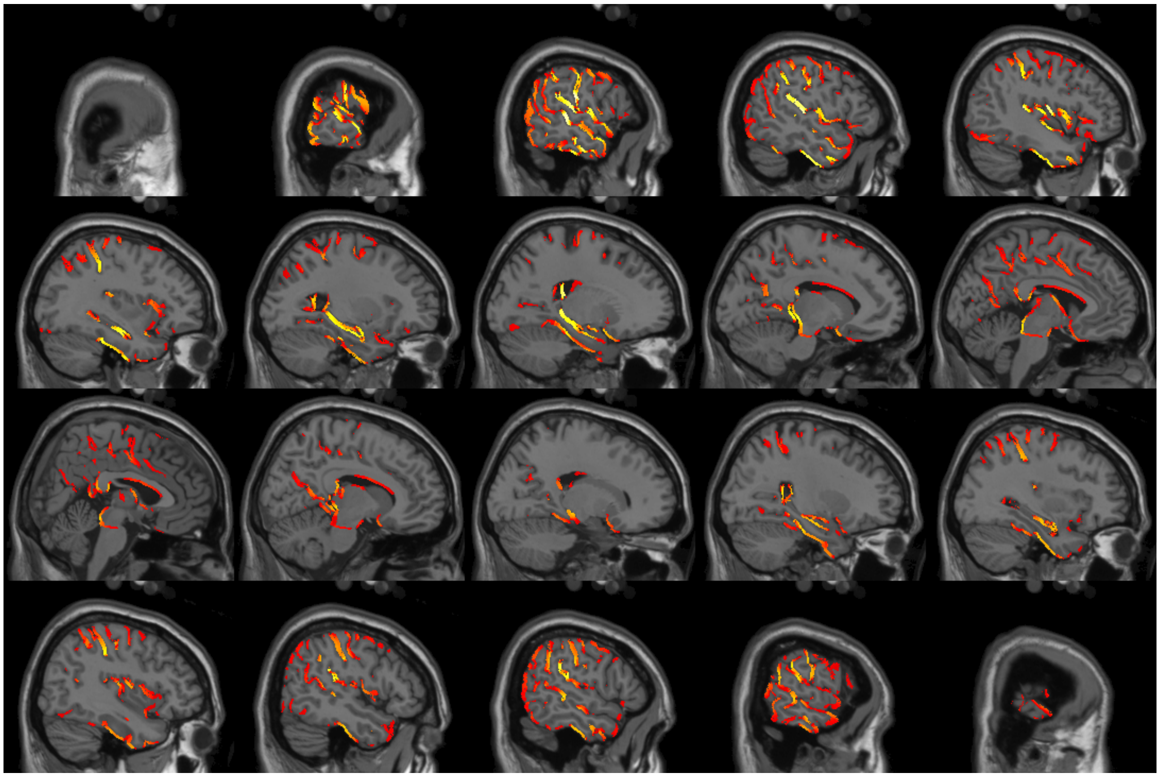

Figure H-3. The sagittal view of P300 in unfiltered conditions: 20 slices from left to right.

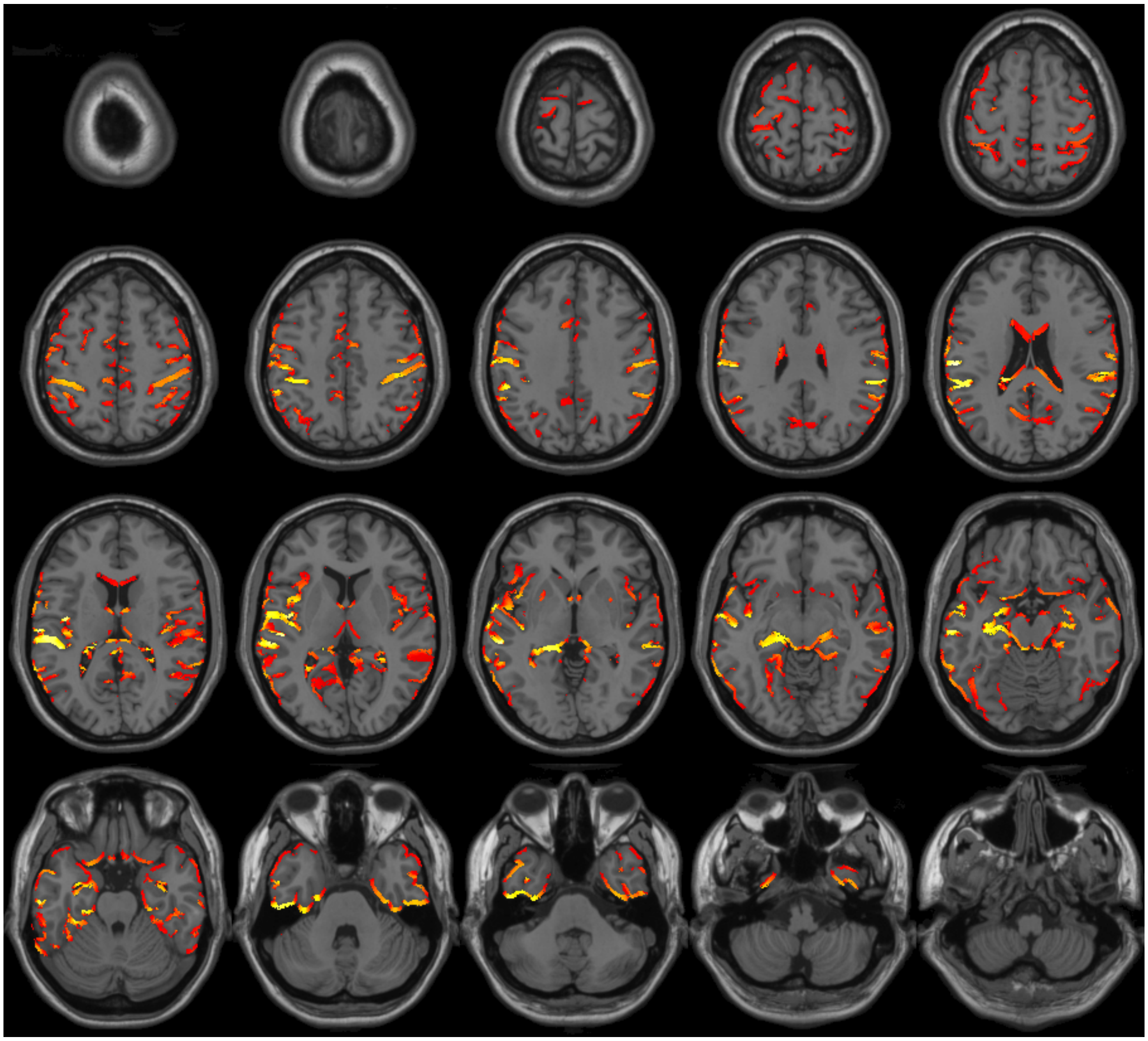

Figure H-4. The axial view of P300 in unfiltered conditions: 20 slices from top to bottom.

H.2 VOLUME SEQUENCES FOR N400 IN EXPERIMENTAL CONDITIONS

H.2.1 N400 in filtered conditions

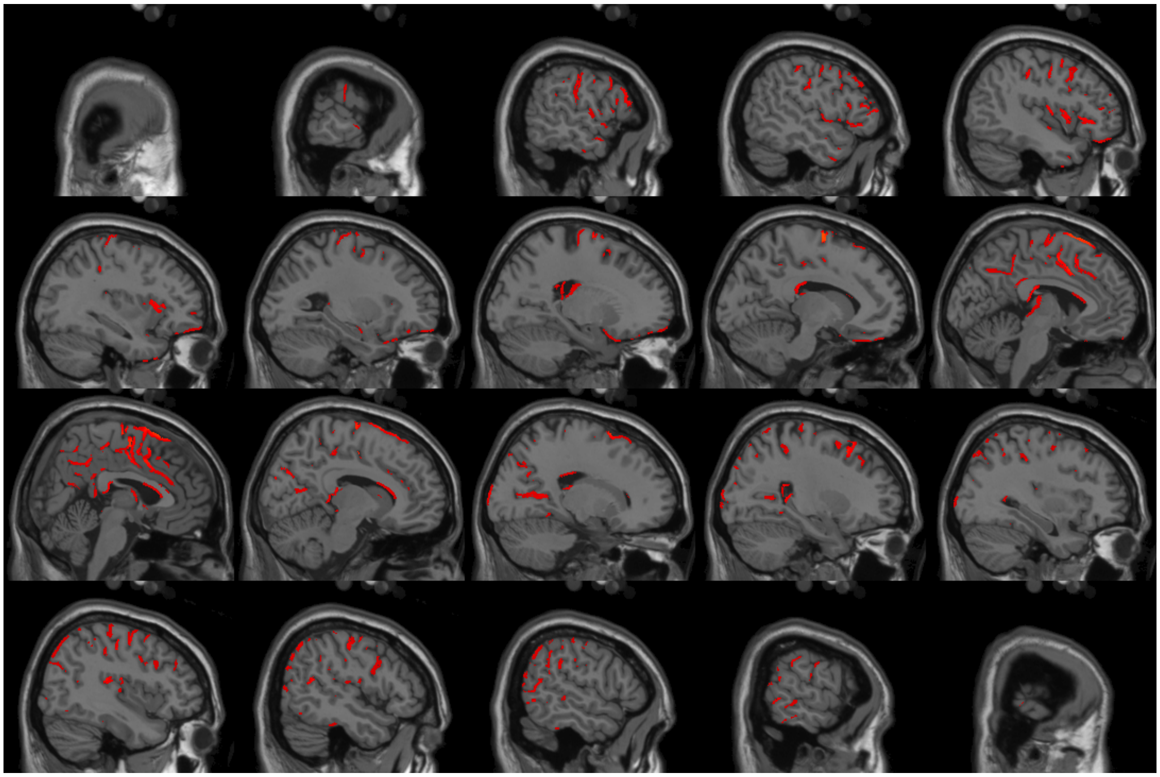

Figure H-5. The sagittal view of N400 in filtered conditions: 20 slices from left to right.

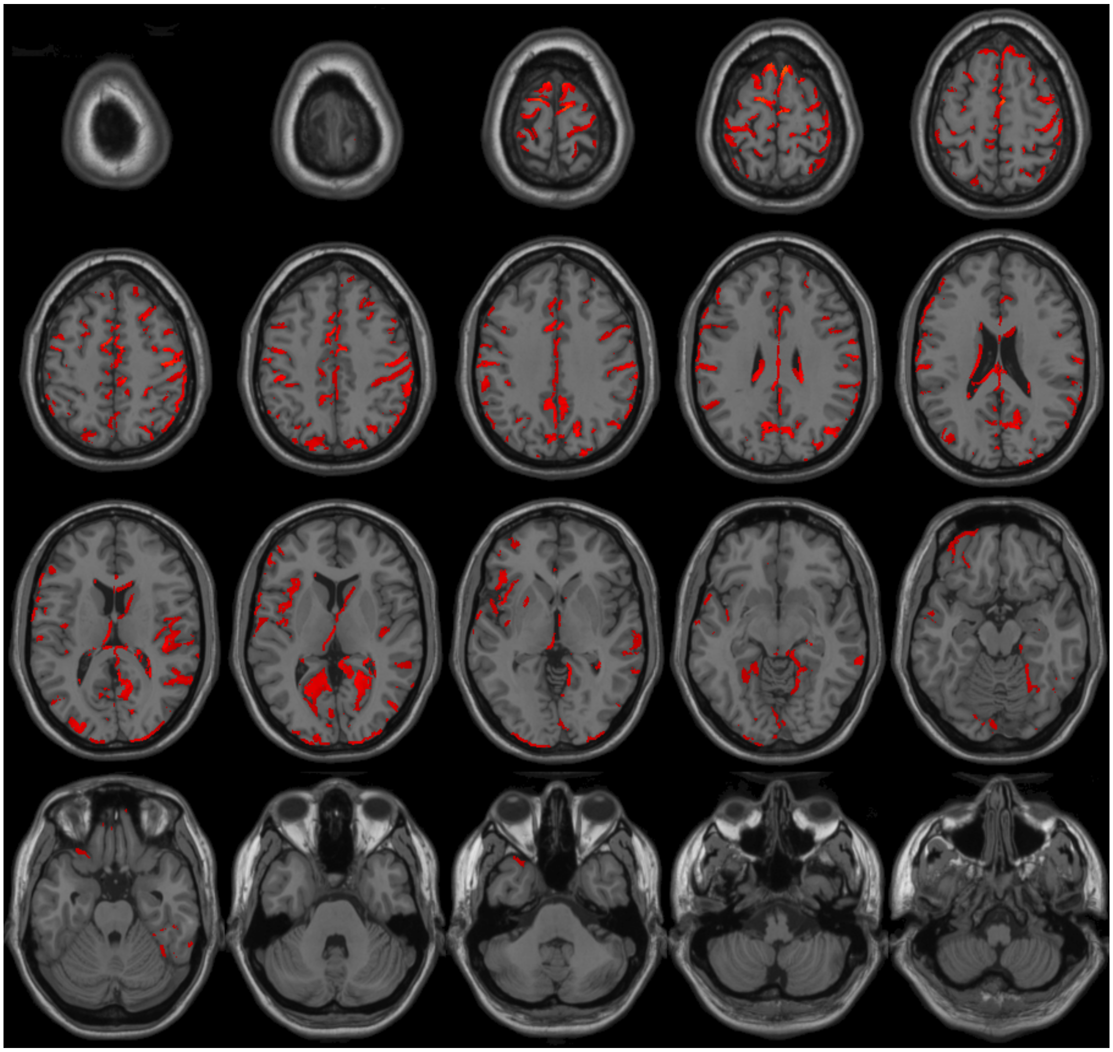

Figure H-6. The axial view of N400 in filtered conditions: 20 slices from top to bottom.

H.2.2 N400 in unfiltered conditions

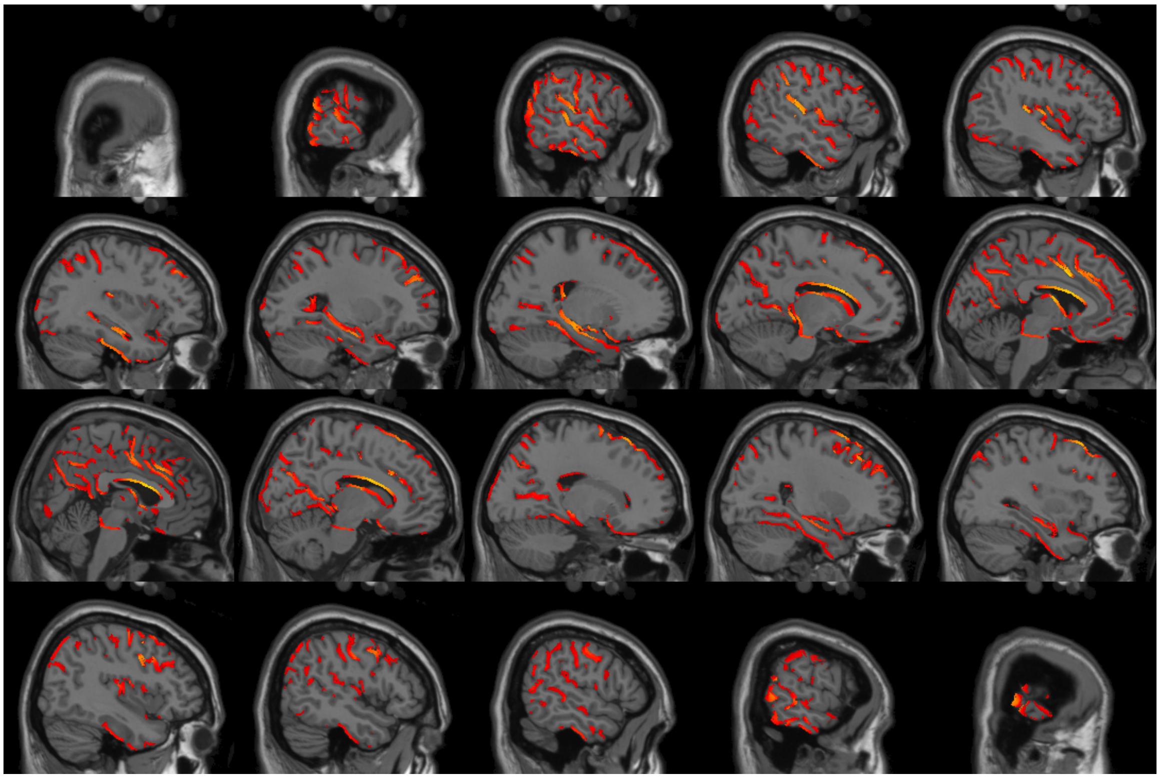

Figure H-7. The sagittal view of N400 in unfiltered conditions: 20 slices from left to right.

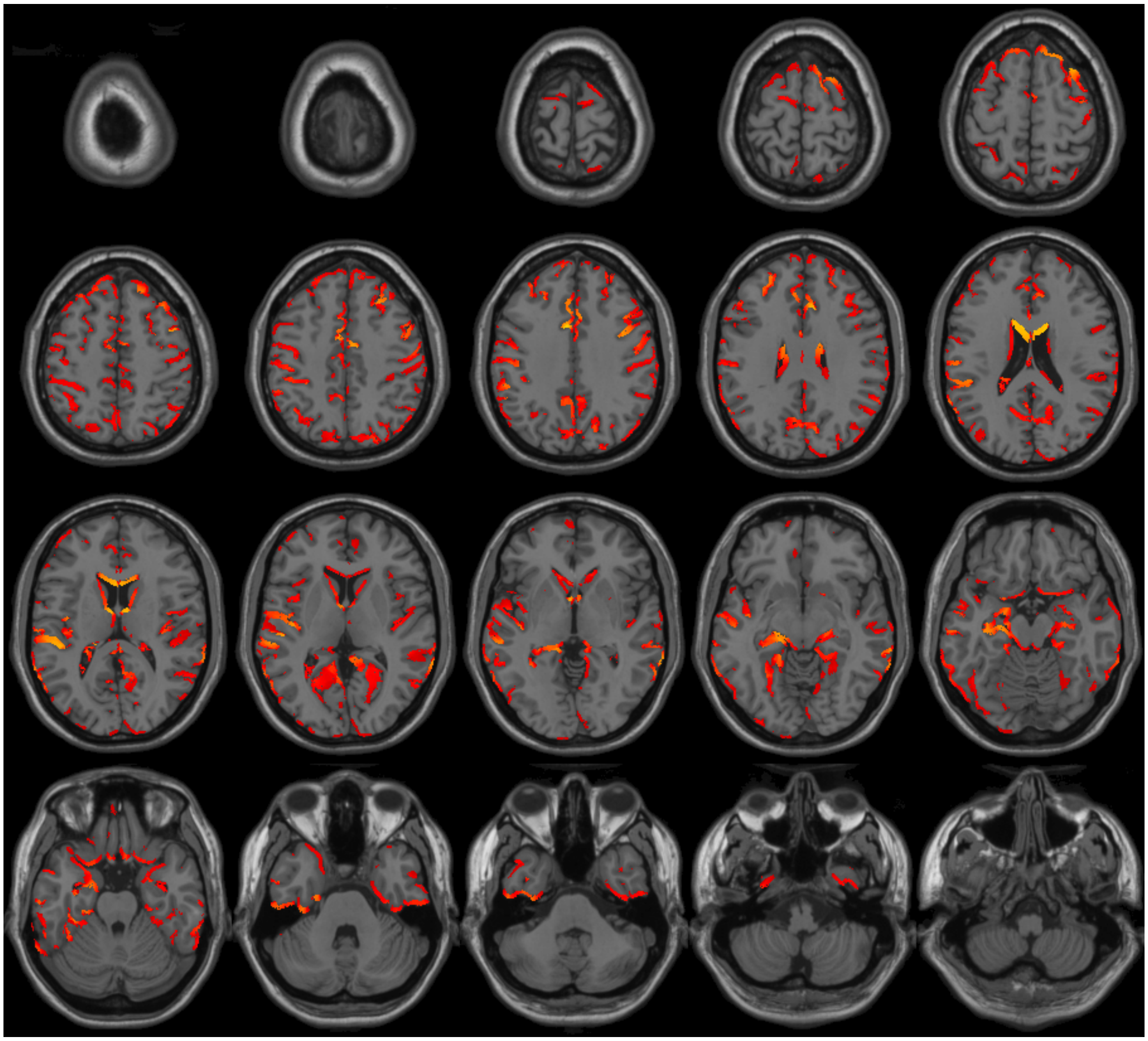

Figure H-8. The axial view of N400 in unfiltered conditions: 20 slices from top to bottom.

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