Electrophysiological Correlates of Phonological Processing During Spoken Word Recognition

by

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Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

at

Dalhousie University
Halifax, Nova Scotia
April 2004

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Dedication

No one comes from the earth like grass.
We come like trees. We all have roots.
- Maya Angelou

To my parents, Sandra and William Newman, whose faith and love keep me grounded
And
In loving memory of my grandparents,
Alexander and Marguerite MacNeil and Maxwell and June Newman

Dad, years ago you sent me a note after I had an especially bad day. In your note you told me what I didn't want to hear – that I was going to have more days like this (you weren't kidding!). But then you told me what I needed to hear – that no matter what, you and Mom were behind me every step of the way and that you loved me. Your faith, love and support have made more difference in my life than you could ever imagine.

Mom, I look to you in times of uncertainty and receive the strength, faith, and love that allow me to face whatever life throws my way. All the 'little' things you do, and all the 'little' things you say add volumes to my life, and for this I am truly blessed.

Table of Contents

List of Tables.....vii

List of Figures.....ix

Abstract x

List of Abbreviations and Symbols Used.....xi

Acknowledgements.....xii

Chapter 1 – General Introduction: Spoken Word Recognition from a Behavioral and Electrophysiological Perspective.....1

1.1. Models of Spoken Word Recognition.....1

1.2. Direction of Information Flow: Is it Sounds to Words or Words to Sounds?.....3

1.3. Overview of Electrophysiological Methodology 9

1.4. ERPs Reflect Distinct Levels of Psycholinguistic Processing 12

1.5. ERPs & Spoken Word Processing 15

1.6. Thesis Objectives 33

Chapter 2 – The Influence of Phonological Similarity on the PMN.....35

2.1. Summary.....35

2.2. Introduction 36

2.3. Materials & Methods 39

2.4. Results 44

2.5. Discussion 67

Chapter 3 – Lexical Influences on the PMN 72

3.1. Summary 72

3.2. Introduction 73

3.3. Materials & Methods 75

3.4. Results 80

3.5. Discussion 113

Chapter 4 – Initial versus Final Consonant Mismatch Effects on the PMN 113

4.1. Summary 117
4.2. Introduction 118
4.3. Materials & Methods 121
4.4. Results 125
4.5. Discussion 151

Chapter 5 – General Discussion: Functional Interpretation of the PMN.....154

5.1. Incorporation of the PMN into Models of Spoken Word Recognition 154
5.2. The PMN and its Relationship to Other ERP Components 159
5.3. Potential Clinical Applications of the PMN 155
5.4. Future Directions.....164
5.5. Conclusions.....167

References 168
Appendix A.....183
Appendix B.....186
Appendix C.....191

List of Tables

Table 1.....51

Table 2.....52

Table 3.....54

Table 4.....58

Table 5.....62

Table 6.....66

Table 7.....87

Table 8.....90

Table 9.....93

Table 10.....94

Table 11.....95

Table 12.....102

Table 13.....105

Table 14.....106

Table 15.....112

Table 16.....133

Table 17.....134

Table 18.....136

Table 19.....139

Table 20.....142

Table 21.....143

Table 22.....149

Table 23.....150

List of Figures

Figure 1.....42

Figure 2.....45

Figure 3.....48

Figure 4.....49

Figure 5.....56

Figure 6.....64

Figure 7.....77

Figure 8.....81

Figure 9.....84

Figure 10.....85

Figure 11.....99

Figure 12.....110

Figure 13.....111

Figure 14.....126

Figure 15.....129

Figure 16.....130

Figure 17.....138

Figure 18.....147

Figure 19.....148

Abstract

The aim of this thesis was to clarify functional interpretations of the Phonological Mismatch Negativity (PMN), a negative-going event-related brain potential (ERP) elicited at 250-350 ms in response to deviations in phonological expectations during spoken word recognition. A phoneme deletion task, which necessitates phonological processing independently from lexical/semantic influences, was employed in three experiments. Experiment 1 examined whether the PMN is sensitive to whole-item phonological similarity or whether a mismatch in one phoneme is sufficient to augment the response. Participants were instructed to omit the initial phoneme from a prompt word (e.g., *clap, /k/*) and to anticipate the correct answer. They then heard a correct (e.g., *lap*) or incorrect answer that was phonologically similar (e.g., *cap*) or dissimilar to the anticipated answer (e.g., *nose*). The PMN was largest to incorrect items and did not differentiate between phonologically similar and dissimilar items. It was concluded that the PMN is not modulated by phonological similarity. Experiment 2 examined top-down influences on the PMN by manipulating the lexicality of the prompt. A word/nonword prompt (e.g., *snoth, /s/)* was followed by a word/nonword response that matched/ mismatched expectations (e.g., *noth/toth*). The PMN was largest to mismatching responses and did not differentiate words from nonwords. Results indicate that the PMN is not dependent on lexical mechanisms. Experiment 3 measured whether the PMN is sensitive to mismatches beyond the initial phoneme. A prompt (e.g., *snoob*) was followed by a response that matched (e.g., *moob*) or mismatched expectations at either the initial (e.g., ***f**oob*) or final phoneme (e.g., *moo**p***) position. As expected, the PMN was elicited to initial mismatch items. In addition, a negativity elicited at 500 ms was augmented in the Final Mismatch condition and was interpreted as a PMN-like response involved in monitoring the position of phoneme mismatch. Findings presented in this thesis indicate that the PMN serves as a neural marker for a pre-lexical stage of spoken word recognition involving the analysis of speech input merging with phonemic expectations developed by the linguistic context. Implications for models of spoken word recognition, as well as clinical applications are discussed.

List of Abbreviations and Symbols Used

ANOVA	analysis of variance
CSD	current source density
CC	consonant cluster
CVC	consonant-vowel-consonant
dB	decibels
EEG	electroencephalogram
EOG	electrooculogram
ERP	event-related brain potential
fMRI	functional magnetic resonance imaging
Hz	Hertz
KΩ	kilo-ohm
ms	milliseconds
M	mean
MEG	Magnetoencephalography
PMN	Phonological Mismatch Negativity
RT	reaction time
SD	standard deviation
μV	microvolts

Acknowledgements

To my supervisor Dr. John Connolly, thank you for providing me with the opportunity to grow as a scientist. Your encouragement, advice, and wit have made graduate school an enjoyable experience. To Dr. Elisabet (Lili) Service, thank you for your advice and mentorship. Together, you and John have inspired my confidence and enthusiasm for research. I look forward to continuing our collaboration in the future.

Thank you to members of my thesis committee, Dr. Patricia Cleave, Dr. Tracy Taylor-Helmick, Dr. Margot Taylor (external) and Dr. Ron Leslie for dedicating your time and energy to reading my thesis, and for challenging my thinking. I would like to extend my gratitude to members of my comprehensive committee, Dr. Wayne MacDonald, Dr. Sherry Stewart, and Dr. Matthias Schmidt for broadening my knowledge. I wish to also thank a number of professors, most notably Dr. Pat McGrath, Dr. Kazue Semba, and Dr. Kathleen Bloom, whom I have come to admire and respect for their dedication to science and to higher learning.

Thank you to members of the Connolly lab, past and present, for your support and expertise. Our lab has always been an inviting place to work, and it is because of all of you. So thank-you to Dr. Ryan D'Arcy, Alma Major, Dr. Yannick Marchand, Dr. Cassie Mayo, Dr. Tian Wang, Dr. Mara Morr, Jeannine Gravel, Chris Striemer, Troy Harker, Celeste Lefebvre, Paula Douglas, and the countless number of exceptional undergraduate students (notably, Kim McIvor, Kaia Vilberg, Stephanie McKenzie and Jessica Wylie) that have worked and studied in the lab. Special thanks are extended to Ryan D'Arcy and Alma Major. Ryan, you are among my best teachers, and your advice, even when I didn't want to hear it, has always been appreciated. Alma (a.k.a. lab Mom), your kindness, courage, and friendship will follow me no matter where I go.

Thank you to members of my family for all of your love and encouragement. I can't possibly list all of you or this thesis would double in size, but I must say special thanks to Aunt Lorraine, Jenny, Aunt Beverly, and Aunt Marina. Whether it be a card, a phone call, or a get together 'the river', you have always made me feel loved and welcome at home. Thank you to numerous family friends, in particular Georgie Stewart, Sadie Wong, June Robertson, Bernice Steel, and Ethel Anderson and the Choir, for your support and prayers.

Thank you to my friends, Lauren Clare, Sean Duggan, Laura Gibson (de la Mothe), Morgan Gibson, Shana Nichols, JP Grossman, Tamara Brogan, Robert Boudreau, Mara Morr, and Nicole Blanchet for providing me with a network of support when I needed it most. I doubt that I can find the words to express what some of you have meant in my life, but I'll give it a try. Shana, thank you for opening my eyes to new things, for being there to listen, to laugh with, and to share a bottle of wine with! Rob, thank you for knowing what to do and say to make my day brighter, for understanding like few people can, and for changing my tires! Finally, thank you to two of the most important people in my life, Lauren and Laura. The two of you have taught me that sisterhood is not simply a birth rite; it is something that can be achieved. Thank you for your laughter, your tears, your love and most of all for your faith.

CHAPTER 1: GENERAL INTRODUCTION – SPOKEN WORD RECOGNITION FROM A BEHAVIORAL AND ELECTROPHSYIOLOGICAL PERSPECTIVE

1.1. MODELS OF SPOKEN WORD RECOGNITION

One of the most remarkable feats of the human cognitive system is the ability to recognize speech. What makes this process so remarkable is that conditions in the listening environment are rarely, if ever, free of potential disruptions. Obstacles to auditory word recognition may include the masking of speech sounds due to environmental noise (e.g., static on a cell phone), misarticulations due to speech errors, or an unfamiliar dialect. As if these barriers were not enough, we must learn to segment words from the continuous flow of speech input. That is, the onset and endings of spoken words are not typically defined by obvious word boundaries (Connine, Blasko, & Titone, 1993). This same barrier is not present in printed word processing, where written words are separated by white spaces. Despite all of these possible impediments, word recognition proceeds with few errors. It is not surprising then, that research over the last quarter of a century has been focused on defining the mechanisms that accomplish word recognition.

The architecture of modern spoken word recognition models converge on several fronts. Namely, they specify the presence of a mental lexicon, which consists of all the words we know, and of smaller units (e.g., phonetic features, phonemes, syllables) that are activated in the course of recognizing words. Models also typically incorporate the idea that multiple lexical candidates are activated in the course of speech perception, and

that selection of the target candidate occurs once a match is achieved between sensory input and a lexical representation (Marslen-Wilson, 1987; McClellan & Elman, 1986; Norris, 1994; Norris, McQueen & Cutler, 2000). Despite this general consensus, there remains at least one contentious issue - the direction of information flow between pre-lexical (e.g., phonetic features, phonemes) and lexical levels of representation (e.g., words).

1.2. DIRECTION OF INFORMATION FLOW: IS IT SOUNDS TO WORDS OR WORDS TO SOUNDS?

With regard to the directionality debate, there are proponents that maintain the autonomy of pre-lexical representations from lexical representations (Norris, 1994; Norris et al., 2000), while others stress the importance of influences from higher-level representations to lower level representations (McClelland & Elman, 1986, Samuel, 2001). TRACE (McClelland & Elman, 1986) and Shortlist (Norris, 1994) are two models that occupy opposite ends of the feedback continuum. TRACE mimics word recognition within an interactive activation framework, consisting of three levels of processing: 1) phonetic feature, 2) phonemic, and 3) word level. Activation spreads from the feature level to the phoneme level and finally to the word level. Feedback connections from the word level to the phoneme level operate to influence the interpretation of pre-lexical processes (e.g., bottom-up processes such as acoustic and phonemic analysis). Inhibitory connections between word nodes at the lexical level operate to select the appropriate lexical item. In contrast to TRACE, the architecture of Shortlist (Norris, 1994) is autonomous. That is, speech perception is simulated in a strictly bottom-up fashion, in which there are no direct connections between the phoneme level and the lexical level. In Shortlist, a lexical search selects a set of word candidates (i.e., the Shortlist) based on the degree of fit between the speech input and the lexical representation. The set of candidates is based exclusively on bottom-up evidence, such that lexical feedback is prohibited. Candidates become part of a so-called lexical network, and compete with each other via inhibitory links. A 'winning candidate' is eventually selected based on the

degree of fit between a candidate and the input.

There is convincing evidence that lexical representations are able to influence phonetic decisions. For example, in a phoneme monitoring task in which listeners are required to detect a target phoneme, detection is faster in words than in nonwords (Cutler Mehler, Norris, & Seguí, 1987), as well as in nonwords that more closely resemble words (Connine, Titone, Deelman & Blasko, 1997). Phoneme categorization tasks are also susceptible to lexical influences. Ganong (1980) showed that listeners exhibit a lexical bias when classifying an ambiguous phoneme in the middle of a /*t*/ /*d*/ continuum, so as to be consistent with a word (e.g., *type*) versus a nonword (e.g., *dype*). In order to account for such influences, Norris et al. (2000) have recently designed a model of phonetic decision making, which like Shortlist is autonomous. Information flows from the bottom-up to the lexical level. There is no feedback from the lexical level to the pre-lexical level. However, MERGE incorporates a phoneme decision level consisting of phoneme decision nodes, which receive and merge input from the phoneme and lexical levels. Thus, whereas the perceptual level is free from direct lexical effects, the phoneme decision level is susceptible to such influences. It should be noted that MERGE was designed to fit into the general theory of spoken word recognition as outlined in Shortlist (McQueen, Norris, & Cutler, 1999; Norris et al., 2000). Phoneme representations generated in Shortlist provide pre-lexical input to the phoneme decision nodes in MERGE, while the lexical representations in Shortlist provide lexical input to the phoneme decision nodes in MERGE. The phoneme decision nodes are able to account for lexical influences on phoneme decision-making. Whereas TRACE predicts that lexical

knowledge increases the activation of phonemes at the pre-lexical level, MERGE predicts that lexical influences operate at a post-perceptual level by influencing the phoneme decision level.

There is good evidence that words may be recognized in context before sufficient acoustic-phonetic information has accumulated to allow for their identification on the basis of sensory information alone (Marlsen-Wilson, 1987; Zwitzerlood 1989). For instance, Marlsen-Wilson (1987) showed that presentation of the initial portion of a word (e.g., */kapt/* as in *captain* or *captive*) facilitates lexical decisions to words that could be associated with the initial sequence (e.g., *ship* as to *captain* or *guard* as to *captive*). Based on these results, Marslen-Wilson (1987) concluded that semantic information of both word candidates (e.g., *captain/captive*) is activated on the basis of partial acoustic information. A study by Zwitzerlood (1989) is frequently cited as evidence that words may be recognized from partial acoustic input. As in Marslen-Wilson's study (1987), the degree of lexical activation of a candidate word was based on the degree to which it primed a visually presented candidate. In order to create an appropriate context, a sentence frame preceded the auditory prime, which as in Marlsen-Wilson's study (1987) was the initial portion of a word (e.g., */gen/* as in *general* or *generous*). The auditory prime was followed by a visual probe that was related to one of the incomplete word sequences (e.g., *army* or *gift*). Zwitzerlood (1989) found that with brief acoustic input, both related visual probes yielded faster lexical decisions, despite the context provided by the sentence frame. However, when the length of the acoustic sequence was extended, only the semantically appropriate probe was primed (e.g., *gift*, but not *army*). Zwitzerlood

(1989) hypothesized that while semantic processing begins on incomplete acoustic input, semantic integration is delayed until sufficient bottom-up information has accumulated to allow for word identification.

Marslen-Wilson's (1987, 1989) model of spoken word recognition, the Cohort model, was designed to account for the process of early selection, whereby words are identified prior to the reception of sufficient sensory information. Like Shortlist and MERGE, the Cohort model places restrictions on the flow of information from the lexicon to pre-lexical representations. The Cohort model of word recognition includes three stages of word recognition: lexical access, lexical selection, and lexical integration. During the lexical access stage, a set of word candidates (e.g., the word initial cohort) is developed from the initial portion of the speech signal. This activation of word candidates via acoustic-phonetic input is a strictly bottom-up process; activation of word candidates by top down mechanisms is prohibited. However, contextual information is permitted to interact with bottom-up processes during lexical selection in order to reduce the number of activated candidates. The process of lexical selection continues until the incoming acoustic-phonetic information is compatible with only one member of the cohort, and a word is recognized. At the final stage of word recognition (i.e., lexical integration), lexical information about the word is incorporated within the context of the preceding discourse.

The most recent version of the Cohort, the Distributed Cohort Model (DCM; Gaskell & Marslen-Wilson, 1997, 1999) maintains the principal of parallel activation of multiple lexical candidates, but no longer maintains the independence of word candidates.

In the DCM, the activation of word candidates overlaps, producing interference across the distributed representations of both words. For example, for the incoming speech */kaepti/*, two word candidates are activated: *captain* and *captive*. The model attempts to activate both words, resulting in a blend state that is similar to both words, such that their activation is higher than other words, but identical to neither. The corollary is that the greater the number of activated word candidates, the less successful is the blend state at representing those words. Thus, the larger the word initial cohort, the weaker will be the activation of lexical candidates.

Relevant to a discussion of the Cohort models of word recognition is the concept of the recognition point, defined as the point at which a word may be identified from all other members of the word-initial cohort (Grosjean, 1980; Tyler & Wessels, 1985). The recognition point for any given word is determined with the gating technique, whereby brief sequences of a word are presented in successively longer segments (50 ms, 75 ms, 100 ms, and so on) until a word is identified correctly. The recognition point for any given word may be later if presented in isolation, or earlier if presented in context (Salasoo & Pisoni, 1985). The concept of recognition point is important for interpreting studies of early contextual influences. For instance, in Zwitzerlood's study (1989) described above, the amount of acoustic information required to prime the appropriate visual probe (e.g., *gift*) corresponded to the recognition point in the auditory prime (i.e., recognition point in *generous*). A related measure is the uniqueness point. The difference between the two terms has to do with the method used in defining the point. The uniqueness point typically refers to the first phoneme that differentiates a word from its

cohort even if it has not been identified, whereas the recognition point is based on the point at which a word is identified with high confidence ratings after increasingly longer acoustic segments have been presented.

Norris (1994) states that "speech is an inherently temporal signal", and like other researchers interested in speech perception, he attempts to capture the sequencing and interactivity of the stages involved in word recognition. Much of the empirical support obtained for the various models discussed above, involve the application of behavioral measures. Such measures represent the end stage of processing and thus, are not able to delineate the temporal microstructure of events that intervene between input of the speech signal and output from the lexicon. Event-related brain potentials (ERPs) provide a real-time, continuous index of the time course of cognitive processes, and thus may provide a method for constraining theories of spoken word recognition.

1.3. OVERVIEW OF ELECTROPHYSIOLOGICAL METHODOLOGY

Evoked potentials (EPs) represent the summed activity of inhibitory (IPSPs) and excitatory (EPSPs) postsynaptic potentials of an active neuronal mass (Knight, 1997). Thus, by time-locking recordings to the onset of a stimulus, EPs provide superior temporal information pertaining to the brain's reception and response to a stimulus. EPs can be classified as sensory or cognitive. Sensory EPs are sensitive to such stimulus parameters as intensity and duration, and are not influenced by cognitive factors. Common sensory EPs include the brainstem auditory evoked potential (BAEP), the visual evoked potential (VEP), and the somatosensory evoked potential (SEP). In contrast to sensory EPs, cognitive EPs provide information about the mental operations (i.e., semantic evaluation, recognition) being performed on a stimulus. That is, cognitive EPs are elicited in response to the cognitive processing of a stimulus, as opposed to the effects of stimulus presentation. Because cognitive EPs are associated with a cognitive event, rather than merely the presentation of a stimulus, they are referred to as event-related brain potentials (henceforth, ERPs), in order to indicate that they are related to but not strictly evoked by a stimulus presentation.

Typically, ERPs are measured by attaching electrodes to the scalp with a conductive substance. The brain's electrical activity, typically represented as the electroencephalogram (EEG), is recorded in either a bipolar or unipolar montage which measures potential differences between two electrodes placed on the scalp that both record brain activity (the bipolar montage) or between a scalp electrode site (i.e., an active location) and a reference site (i.e., a relatively neurologically inactive location such as the

earlobe). Several hundred measurements of potential differences between a given pair of electrodes are recorded per second. Thus, large amounts of data are collected particularly when recordings are obtained from numerous electrode sites.

The amplitude of ERPs is small (i.e., 0.5-20 μV) in comparison to background EEG activity (i.e., 20-100 μV). However, the process of signal averaging increases the signal-to-noise (SNR) ratio, allowing for components to be "extracted" from the raw EEG signal. As multiple trials are averaged, activity unrelated to the stimulus (i.e., EEG) will sum to zero, while activity time-locked to the stimulus will summate and "emerge" from the EEG. The number of trials required to extract the evoked response depends on the size of the component under investigation. Generally speaking, most ERP components will be detectable after 20-50 trials are averaged. An ERP component is identified as the peak or trough of a curve in the ERP waveform, which is hypothesized to reflect maximal activation of a specific cognitive process (Brandeis & Lehmann, 1986). Traditionally, ERP components are labeled according to polarity and time of onset following an event. Thus, the N400 is named because it is a negative-going waveform that typically peaks at 400 ms post-stimulus onset.

The advantages of using ERPs to investigate linguistic processes are numerous. The recording of ERPs is noninvasive for the participant, as well as unobtrusive to the process under investigation. ERPs do not require an overt behavioral response, and thus may provide a means of measuring language functioning in non-communicative individuals (see Connolly & D'Arcy 2000; Connolly, D'Arcy, Newman, & Kemps, 2000 for reviews). ERPs provide continuous temporal information, thus allowing the

sequencing of stages involved in language processing to be delineated. Although the spatial resolution of ERPs[1] is not nearly as fine-grained as their temporal resolution, the scalp distribution of ERPs provide some clues as to the locus of brain activity involved in a particular process. The use of ERPs is not limited to the study of adult cognition; ERPs may be used to study the neurodevelopment of cognitive functions in infants (Morr, Shafer, Kreuzer, Kurtzberg, 2002; Pang, Edmonds, Desjardins, Khan, Trainor, & Taylor, 1998) and children (Coch & Holcomb, 2003; for review see Taylor & Baldeweg, 2002). Finally, ERPs have proven to be valuable in clinical investigations, particularly in the area of dyslexia research (Newman, Hellman, Striemer, Mathieson, & Connolly, in preparation; Robichon, Besson, & Habib, 2002; Taylor & Keenan, 1999).

---

[1] High-resolution recording montages, and source modeling techniques (i.e., Curry and BESA), have improved the spatial resolution of ERP methods. However, metabolic techniques such as fMRI continue to provide superior spatial resolution, although it remains to be determined if they reflect similar types of activation and cognitive function.

1.4. ERPS REFLECT DISTINCT LEVELS OF PSYCHOLINGUISTIC PROCESSING

Over twenty years of research has shown that ERPs reflect distinct levels of psycholinguistic processing, such as phonological, orthographic, semantic, and syntactic. One of the most influential reports in ERP research was the identification of a negative component peaking at 400 ms, as the semantic congruity of a target word was manipulated (Kutas & Hillyard, 1980). In this study, the terminal words of sentences were manipulated, such that they were either semantically congruous (e.g., *The piano was out of tune.*) or incongruous (e.g., *The pizza was too hot to sing. [eat]*) to the sentence context. An ERP response, termed the N400, appeared to be mediated by semantic congruity, such that it was maximal to incongruous sentence endings, and attenuated to congruous sentence endings. Subsequent research showed that the N400 was linearly related to the cloze probability of terminal words (Kutas, Lindamood, & Hillyard, 1984) and thus, was related to contextual constraint factors as well as semantics. High Cloze probability refers to the likelihood that a sentence will terminate with a specific word. For example, a cloze probability of 0.80 would indicate that 80% of the time, people will end a sentence with a particular word. Kutas et al. (1984) showed that the N400 was larger in amplitude to low cloze probability sentence endings (e.g., *Captain Sheir wanted to stay with the sinking raft. [ship]*), than to high cloze probability endings (e.g., *She called her husband at his office.*).

Since these early studies, the N400 has been observed in a variety of task manipulations, including auditory replications of the sentence-processing task (Connolly, Stewart, & Phillips, 1990; Connolly, Phillips, Stewart, & Brake, 1992; Holcomb &

Neville, 1990; McCallum, Farmer, & Pocock, 1984), in semantic priming tasks involving word pairs presented visually or aurally (Bentin, Kutas, & Hillyard, 1993; Bentin, McCarthy, & Wood, 1985; Holomb & Neville, 1990), and in tasks combining pictures with speech and/or text (Connolly, Byrne, & Dywan, 1995; Ganis, Kutas, & Sereno, 1996). The functional role of the N400 has been debated (Brown & Hagoort, 1993; Deacon, Hewitt, Yang, & Nagata, 2000; Deacon, Uhm, Ritter, Hewitt, & Dynowska, 1999; Holcomb 1993). At the center of the debate is whether the N400 reflects lexical access, or post-lexical integration processes. Lexical access mechanisms are proposed to represent the automatic process of mapping a linguistic signal onto a representation in the mental lexicon. The amplitude of the N400 then, reflects the extent to which the preceding context has raised the activation level of a specific word in the lexicon (Deacon, Uhm, Ritter, Hewitt, & Dynowska 1999). In contrast, post-lexical integration processes are assumed to be slow-controlled processes reflecting the incorporation of a word's meaning into the context in which it occurred. In this case, the amplitude of the N400 reflects the ease with which a target word may be integrated into the preceding context (Brown & Hagoort, 1993; Holcomb, 1993). There is converging evidence in favor of the post-lexical integration account (Brown & Hagoort, 1993; Brown, Hagoort, & Chwilla, 2000; Chwilla, Brown, Hagoort, 1995; Holcomb, 1993); however, recent evidence is challenging this claim (Deacon et al., 1999, 2000).

The scalp distribution of the N400 is dependent on experimental design (see reviews Kutas, Van Petten, & Besson, 1988; Kutas & Van Petten, 1994). The N400 observed in the visual sentence-processing task has been reported to be larger over

centroparietal regions, and larger over the right hemisphere than over the left hemisphere (Kutus et al., 1988, Pritchard et al., 1991). In contrast, the auditory N400 shows a frontal or frontocentral distribution (Connolly & Phillips, 1994; Connolly et al., 1990, Connolly et al., 1992; Holcomb & Neville, 1990). A similar trend toward a more anterior distribution has also been reported in visual semantic priming tasks (Bentin, 1987; Bentin et al., 1985). In addition, there are reports of a left greater than right asymmetry, in visual sentence-processing tasks (Boddy, 1986, Kutas et al., 1988) and in a word/nonword reading task (Nobre & McCarthy, 1996).

The time course of the N400 in the auditory modality has been a topic of some debate (Connolly, Phillips, & Forbes, 1994; Hagoort & Brown, 2000; Van Petten, Coulson, Rubin, Plante, & Parks, 1999). Specifically, evidence for a so-called early N400 effect (Van Petten et al., 1999) conflicts with reports claiming that two functionally distinct ERP components monitor the time-course of spoken word recognition: an early negativity peaking between 200-350 ms and the N400 (Connolly & Phillips, 1994; Hagoort & Brown, 2000). The literature pertaining to these two differing interpretations will be reviewed.

1.5. ERPS & SPOKEN WORD PROCESSING

Holcomb and Neville (1990) recorded ERPs during a lexical decision task in order to investigate semantic priming in both the visual and auditory modality. In their study primes (e.g., *dog*) were followed by target words that were semantically related (e.g., *cat*) or semantically unrelated to the prime (e.g., *hat*), or by phonologically legal (e.g., *jank*), or illegal nonwords (e.g., *nlps*). In both modalities, targets that were unrelated to the prime, whether a word (e.g., *hat*) or legal nonword (e.g., *jank*), elicited the largest N400 components. As had been previously observed, (Bentin et al., 1985; Rugg & Nagy, 1987) phonologically illegal nonwords failed to produce an N400 effect.

Holcomb & Neville (1990) observed two notable differences between the auditory and visual N400. The auditory N400 began earlier, lasted longer, and was larger than that in the visual modality. In addition, while the visual N400 was larger over the right hemisphere, the auditory N400 was larger over the left hemisphere. These researchers argued that the early onset N400 was consistent with theories of spoken word recognition contending that processing of a spoken word begins on incomplete information and is influenced by the preceding context (Marslen-Wilson & Tyler, 1980; Marslen-Wilson, 1987).

In an auditory version of the Kutas and Hillyard (1980) study, McCallum, Farmer, and Pocock (1984) did not observe onset latency changes in the N400. However, as noted by several groups (Connolly, Phillips, & Stewart, 1990; Holcomb & Neville, 1991) McCallum et al. (1984) did not use naturally connected speech and instead, spliced in terminal words recorded in other sentence contexts. Holcomb & Neville (1991) suggested

that cues present in connected speech, such as prosody and coarticulation, might provide clues as to the identity of the target word, and thus influence the N400. To address this issue, Holcomb & Neville (1991) conducted two experiments, the first employing naturally connected speech, and the second introducing a 750 ms ISI separating spoken words. In both studies, the participants listened to sentences terminating with the best completion word (e.g., *December is the last month of the year.*), an unrelated anomalous word (e.g., *The bird built a nest in which to lay her cars. [eggs]*), or an anomalous word that was nevertheless related to the best completion word (e.g., *The sink was so plugged they called a pipe. [plumber]*).

In both experimental contexts, an N400 was largest to anomalous words relative to best completions, and began earlier and lasted longer for unrelated anomalies in comparison to related anomalies. This result replicated previous findings (Holcomb & Neville, 1990) showing that semantic relatedness modulates N400 amplitude. However, the major finding of their study was that the N400 began earlier in the connected speech context than it did in the 750 ISI context. They argued that non-semantic factors such as prosody and coarticulation facilitated processing in the connected speech context over and above that produced by semantic factors alone. Thus, they concluded that sentence level contextual factors, both semantic and non-semantic, influence spoken word processing before a word can be identified on the basis acoustic information alone.

Relevant to this discussion is research that has identified an N400-like response sensitive to phonological manipulations as opposed to semantic factors. This response has been shown in both the visual (Rugg, 1984a, 1984b; Rugg & Barrett, 1987) and auditory

modalities (Praamstra & Stegeman, 1993; Praamstra, Meyer, & Levelt, 1994). For instance, Rugg (1984a, 1984b) had participants judge whether visually presented pairs of words or nonwords rhymed. He observed a negative wave that peaked at about 450 ms after the onset of the second member of the stimulus pair. Despite the fact that the N450 displayed a slightly different topographical distribution than the semantic N400, many consider the N450 and N400 to be one in the same (Kutas and Van Petten, 1988). Praamstra and Stegeman (1993) observed an N400-like response in an auditory version of Rugg's rhyme-judgment task. In an aurally presented lexical decision task, Praamstra and Stegeman (1993) varied the phonological relationship between word targets and word/nonword primes. They observed a negative enhancement peaking about 450 ms after the onset of words that did not rhyme with the preceding prime. This effect was not observed for word-nonword prime-target pairs.

In a follow-up study to Praamstra and Stegeman (1993), Praamstra, Meyer, & Levelt (1994) varied the phonological relationship of the prime-target pair in two separate lexical decision experiments. In both experiments, the primes were Dutch words, and targets were words or nonwords that were either related or unrelated to the prime. In their first experiment, related prime and targets rhymed (e.g., *graaf-staaf*) and in the second they alliterated (e.g., *beeld-beest*). Results of their first experiment replicated those of Praamstra and Stegeman (1993), with an N400-like response augmented to non-rhyming word-word pairs, but not to non-rhyming word-nonword pairs. In experiment 2, an N400-like response was observed to both word and nonword targets that did not alliterate with the prime. In addition, the negativity observed in experiment 2, began about 200 ms

earlier than the response exhibited in experiment 1. Due to the nature of contrasting results obtained in their two experiments, their findings and conclusions warrant further discussion.

The lexicality influences observed in experiment 1 but not in experiment 2 are likely the result of the positioning of phonologically illegal consonant clusters at the beginning of nonword targets. As pointed out by the authors, the detection of the illegal consonant cluster would have given away the lexicality of the target before priming effects could develop. In contrast, priming effects were allowed to develop in experiment 2, since illegal consonant clusters were positioned at the end of nonwords. This proposal was supported by behavioral measures, which indicated that responses to nonwords were faster in experiment 1 than in experiment 2. Differences in the timing of the ERP effect between the two experiments (i.e., earlier in experiment 2) were attributable to variations in the position of the shared segments. In the first experiment (i.e., rhyming), the shared segments were at the final position (e.g., *schat-krat*), while in the second (i.e., alliteration) the shared segments were at the initial position (e.g., ***telg-test***). Targets in experiment 2 would have been detected as unrelated to the prime at the onset of the initial segment, thus producing an early ERP differentiation.

Praamstra et al. (1994) questioned whether differences in the timing of the negative effect between the two experiments reflected the presence of a different ERP component. Initially they hypothesized that the early effect might be a MMN or an N2, but concluded that the experimental manipulations present in their study were not consistent with those required to elicit either of these components. However, based on the

compatibility of their findings with previous results (Holcomb & Neville, 1991), and on shared topographical distributions in their two experiments, they concluded that the early negativity was "similar enough to the classical N400 to be provisionally placed in the same category" (Praamstra et al., 1994, p. 215).

Given that spoken word processing is extended in time relative to visual word processing, it seems surprising that the N400 would onset earlier in the auditory modality. Also, modulations of N400 latency as reflecting early contextual influences on spoken word recognition is inconsistent with the predominant view that the N400 reflects lexical integration (Hagoort & Brown, 1993). Prior to Praamstra et al.'s (1994) study, Connolly and colleagues (1990, 1992) had shown evidence in favor of the separation of the negativity produced to aurally presented semantically anomalous words (what was traditionally labeled the N400) into functionally distinct early and late components. In work using spoken sentences varying in contextual constraint, Connolly, Stewart and Phillips (1990) observed an early negativity peaking around 250 ms that appeared to reflect a sub-process preceding the contextual integration reflected by the N400. To demonstrate the independence of this early negativity, now referred to as the Phonological Mismatch Negativity (PMN, or the N200 as it was called in those reports) from the N400, Connolly et al. (1992) used a phonological masking procedure during the presentation of low and high contextually constrained sentences. These sentences were taken directly from the Speech Perception in Noise test (SPIN; Kalikow, Stevens, & Elliot, 1977). Based on the finding that false speech cues interfere with central language functions that are integral to comprehending speech, rather than with acoustic/phonetic mechanisms

(Hutcherson, Dirks, & Morgan, 1979; Kalikow et al., 1977), it was hypothesized that masking would interfere with semantic comprehension as manifested by the N400, without having an effect on earlier phonological mechanisms as reflected by the PMN. The PMN and N400 amplitudes proved to be larger to sentences of low versus high constraint. However, the masking differentially affected the onset latency of the two responses. While the masking delayed the onset of the N400, it had no effect on PMN latency. These results led to the proposal that the PMN reflects acoustic-phonetic mechanisms operating during speech comprehension.

To test the hypothesis that the PMN was a distinct component representing a phonological processing stage of spoken word recognition, Connolly and Phillips (1994) designed a study to double dissociate the PMN and N400. Their experiment consisted of four conditions in which the semantic and phonological expectancies of medium to low cloze probability terminal words were manipulated. In the Phoneme Match-Semantic Match condition, sentences ended with the highest cloze probability word (e.g., *The piano was out of tune.*). In the Phoneme-Mismatch-Semantic Mismatch condition, the terminal word was semantically incongruent and its initial phoneme differed from that of the highest cloze probability word for that sentence (e.g., *Joan fed her baby some warm nose. [food]*). In the Phoneme Mismatch-Semantic Match condition, the terminal word was semantically congruent but its initial phoneme differed from that of the high cloze probability ending for that sentence (e.g., *The pig wallowed in the pen. [mud]*). Finally, in the Phoneme Match-Semantic Mismatch condition, the initial phoneme of the terminal word matched that of the highest cloze probability ending, but the word was semantically

inappropriate (e.g., *The gambler had a streak of bad luggage. [luck]*). Results of the Connolly and Phillips (1994) experiment showed that the Phoneme Match-Semantic Match condition failed to elicit a robust PMN or N400, while both of these components were observed in the Phoneme Mismatch-Semantic Mismatch condition. In the critical conditions designed to dissociate the PMN and N400, the hypothesized effects were observed. Only a PMN was seen in the Phoneme Mismatch-Semantic Match condition, while only an N400 was apparent in the Phoneme Match-Semantic Mismatch condition. Connolly and Phillips (1994) concluded that the PMN represents a process in which the initial segment of a word is compared against a phonological template developed on the basis of the preceding sentence context. They further hypothesized that the PMN and N400 are sensitive to distinct stages of spoken word recognition: the former represents an earlier stage involved in processing initial phonological information in the speech signal, while the latter is involved in integration processes representing the incorporation of word meaning with sentence context.

It seems reasonable to hypothesize that, not unlike Connolly et al. (1994), the manipulation employed by Praamstra et al. (1994), particularly in experiment 2, produced two components, one related to the PMN and the second to the N400. Recall that target stimuli in experiment 2 (i.e., the alliterating experiment) were primed to begin with a particular initial segment (e.g., ***telg-test***). Stimuli that failed to conform to such expectations elicited an early negativity that appeared distinct from the N400, particularly at centro-parietal sites (see Figure 2 in Praamstra et al. 1994). It is noteworthy that since the publication of his report, Praamstra has stated that the early N400 effect was likely

what Connolly and colleagues refer to as a PMN (personal communication to John F. Connolly, Boston, 1999).

A recent study (Dumay, Benraiss, Barriol, Colin, Radeau, & Besson, 2001) manipulating the position of shared segments in a lexical decision is relevant to the discussion of Connolly and Phillips (1994) and Praamstra et al's results (1994). Dumay et al. (2001) primed aurally presented bisyllabic target words/nonwords (e.g., *CV.CVC; tirage*) with aurally presented bisyllabic primes. The position of overlapping segments between primes and targets was varied, such that related targets shared the final syllable (e.g., *CV.**CVC; lurage***), rime[2] (e.g., *CV.CVC; lubage*) or coda (e.g., *CV.CVC; lusoge*) with the prime. Unrelated targets contained no phonological overlap with primes (e.g., *lusole*). The first syllable was the same for all primes (e.g., *lu* in the above example). For words, the N400 was largest for coda overlap and for unrelated targets, which did not differ, intermediate for rime overlap, and smallest to syllable overlap. For nonwords, the N400 was smaller for syllable overlap items than for unrelated targets. However, no differences in N400 amplitude were observed between rime, coda and syllable overlap items. In general, the N400 was larger for word than for nonword targets. Dumay et al. (2001) hypothesized that non-lexical mechanisms contributed to phonological priming effects for syllable overlapping words and nonwords, whereas lexical selection mechanisms were responsible for the further phonological priming effects observed for words but not for nonwords.

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[2] Rime is a linguistic term that refers to the vowel and final consonant (or consonant cluster) of a syllable (e.g., *ap* in *clap; age* in *lubage; ack* in *stack*).

Dumay et al.'s (2001) manipulation of overlapping segments does not appear to have produced a distinct early negativity. The PMN might have been expected to occur when the target mismatched expectations created by the prime. However, the inclusion of all conditions in the same task makes it impossible for participants to form specific expectations as to the nature of the final syllable. That is, participants would not have known whether to anticipate a syllable, rime, or coda overlap. Furthermore, it is plausible that a PMN was elicited in the task, but was obscured by the N400 response.

Notwithstanding the creative design and interesting results obtained by Dumay et al. (2001), their findings should be viewed with some caution. The intervals used for analyzing their waveforms were very broad (400 – 1000 ms (350-900 nonwords) and 1000 - 2000 ms), and thus failed to characterize the conditional and topographic modulations of the ERP components observed in their study. For instance, the early interval (400 – 1000, 350 – 900 ms) encompassed the N400 as well as a substantial portion of the late positive component (LPC), and yet the authors focused on modulations of the N400. It is possible that some of their results were attributable to variations in the LPC, as opposed to the N400. Smaller intervals and/or peak scoring would have allowed for a better characterization of their results.

Connolly, Phillips, and Forbes (1995) established the modality specificity of the PMN by studying the effects of manipulating phonological and semantic features of sentence ending word on visual ERPs. The stimuli used in this experiment were identical to those used in the 1994 study conducted by Connolly and Phillips (1994). While results of the 1995 study did find evidence of a negativity preceding the N400, it was not

sensitive to phonological features of terminal words. This early negativity, termed the N270, was seen in all conditions but was largest when the terminal word violated both semantics and phonology and when the terminal word violated semantics but not phonology. If the N270 had proved to be the visual equivalent of the PMN, then it would only have been observed in those conditions that violated phonological expectations.

Connolly and colleagues' finding of an early occurring negativity has been independently replicated, albeit with differing interpretations as to its function (Hagoort & Brown 2000; van den Brink, Hagoort & Brown, 2001). However, as in previous research (Holcomb & Neville, 1990, 1991), more recent work argues in favor of an early N400 effect rather than a separate negativity (Van Petten et al. 1999). It should be noted that inspection of the waveforms in Van Petten et al.'s (1999) study, as well as in Holcomb and Neville's studies (1990, 1991), suggests the presence of a separate negativity preceding the N400. Due to the contrasting interpretations and results of these more recent studies, each will be discussed in turn.

The Van Petten et al. (1999) study was similar to that of Connolly and Phillips (1994), consisting of sentences varying in contextual constraint. The terminal word was either 1) the high cloze probability ending for the sentence (e.g., *It was a pleasant surprise to find that the car repair bill was only seventeen dollars.*), 2) a word that rhymed with the high cloze ending (e.g., *It was a pleasant surprise to find that the car repair bill was only seventeen scholars.*), 3) a word that shared the initial phonemes of the high cloze ending but was semantically incongruent (e.g., *It was a pleasant surprise to find that the car repair bill was only seventeen dolphins.*) or 4) a word that was

semantically incongruent and did not share the initial phonemes of the expected completion (e.g., *It was a pleasant surprise to find that the car repair bill was only seventeen bureaus.*). ERPs were recorded from both the onset of the terminal word and from the isolation point (IP; determined in a separate experiment), defined as the minimum amount of acoustic information necessary for a participant to correctly identify a word from a fragment in the absence of contextual information.

Van Petten et al.'s results indicated that the N400 was largest in the three semantically incongruent conditions; however, the latency of the N400 was differentially influenced by the nature of the anomalous endings. When ERPs were recorded from word onset the incongruency effect occurred earlier in the completely incongruent condition (e.g., *bureaus*) and rhyme condition (e.g., *scholars*), relative to the condition that shared the same initial phonemes as the expected ending (e.g., *dolphins*). Similarly, when ERPs were recorded from the IP the N400 response began prior to the IP of sentence ending words in the completely anomalous and rhyme conditions, while the onset of the N400 corresponded to the IP in sentence ending words that shared the same initial phonemes as the high cloze ending. The onset of the N400 effect prior to the IP led Van Petten et al. (1999) to conclude that semantic processes are able to operate on incomplete acoustic information such that the meaning of incoming acoustic input is compared to a semantic template derived from the sentential context. Their argument for a semantic explanation as opposed to a phonological one is largely based on their observation that the N400 effect did not differ between the completely incongruous condition and the rhyme condition. A phonological explanation would have predicted a reduced N400 in the

rhyme condition due to the priming of phonological expectations. However, since many of their sentences were not of high cloze probability (average cloze was 58%), the phonological manipulation of expectations would have been inadequate to test these hypotheses. Further, Van Petten et al. (1999) argue against Connolly and Phillips' (1994) claim that the PMN is a separate component, yet in their third experiment there appears to be a PMN in the completely incongruous and rhyme conditions (cf. van den Brink et al., 2001, p. 969), which are precisely the conditions that would be predicted to elicit the largest PMN. In fact, it is particularly impressive that the PMN could be seen in their study insofar as it is typically not as clear in grand averages to sentence stimuli but is often best seen in individual subject waveforms. It was not possible to examine individuals' ERPs in this study as the waveforms were contaminated with what appears to be alpha activity but could be waveform distortion caused by the under sampling, at 170 Hz, of data collected with a 0.01-100 Hz bandpass (cf. Picton, Lins & Scherg, 1995).

Van Petten et al.'s (1999) interpretation of contextual influences during spoken word comprehension is more or less compatible with that of Hagoort and Brown (2000) and van den Brink et al. (2001) who, however, argue that early contextual influences are manifested by a separate negativity, rather than by an earlier occurring N400. Hagoort and Brown (2000) presented participants with spoken sentences in which the terminal ending was either a semantically appropriate word or a semantically inappropriate word whose initial phoneme did not match that of the appropriate ending. Two negativities were observed to semantically inappropriate endings, a response the authors equated with the PMN but termed the N250, as well as the N400 response. However, Hagoort and Brown

(2000) argued that the N250 represented the activation of early lexical selection processes involved in matching word candidates derived from the acoustic input with semantic expectations based on the sentential context.

In a study similar to those described above, van den Brink et al. (2001) presented participants with sentences terminating with congruent endings, semantically incongruent endings whose initial phonemes differed from the expected completion, or with semantically incongruent endings whose initial phonemes matched those of the expected completion. Aside from finding an N400 response in the semantically incongruent conditions, they observed an early negativity (which they termed the N200) in all conditions, which was larger to semantically incongruent completions whose initial phonemes mismatched those of the expected ending. Van den Brink et al. (2001) argued against Connolly and Phillips' (1994) account that the PMN represents a phonological processing stage of word recognition, since they observed the N200 in all conditions and not just those in which the initial phonemes mismatched those of the expected word. Similar to Hagoort and Brown (2000), Van den Brink et al (2001) argued that the negativity preceding the N400 in spoken word recognition studies is related to top-down contextual influences on spoken word recognition, with its amplitude reflecting the goodness of fit between contextually activated semantic and syntactic features with those of the set of bottom-up activated word candidates. This account rejects the proposal of Connolly and Phillips (1994) that the negativity preceding the N400 reflects a pre-processing stage involving phonological analysis of the acoustic properties of the speech signal.

To clarify the functional significance of the early negativity, hereafter referred to as the PMN, Connolly, Service, D'Arcy, Kujala and Alho (2001) designed a study involving minimal semantic context. This was accomplished by avoiding paradigms typically involved in the elicitation of the N400. In their study, participants studied a visual word/nonword that was followed by the presentation of a prime letter, and were told to anticipate the auditory word/nonword that would begin with the same letter as the visual prime and rhyme with the visual item. Thus, matching trials consisted of auditory targets that matched phonological expectations derived by the prime (e.g[3]., *house, m: mouse* or *telk, w: welk*). Mismatch trials consisted of auditory targets that failed to fit with the phonological expectancies that were primed (e.g., *house, m: barn*). The PMN was elicited in all trials, but was largest to auditory targets that did not phonologically match. There were no significant differences in the amplitude of the PMN on the basis of whether the stimuli were words or nonwords, suggesting that the processing requirements of the task and their subsequent neural manifestations occurred independently of lexical/semantic access mechanisms. If the elicitation of the PMN involved priming of lexical or semantic features, as argued by others (Hagoort & Brown, 2000; van den Brink et al., 2001), then the PMN should have differed between word and nonword trials. Therefore, the results of Connolly et al. (2001) provide support for the argument that the PMN is involved in a pre-lexical stage of speech recognition.

In addition to the PMN, Connolly et al. (2001) observed a negativity peaking at approximately 360 ms in response to word/nonword mismatches. This N400-like

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[3] Note that this study was conducted in Finnish, but English examples are provided for illustrative purposes.

response was clearly distinct from the PMN in both the grand average waveforms, as well as in the current source density maps. The PMN was associated with a left hemispheric anterior source, while the later negativity was associated with a bilateral centro-parietal source. The functional role of this negativity was attributed to on-going phonological processes, and is reminiscent of the negativity observed in experiment 1 of Praamstra et al. (1994). Recall that the difference between rhyming and non-rhyming stimuli in their experiment was distributed over centro-parietal locations.

A recent study employed magnetoencephalography (MEG) in order to localize the neural generators of the magnetic PMN (Kujala, Alho, Service, Ilmoniemi, & Connolly, 2003). Kujala et al. (2003) used the same stimuli and paradigm as in Connolly et al. (2001) to allow for a direct comparison between the electric PMN and its magnetic counterpart (PMNm). The results of Kujala et al. (2003) replicated those of Connolly et al. (2001). The amplitude of the PMNm was largest to mismatching items, and failed to differentiate words from nonwords. The latency of the PMNm differed for words (~270 ms) and nonwords (~300 ms); however, this difference was not significant for the participants that showed PMNm responses to both words and nonwords (n = 4). Thus, Kujala et al. (2003) attributed the apparent latency differences to normal variation. As in the ERP version of this study, a later negativity (referred to as N400-like) was elicited to mismatching words and nonwords. In support of the electrical data, the PMNm and N400m were differentiated based on their timing, as well as on the location of their neural generators. The current source of the PMNm was located anterior to that of the N400m in the left temporal cortex.

A recent experiment employed high-resolution ERP recordings to investigate phonological and semantic processing in a novel visual/auditory priming task (D'Arcy, 2002; D'Arcy, Connolly, Service, Hawco, & Houlihan, in press). Participants were presented with a visual sentence (e.g., *The man is in the classroom*), and were instructed to anticipate the superordinate (i.e., a word higher in the semantic hierarchy than the prime – *classroom*) terminal word (e.g., *school*). Following the prime, a spoken sentence was presented that ended with a target word that was congruent to the prime or that was incongruent to the prime (e.g., *The man is in the school/barn*). Target words in the Incongruent condition mismatched initial phonological expectations as well as semantic expectations. In order to measure the influence of active lexical candidate numbers on the PMN and N400, the probability of target stimuli were divided into high/low congruent conditions, such that the Low Congruent condition was characterized as having more possible lexical candidates than the High Congruent condition. For example, in the High Congruent condition, target sentences ended with a high probability congruent ending (e.g., *The boy is swimming in the shallow end. – The boy is in the pool).* In the Low congruent condition, the target sentences ended with a low probability congruent ending (e.g., *The woman is swimming in the sunken ship. – The woman is in the ocean* [*water, sea, lake* also being possible candidates]. As expected, incongruent terminal words elicited both PMN and N400 responses. The manipulation of high/low probability differentially influenced the PMN and N400. In the Low Congruent condition, a PMN, but no N400 was observed. Neither component was elicited in the High Congruent condition. On the basis of these findings, D'Arcy et al. (in press) suggested that the PMN

is sensitive to the number of activated lexical candidates, thereby reaffirming views of the PMN as having a role in the formulation of a cohort or shortlist of candidate words (Connolly & Phillips, 1994; Connolly et al., 2001). Indeed, the finding that the PMN appears to be modulated by the number of activated candidates is consistent with theories of spoken word recognition arguing for the parallel activation of multiple lexical candidates (Marslen-Wilson, 1987; Norris, 1994).

The functional independence of the PMN and N400 were further substantiated by the localization of PMN and N400 dipoles to distinct neuroanatomical regions. PMN sources were localized to the left inferior frontal region (Broca's area) with some homologous activation in the right hemisphere, and to the left inferior parietal lobe. In contrast, the N400 was localized to the left posterior superior temporal gyrus (Wernicke's area), to the left superior temporal plane and to the left polymodal area (temporo-parietal-occipital region). It is noteworthy that the localization of the PMN in this study differs from that reported by Kujala et al. (2003), who located the source of the PMNm to anterior regions of the temporal cortex. Differences between these two studies do not necessarily imply erroneous modeling; such discrepancies are likely a reflection of the paradigms employed to elicit the response. Recall that Kujala et al. (2003) employed a cross-modal phonological priming task, whereas D'Arcy et al. (in press) employed an auditory comprehension task. The different tasks will have almost certainly engaged somewhat distinct cognitive mechanisms. As D'Arcy et al. (in press) point out, the left inferior frontal gyrus activation is indicative of the involvement of sub-vocal articulatory mechanisms involved in maintaining speech input in verbal working memory. Such

rehearsal of the auditory prime in Kujala et al. (2003) may not have been engaged to the extent that it was in the sentential context, and perhaps was obscured by the emphasis on phonological analysis required to judge the phonological similarity of the prime and target. It is probable that the PMN is modulated by working memory influences and/or by the type of phonological processing required.

1.6. THESIS OBJECTIVES

The literature reviewed above suggests that two functionally distinct ERP components monitor the time-course of spoken word processing: the PMN and an N400 or N400-like component. In their paper, Spoken Word Access Processes, McQueen and Cutler (2001) emphasize the need for a measure of pre-lexical processing in order to resolve disagreement surrounding the direction of information flow in spoken word recognition. They argue that measures such as phoneme monitoring and phoneme categorization involve phoneme decisions that can be explained by both feedback (as in TRACE) and feedforward (as in MERGE, Cohort, and Shortlist) models of word recognition. However, they suggest that identification of a measure that operates solely at the perceptual level would allow for the demonstration of whether or not lexical knowledge influences pre-lexical processes via direct feedback.

The findings of Connolly and Phillips (1994) and Connolly et al. (1990, 1992, 2001) lead to the intriguing possibility that the PMN is such a measure. However, before the PMN can be used to explicitly test theories of spoken word processing, a number of important issues pertaining to its function must be addressed. First, it is not clear whether the PMN is sensitive to phonological similarity, or whether a mismatch in one phoneme is sufficient to augment the response. The first experiment in this thesis addresses this issue by manipulating the degree of phonological overlap between responses. Second, while the PMN to words/nonwords have been compared in parallel ERP (Connolly et al., 2001) and MEG (Kujala et al., 2003) studies, the small amplitude of the response in the ERP study, and apparent peak latency differences between words and nonwords in the

MEG study, warrant further investigation of lexicality effects on the PMN. Accordingly, experiment 2 directly compares PMN responses to words and nonwords. A third issue, yet to be explicitly investigated, is whether the PMN is sensitive to phonemic deviations occurring at various positions in a word/nonword. Previous investigations of the PMN have focused on the consequences of a word/nonword initial phoneme mismatch. Some of the most influential studies in the psycholinguistic literature involve varying the position of phonemic mismatch occurring in words/nonwords (e.g., Connine, Blasko, & Titone, 1993; Frauenfelder, Scholten, & Content, 2001). Such studies have been important for defining competition effects in lexical selection (Frauenfelder, Scholten, & Content, 2001) as well as defining the importance of word onset in activating (or deactivating) lexical representations (Connine, Blasko & Titone, 1993). If the PMN is to contribute to an understanding of these processes, then it must analyze speech input in a continuous fashion, so as to be sensitive to mismatches occurring in positions other than the initial. To this end, experiment 3 manipulates the position of phoneme mismatch in order to determine whether the PMN tracks speech input in a continuous fashion.

In summary, the motivation behind the three experiments presented in this thesis is to clarify functional interpretations of the PMN.

CHAPTER 2: THE INFLUENCE OF PHONOLOGICAL SIMILARITY ON THE PMN

2.1. SUMMARY

Event-related brain potentials (ERPs) were recorded to investigate phonological processing independently from lexical/semantic influences during a task requiring metalinguistic analysis of speech stimuli. Participants were instructed to omit the initial phoneme from a word (e.g., *clap without the /k/*) after which they heard a correct (e.g., *lap*) or incorrect (e.g., *cap, ap, nose*) answer. The PMN (peaking at 270 ms) was largest to incorrect items and did not differentiate between items that shared the same rime and items that were phonologically unrelated to the correct choice. Further, the PMN did not differ between word (e.g., *cap*) and non-word (e.g., *ap*) choices. The P300 was largest to correct items but was also seen to choices that rhymed with the correct answer. An N400-like response differentiated incorrect choices that were phonologically dissimilar from phonologically similar items, suggesting its involvement in on-going phonological processes. Based on these findings, it was hypothesized that the PMN reflects the process of mapping speech input against a phonological template formed by the linguistic context.

2.2. INTRODUCTION

In their experiment, Connolly et al. (2001) speculated as to whether the amplitude of the PMN represented a phonological matching process, in which the phonological form of the auditory target is compared with a phonological template formed by the visual prime sequence. They reasoned that a high degree of match between the auditory target and phonological template would require less phonological work resulting in a small PMN, whereas auditory targets that mismatched the template would require more extensive phonological analysis leading to the occurrence of a large PMN. Their findings lead to two possible hypotheses regarding the characteristics of this matching process. One possibility is that all phonetic features or individual phonemes of the heard target are compared with the template to assess their degree of phonological match. In this case, gradations in the PMN should occur with corresponding gradations in the degree of match between the auditory target and phonological template. In other words, in the paradigm employed by Connolly et al (2001), the PMN should be smaller on mismatching trials that share the same rime but not the same onset as the visual prime (e.g., *hat, c: bat*), than on mismatching trials that share no phonological relation with the visual prime (e.g., *hat, c: mop*). Consequently, the more mismatching features that are encountered during this matching process, the larger the PMN. Another interpretation is that the matching process is terminated once a mismatch between the heard target and template is encountered. In this case, no gradations in the amplitude of the PMN would be anticipated since the matching process would be terminated as soon as a mismatch is encountered. Thus, the same amount of phonological work, indexed by an equivalent electrophysiological

response, would be generated whether the prime and target shared the same rime or not. However, trials in which the mismatching auditory stimulus rhymed (e.g., *hat, c: bat*) with the prime were not included in that study, leaving the effects of phonological relatedness untested.

The present study was designed to specifically test whether the PMN reflects overall phonological relatedness or an all-or-none process in which the matching process is aborted once a mismatch occurs. A phoneme deletion task requiring participants to segment an auditory prime into its constituent phonemes, rather than to simply discriminate between rime units, was employed. Participants heard a set of instructions asking them to delete the initial sound of a word (e.g., *clap without the /k/ sound*) and to anticipate the resultant word segment. After the instruction stimulus, participants heard a response that did (e.g., *lap*) or did not (e.g., *ap*) conform to the phonological template they had formed. Incorrect answers varied in the degree to which they matched the correct answer. In the Wrong Consonant (WC) deleted condition, the incorrect response was a word that shared the same rime as the correct response, but began with a different onset (e.g., *cap*). In the Irrelevant Word (IW) condition the incorrect answer began with a different onset and also had a different rime than the anticipated segment (e.g., *nose*). In the Consonant Cluster (CC) deleted condition, both consonants were deleted and only the rime remained (e.g., *ap*) making it the most phonologically similar to the anticipated answer. If the PMN is a marker for phonological relatedness, then gradations in the response were anticipated such that the largest PMN would be elicited in the IW condition, followed by the WC and CC conditions. However, if the PMN represents an

all-or-none process, then the PMN should be equivalent in the WC, CC, and IW conditions, since they all differ from the anticipated segment at the initial phoneme. The P300, a response associated with extended stimulus processing and memory retrieval functions (Polich & Kok, 1995), was hypothesized to occur to correct answers, indicating a match between the heard response and the phonological template.

2.3. MATERIALS AND METHODS

Participants

Twenty right-handed English-speaking subjects (M = 22.5 yrs [SD = 7.4; Range = 18-35], 15 females) participated in this study. All participants reported normal hearing and were screened with a self-report health questionnaire for a history of neurological, audiological and/or psychological problems. Participants were screened for reading ability and phonemic awareness using the Word Attack and Word Identification subtests of the Woodcock Diagnostic Reading Battery (Woodcock, 1998), and the Rosner Auditory Discrimination test (Rosner & Simon, 1971). All participants achieved average to above average scores on these measures, and thus none were excluded from the subsequent analysis. All participants provided informed consent, and the responsible ethics board approved the study.

Stimuli and Procedures

160 English monosyllabic words, all beginning with a consonant cluster (e.g., *clap*), were presented to participants in trials consisting of spoken instructions asking them to delete the initial consonant (C) of a target word (e.g., *clap without the /k/ sound*). Following an interstimulus interval (ISI) of 2 seconds, participants heard a correct (C) (e.g., *lap*) or incorrect (e.g., *cap*) answer. Incorrect answers fell into one of three categories: 1) wrong consonant (WC) deleted (e.g., *cap*); 2) consonant cluster (CC) deleted (e.g., *ap*); or 3) irrelevant word (IW) (e.g., *nose*). All answers in the C, IW, and WC conditions were Consonant-Vowel-Consonant (CVC) or CVCC words while answers in the CC condition were VC or VCC non-words. See Appendix A for a list of stimuli

used in this experiment. Participants were instructed to determine the resulting segment once the initial consonant had been removed. They were given a two-button response pad and instructed to press the right button to segments that matched their expectations and the left button for those that did not. Participants were encouraged to response as quickly and accurately as possible. For the 160 target words, there were 160 possible answers divided evenly into 4 categories (i.e., 40 C + 40 WC + 40 CC + 40 IW). All stimuli were spoken by a female voice, recorded with the NeuroStim Sound (NeuroScan Inc.) program digitized at 20, 000 Hz and presented binaurally through headphones at 90 dB.

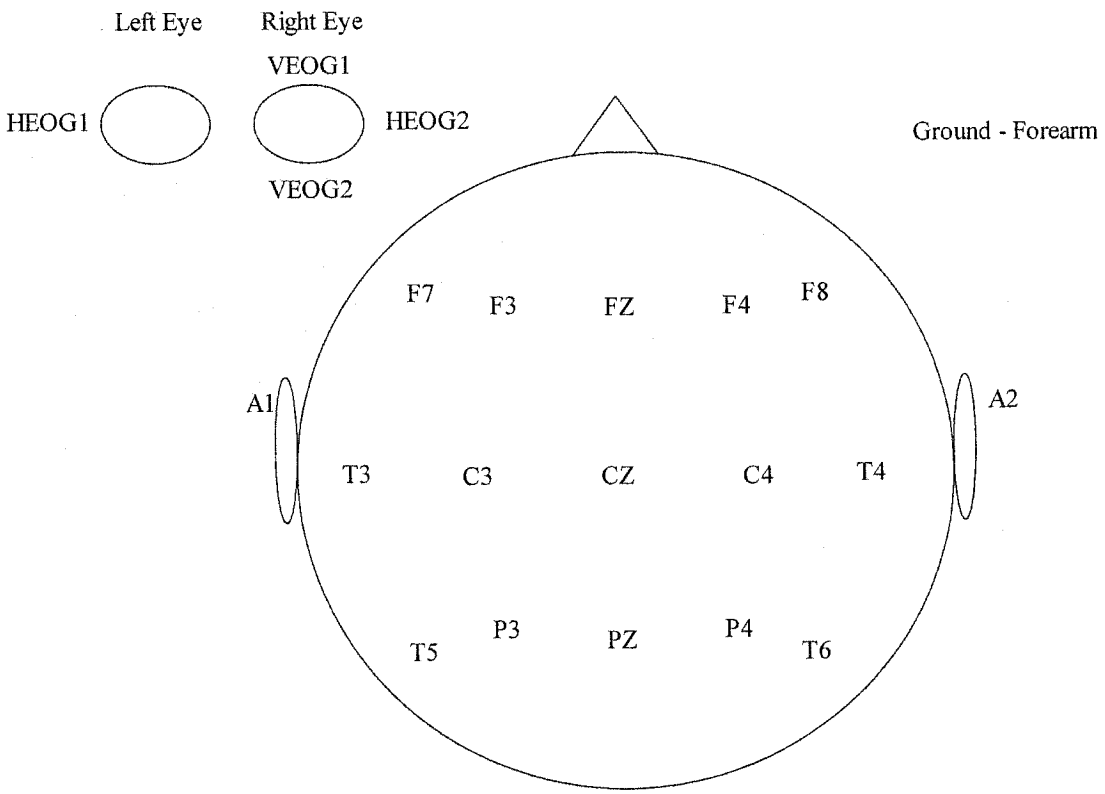
Electrophysiological Recording

EEG activity was recorded at 15 sites (Fz, F3, F4, F7, F8, Cz, C3, C4, Pz, P3, P4, T3, T4, T5, T6) using Ag/AgCl electrodes embedded in an Electro-Cap and referenced to linked ears according to the international 10-20 system (Jasper, 1958). The electrooculogram (EOG) was recorded with electrodes placed above and below the right eye (vertical), and on the outer canthus of each eye (horizontal), and an electrode placed on the forearm served as ground. See Figure 1 for an illustration of EEG and EOG electrode positions. Impedance was kept at or below 5 kΩ. EEG was amplified by a Grass amplifier and acquired with NeuroScan software (version 3.0). Stimuli and trigger codes were delivered by NeuroScan's Stim program (version 3.0) and data processing was performed using NeuroScan's Edit program (version 3.0). EEG was collected with a bandpass of .1 to 100 Hz and sampled at 500 Hz from 100 ms before stimulus presentation to 1000 ms post stimulus. Data were digitally filtered offline with a low pass filter setting of 20 Hz. Trials contaminated with EOG activity greater than +/- 75

microvolts (μV) were rejected from the analysis. EEG data on trials that participants responded to correctly were averaged separately across the four conditions. Fourteen percent of trials were rejected from further analyses due to artifacts and/or behavioral errors.

Figure 1

The diagram below illustrates the approximate positions of the 15 channels of EEG activity that were recorded in experiment 1. These positions are based on the international 10-20 system (Jasper, 1958). The positions of the horizontal electrooculogram (HEOG) and vertical electrooculogram (VEOG) are illustrated in the top left hand corner of the figure. A1 and A2 refer to the linked ear reference.



Data Analysis

In order to analyze these data, two scoring methodologies were implemented: The interval and the peak scoring methods. In the interval scoring procedure, the amplitude of each component was determined by averaging the amplitude within a defined latency window. The peak amplitude was determined by scoring the most negative or positive peak from baseline within a defined latency range. Finally, the peak latency was scored as the time from stimulus onset to the point scored as the most negative or positive peak amplitude within a defined latency interval. The N100 was scored between 90 ms - 170 ms, the P200 between 170 ms - 230 ms, the PMN between 230 ms - 300 ms, the P300 between 300 ms - 400 ms, and theN400-like response between 400 - 500 ms. Tables denoting the mean amplitude and peak latency of the N100, P200, PMN, P300 and N400 as a function of condition are presented in the results section. However, as the PMN is the focus of this thesis, only information that clarifies the scalp topography of the PMN will be presented in tables.

Repeated measures analysis of variance (ANOVA) using conservative degrees of freedom (Greenhouse & Geisser, 1959) was performed for the average amplitude, peak amplitude and latency of each component. Each ANOVA consisted of two factors, Condition (C, WC, CC, IW) and Site (15 levels). Post-hoc comparisons were conducted using the Tukey HSD test, with $p < .05$ as the required level of significance. The peak amplitude analysis is only reported if it contributes new information not provided by the interval scoring method.

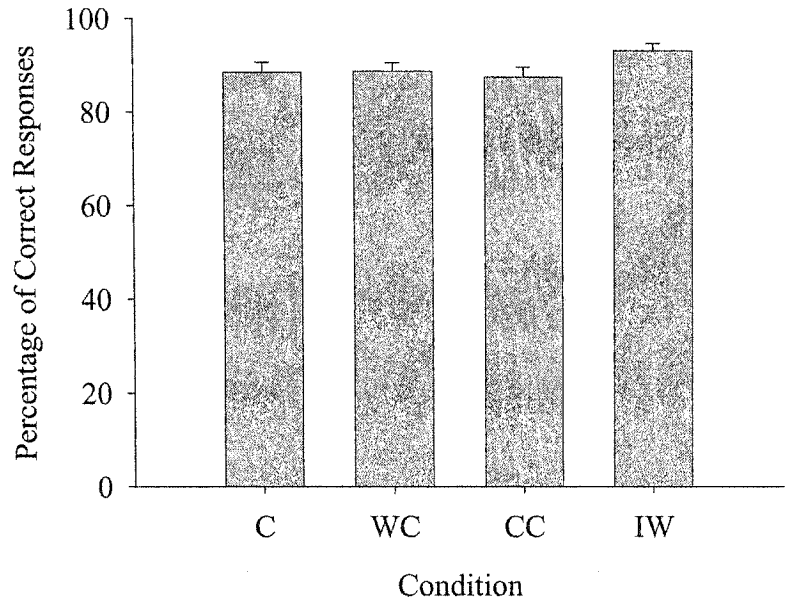
2.4. RESULTS

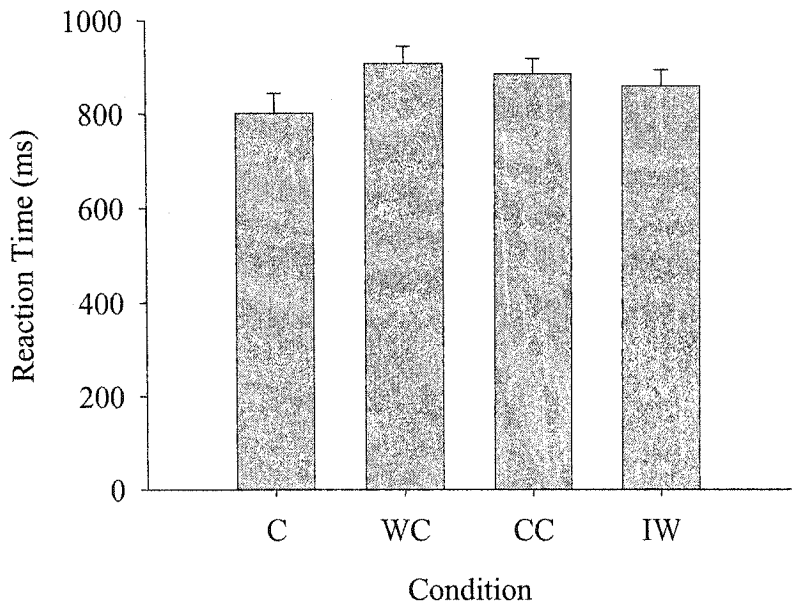
Behavioral Accuracy

Behavioral accuracies and response times were available for 16 out of 20 participants (Figure 2). Data from 4 participants were unavailable due to technical problems. Accuracy and RT data were analyzed with a repeated measures ANOVA and post hoc analyses were conducted with the Tukey HSD test ($p < .05$). The main effect of Accuracy was significant ($F(3,45) = 5.69$, $p < .01$, $\varepsilon = 0.27$), and resulted from higher accuracies associated with the IW (93%) condition, compared to each of the other 3 conditions (C = 88.5%, WC = 89.0%, CC = 87.5%). None of the other mean comparisons were significant. For the analysis of RT data, the main effect of condition ($F(3,45) = 4.51$, $p < .01$, $\varepsilon = 0.22$) was also significant. Post hoc tests showed that RTs in the C (801 ms) condition were faster than those recorded in the CC (886 ms) and WC (908 ms) conditions. Reaction times in the IW (859ms) condition did not differ significantly from any of the conditions.

Figure 2

Accuracy (top) and Reaction Time data (bottom) for the Correct (C), Wrong Consonant (WC) deleted, Consonant Cluster (CC) deleted and Irrelevant Word (IW), conditions.





Electrophysiological Findings

Figure 3 displays the grand average waveforms for correct and incorrect responses across 15 electrode locations, while Figure 4 displays the grand average waveforms at Cz. The waveforms for all 4 conditions include the N100 and P200 components. An anterior negativity peaking at approximately 270 ms, the PMN, differentiates incorrect conditions from the correct condition. A central-parietal positivity, the P300, appears largest in the correct condition, but is also apparent in the consonant cluster (CC) deleted condition. Finally, an N400-like response differentiates the IW condition from all other conditions, particularly over central and parietal sites. An important feature of the grand average waveforms is that the PMN response in the incorrect conditions does not appear to differ.

Figure 3 - Caption

Grand Average waveforms [N=20] recorded across the four experimental conditions: Correct (---), Wrong Consonant (WC) deleted (···), Consonant Cluster (CC) deleted (-··-), and Irrelevant Word (IW) (—) for all 15 scalp sites. The PMN (†) was largest and statistically equivalent in the three incorrect conditions, and the P300 (*) was largest in the Correct condition. An N400-like response (‡) differentiates the IW from all other conditions at parietal sites. Time in milliseconds (ms) is on the x-axis, and amplitude in microvolts (μV) is on the y-axis. Negative is plotted up.

Figure 3

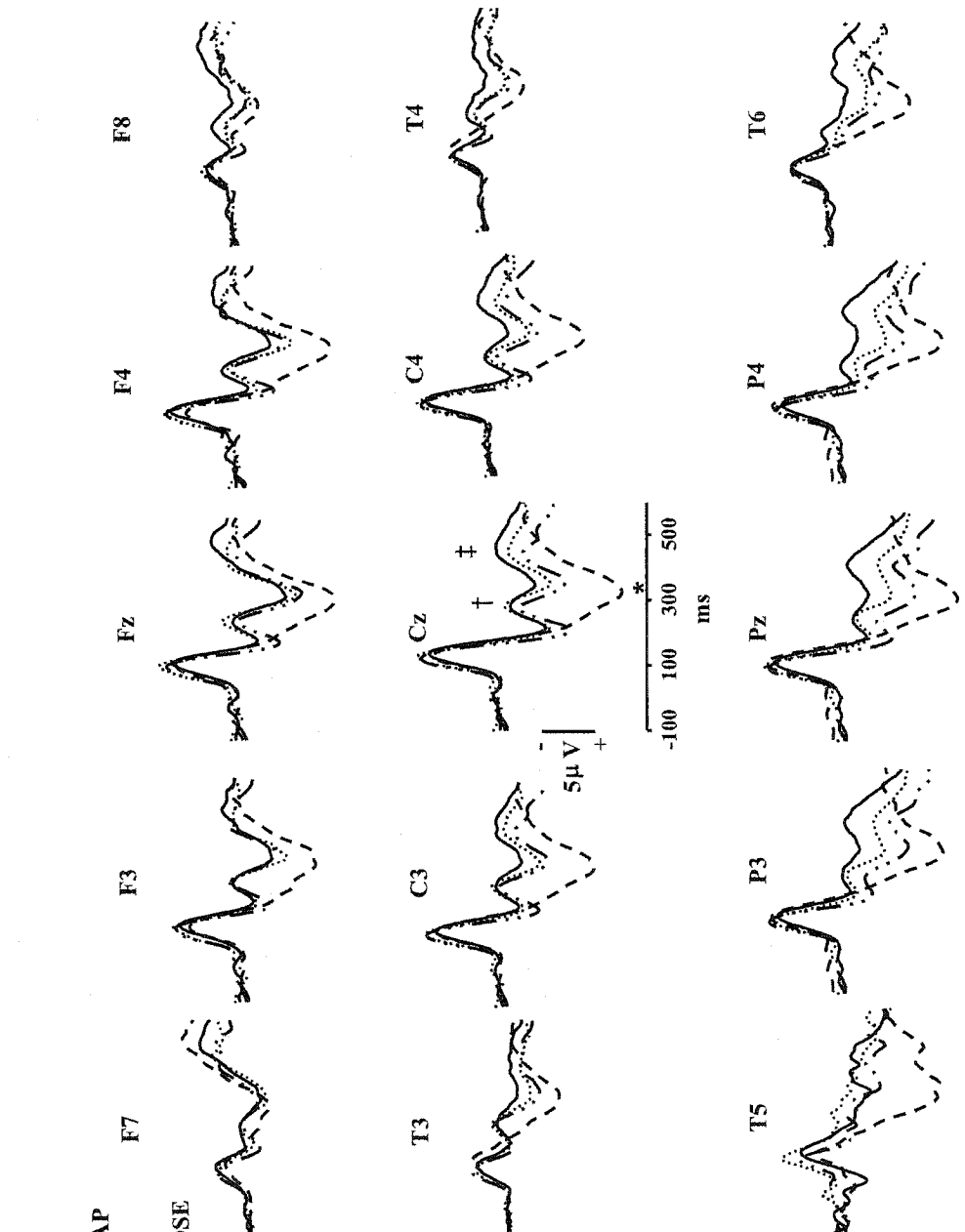
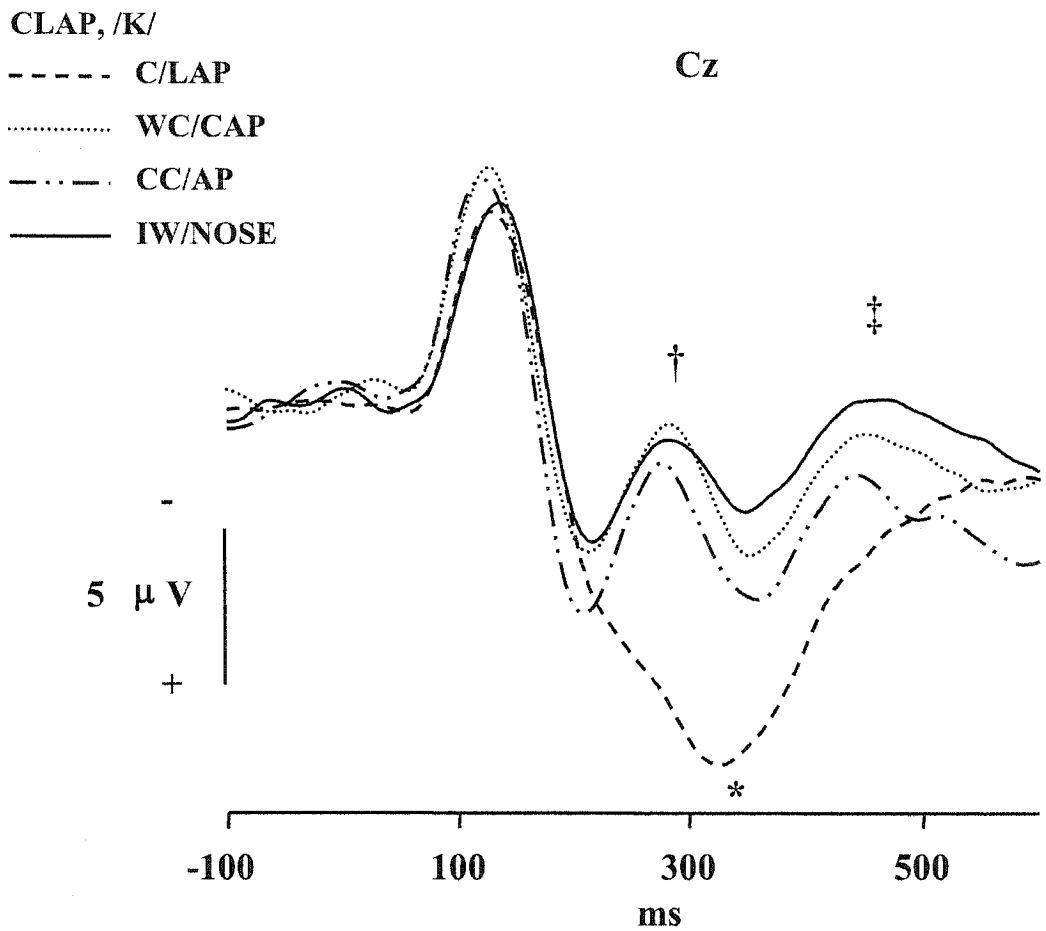

CLAP, /K/
C/LAP
WC/CAP
CC/AP
IW/NOSE
F7
F3
Fz
F4
F8
T3
C3
Cz
C4
T4
T5
P3
Pz
P4
T6
5μV
-100
100
300
500
ms

Figure 4

Enlarged Cz presented in Figure 3. All details as in Figure 3.



N100 and P200

The peak amplitude of the N100 did not vary significantly across conditions (p = .09; Table 1); however the main effect of Site was significant ($F(14, 266) = 17.1$, p <.001, $\varepsilon = 0.47$). The N100 was distributed over midline sites, being strongest at Cz, as well as over lateral central (C3/C4) and parietal sites (P3/P4). The peak latency of the N100 was sensitive to experimental conditions ($F(3,57) = 7.60$, $p < .001$, $\varepsilon = 0.29$), the response peaking earlier in the WC (128 ms) and CC (127 ms) conditions, than in the C (136 ms) and IW (137 ms) conditions (Table 1). N100 latency also varied significantly across sites ($F(14,266) = 3.80$, $p < .01$, $\varepsilon = 0.18$), the response peaking earliest at fronto-central sites.

P200 amplitude was modulated by Condition ($F(3,57) = 5.41$, $p < .01$, $\varepsilon = 0.22$) and Site ($F(14,266) = 10.79$, $p < .001$, $\varepsilon = 0.36$). P200 amplitudes were larger in the CC (1.89 μV) condition, compared to the IW (-0.096 μV) condition (Table 2). Amplitudes in the C (0.37 μV) and WC (0.49 μV) did not differ significantly from each other or from those in the CC and IW conditions. P200 was largest over midline sites, being most prominent at Cz followed by Pz. P200 latency varied across conditions, ($F(3,57) = 7.43$, p < .01, $\varepsilon = 0.28$), the response peaking earlier in the WC (201 ms), CC (199 ms) and IW (202 ms) conditions compared to the C (207 ms) condition (Table 2). P200 latency varied significantly across sites ($F(14,266) = 4.05$, $p < .001$, $\varepsilon = 0.18$); the response peaking earliest at lateral frontal sites (F7/F8).

Table 1

Mean Amplitude (μV) and Peak Latency (ms) of the N100 for the Correct (C), Wrong Consonant Deleted (WC), Consonant Cluster Deleted (CC), and Irrelevant Word (IW) conditions collapsed across the Site factor. Standard Error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	-3.41 (0.45)	136 (3.02)
WC	-4.47 (0.59)	128 (2.16)
CC	-4.12 (0.66)	127 (2.13)
IW	-3.82 (0.46)	137 (2.15)

Table 2

Mean Amplitude (μV) and Peak Latency (ms) of the P200 for the Correct (C), Wrong Consonant Deleted (WC), Consonant Cluster Deleted (CC), and Irrelevant Word (IW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	0.37 (0.76)	207 (4.90)
WC	0.49 (0.57)	201 (4.30)
CC	1.89 (0.65)	199 (4.22)
IW	-0.096 (0.61)	203 (4.38)

PMN

The ANOVA conducted on the PMN amplitude data revealed a significant effect of Condition ($F(3, 57) = 22.52, p < .001, \varepsilon = 0.54$). Post hoc analysis showed that PMN amplitudes in the Incorrect conditions (WC = 0.26 μV, CC = 1.21 μV, IW = 0.027 μV), while not significantly differing from each other, were more negative than amplitudes in the C condition (5.18 μV) (Table 3). Note that the positive amplitudes recorded for the PMN amplitude, reflect the fact the interval encompassing the PMN (230-330) is below baseline (i.e., in the positive region). A main effect of Site, ($F(14, 266) = 10.27, p < .001, \varepsilon = 0.35$) was attributable to a bilateral fronto-temporal distribution. The scalp distribution of the PMN was modulated by the Condition factor ($F(42,798) = 5.37, p < .001, \varepsilon = 0.22$). Post hoc comparisons revealed that in the IW condition, the PMN was larger over right frontal sites than over Fz; while in the CC and WC conditions, the PMN was equally distributed across left and right frontal and temporal sites. The scalp distribution maps (Figure 5) clearly show the fronto-temporal predominance of the PMN in the WC, CC and IW conditions during time points that correspond to the peak amplitude of the PMN (275 ms). The latency of the PMN did not vary across incorrect conditions, all peaks occurring at approximately 268 ms (Table 3).

Table 3

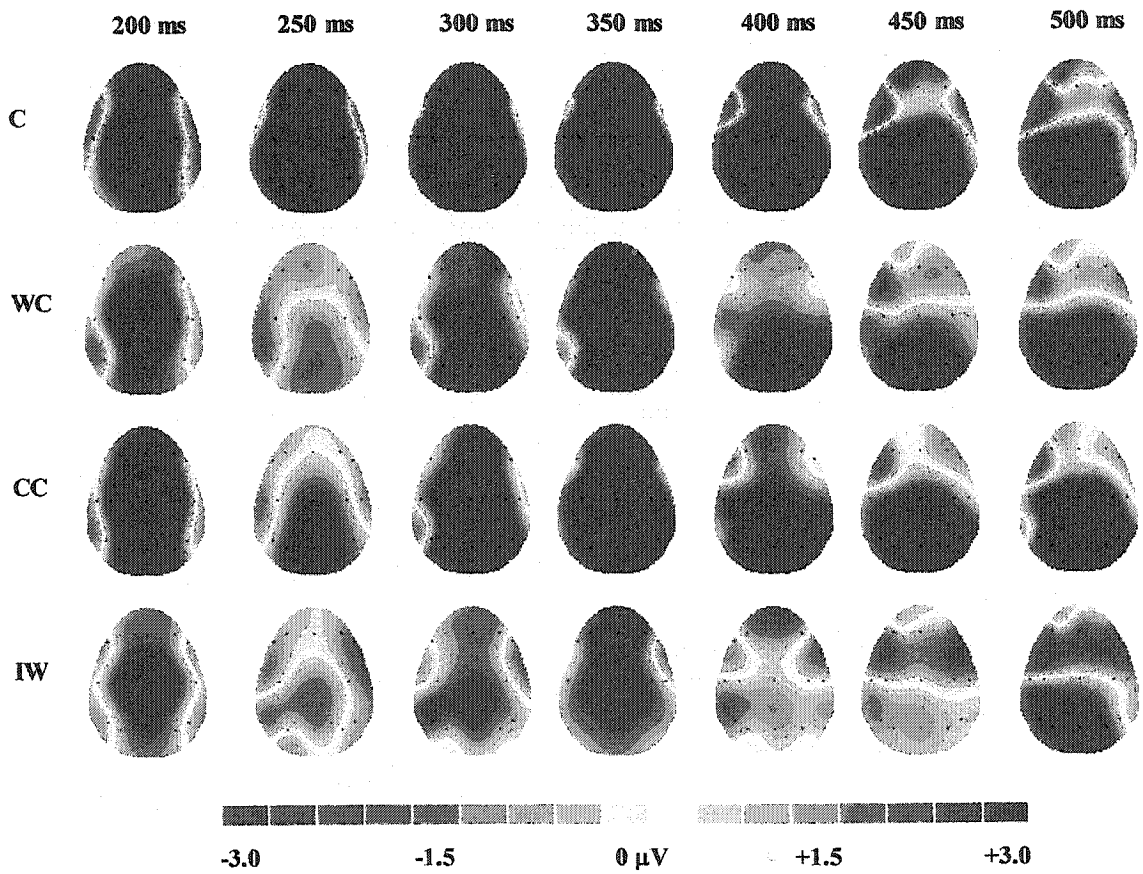
Mean Amplitude (μV) and Peak Latency (ms) of the PMN in the Correct (C), Wrong Consonant Deleted (WC), Consonant Cluster Deleted (CC), and Irrelevant Word (IW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	5.18 (0.92)	242 (2.80)
WC	0.26 (0.72)	268 (2.27)
CC	1.21 (0.92)	267 (3.51)
IW	0.027 (0.72)	269 (3.45)

Figure 5 - Caption

Scalp distribution maps based on the grand average waveforms (N=20) from 200 ms to 500 ms across the four experimental conditions. The distribution of the PMN is highlighted by the negative (blue) focus over anterior regions, particularly at 275 ms. The posterior distribution of the P300 (red) is particularly evident in the C and CC conditions at 300 and 350 ms. Activation of the N400 is most apparent from 400 ms to 500 ms over anterior regions. Increased activation corresponding to the N400 is especially evident in the IW condition.

Figure 5


200 ms
250 ms
300 ms
350 ms
400 ms
450 ms
500 ms
C
WC
CC
IW
-3.0
-1.5
0 μV
+1.5
+3.0

P300

The ANOVA for P300 amplitude (i.e., most positive peak between 300-400 ms) revealed a significant Condition main effect ($F(3, 57) = 23.63$, $p < .001$, $\varepsilon = 0.55$). This effect was attributable to larger P300 amplitudes seen in the Correct (7.59 μV) than in each of the three Incorrect conditions (Table 4). The P300 in the CC (3.75 μV) condition was larger than that observed in the IW (1.48 μV) condition, but was not significantly different from the WC (2.83 μV) condition. The IW and WC condition did not differ significantly. The Site main effect ($F(14, 266) = 12.23$, $p < .001$, $\varepsilon = 0.39$) reflected the general centro-parietal distribution of the P300. The Condition x Site interaction was significant ($F(42, 798) = 6.08$, $p < .001$, $\varepsilon = 0.24$), reflecting the centro-parietal distribution of the P300 condition in the C and in the CC condition. The P300 in the C condition was larger than the P300 in the CC condition over posterior regions. The scalp distribution maps (Figure 5) highlight the posterior distribution of the P300, particularly during the time point corresponding to the peak latency of the P300 in the C and CC conditions (~350 ms).

The ANOVA for P300 peak latency revealed a main effect of Site ($F(14, 266) = 2.32$, $p < .05$, $\varepsilon = 0.11$), associated with the P300 peaking earlier at Cz, Pz, and at lateral parietal sites (P3/P4). Peak latencies were not modulated by Condition (C = 334 ms, WC = 346 ms, CC = 344 ms, IW = 344 ms).

Table 4

Mean Amplitude (μV) and Peak Latency (ms) of the P300 in the Correct (C), Wrong Consonant Deleted (WC), Consonant Cluster Deleted (CC), and Irrelevant Word (IW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	7.59 (0.94)	334 (4.68)
WC	2.83 (0.79)	346 (4.81)
CC	3.75 (0.86)	344 (5.56)
IW	1.48 (0.56)	344 (4.20)

Influence of the P300 on the PMN

The temporal proximity of the PMN and P300 makes it difficult to interpret the conditional and topographical effects observed in this experiment. Specifically, the amplitude of the PMN may have been influenced by the P300, particularly in the CC condition where the onset of the P300 appears to overlap with the PMN (see Figure 3 and Figure 5). Equally, it could be argued that the PMN may be overridden in the C condition by the early onset of the P300. To determine whether the PMN was influenced by the P300 the average integrated amplitude for the 250-300 ms and 325-375 ms latency windows were calculated, and included as levels of Time in a three-way ANOVA that included Condition (as above) and Site (as above) as the other two factors. The intervals were chosen so as to fall approximately 25 ms on either side of the PMN and P300 peak as determined by the analysis of peak latency (i.e., 268 ms for the PMN, and 345 ms for the P300).

Several of the main effects and interactions were significant; however, the effects are best interpreted by post-hoc analysis of the significant three-way interaction between Time x Condition x Site, ($F(42, 798) = 3.96, p < .01, \varepsilon = 0.17$). Post hoc two-way ANOVAs (Condition x Site) were performed for each level of the Time Factor (250-300 ms and 325-375 ms) in order to simplify the three-way interaction. In both cases the Condition x Site interaction was significant, (250-300 ms, $F(42, 798) = 5.82, p < .001, \varepsilon = 0.24$; 325-375 ms, $F(42, 798) = 5.50, p < .001, \varepsilon = 0.23$) and Tukey HSD tests were performed to further investigate the effects of Condition x Site as a function of Time. These analyses demonstrated that the negativity in the WC, CC and IW conditions was

distributed over fronto-temporal sites during the 250-300 ms interval (Table 5). Differences between these three conditions occurred only at parietal sites, where amplitudes were larger (more positive) in the CC condition compared to the IW condition. This finding is consistent with the early onset of the P300 in the CC condition (Figure 5). Importantly, no significant differences were found between the amplitudes of the WC, CC and IW conditions at fronto-temporal sites, providing further evidence of the independence of the PMN from the P300. Amplitudes within the 325-375 ms interval were largest in the C condition and showed a centro-parietal distribution (Table 5). Amplitudes in the CC condition were larger than those observed in the IW condition, and again showed the characteristic centro-parietal distribution of the P300.

The results of the 3-way interaction are consistent with those determined in the average amplitude analyses reported above. To the extent that the PMN (i.e., the 250-300 ms interval) shows a scalp distribution distinct from the P300 (i.e., the 325-375 ms interval), the PMN appears to have not been influenced by the P300 in the CC condition. As further support for this claim, the distribution of negative activation corresponding to the onset and peak of the PMN is indistinguishable across the three incorrect conditions (Figure 5). The P300 does not appear to have affected the amplitude of the PMN in the CC condition. However, it is difficult to determine whether the PMN was influenced by the P300 in the C condition. Statistical analysis would suggest that no PMN was observed in the C condition. However, inspection of Figure 5 reveals clear PMN-like activation at temporal sites (bilaterally) in the C condition that is similar to that observed in the Incorrect conditions. Furthermore, clear PMN responses are evident in the individual

waveforms of some participants (Figure 6).

Table 5

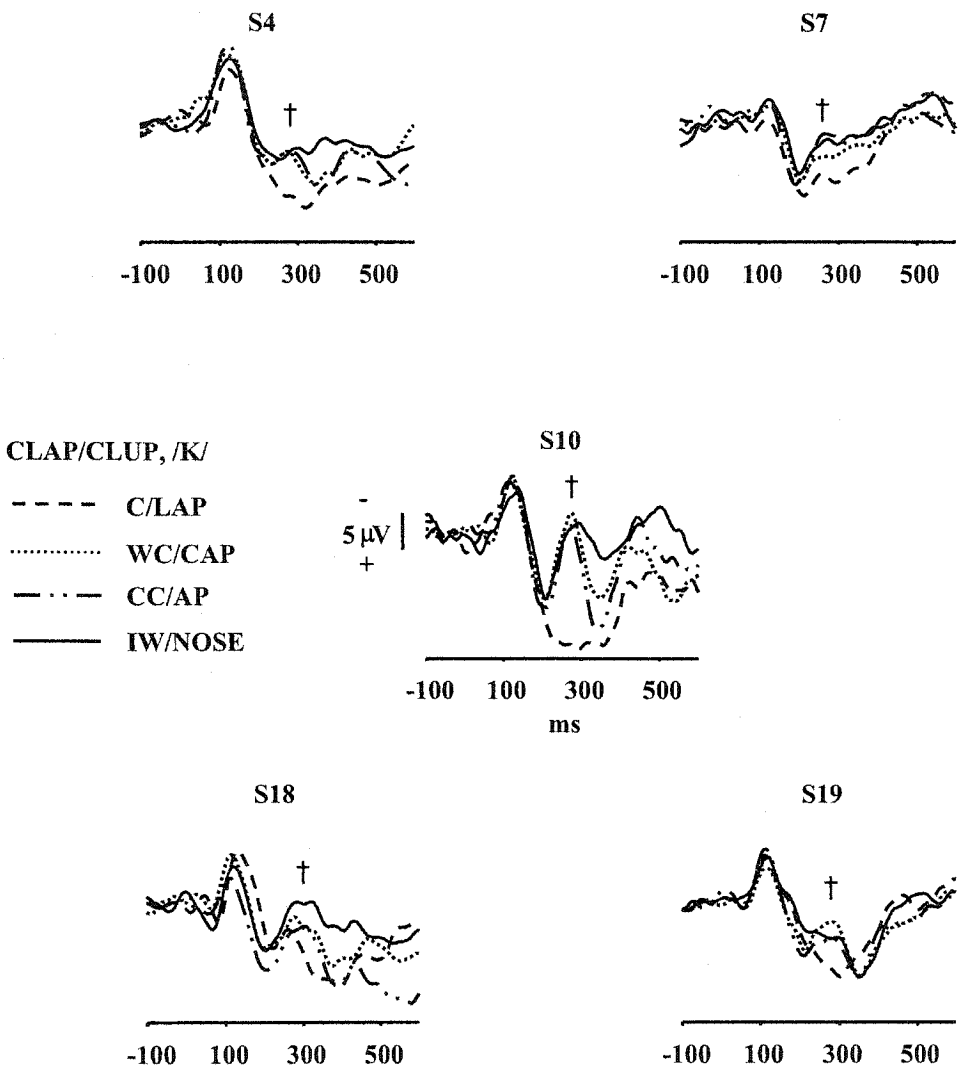
Mean Amplitude (μV) for the 250-300 and 325-375 Intervals for the Condition x Site interaction (midlines only are shown). Standard Error is presented in parentheses.

Condition	Site	250-300	325-375
C	**Fz**	5.91 (1.58)	7.82 (1.55)
	Cz	10.85 (1.45)	12.02 (1.47)
	Pz	10.05 (1.14)	12.68 (1.20)
WC	**Fz**	-0.69 (1.10)	4.42 (1.20)
	Cz	1.23 (1.03)	4.88 (1.13)
	Pz	1.79 (0.88)	4.93 (0.94)
CC	**Fz**	0.60 (1.54)	5.04 (1.09)
	Cz	2.67 (1.30)	6.53 (1.41)
	Pz	4.19 (1.14)	7.46 (1.30)
IW	**Fz**	-0.01 (1.37)	3.78 (0.99)
	Cz	1.58 (1.00)	3.44 (0.90)
	Pz	1.38 (0.72)	2.61 (0.55)

Figure 6 - Caption

Individual waveforms of 5 participants presented at Cz. Note that participants S7, S18 show a distinct PMN (†) in all conditions. Time (ms) is on the x-axis and amplitude (μV) is on the y-axis. Negative is up.

Figure 6


S4
S7
-100 100 300 500
-100 100 300 500
CLAP/CLUP, /K/
C/LAP
WC/CAP
CC/AP
IW/NOSE
S10
5 μV
-100 100 300 500
ms
S18
S19
-100 100 300 500
-100 100 300 500

N400-like Response (referred to as N400 below)

The ANOVA for the amplitude of the N400 revealed a significant Condition main effect ($F(3, 57) = 9.45, p < .001, \varepsilon = 0.33$). This effect was attributable to the larger (more negative) N400 recorded in the IW (0.056 μV) and WC (1.50 μV) conditions, which did not differ significantly from each other. While the amplitude of the N400 in the IW condition differed significantly from that recorded in the C (3.65 μV) and CC (2.30 μV) conditions, the amplitude of the N400 recorded in the WC condition did not differ significantly from either the C or the CC condition (Table 6). The Site main effect ($F(14, 266) = 11.35, p < .001, \varepsilon = 0.37$) reflected the larger N400 amplitudes recorded over frontal locations across the four experimental conditions. However, the scalp distribution of the N400 is best interpreted by the significant Condition x Site interaction ($F(42,798) = 4.24, p < .01, \varepsilon = 0.18$). Further analysis indicated that the N400 in the IW condition was differentiated from the other three conditions at parietal sites. No significant difference was obtained between the WC and IW condition at central locations.

The ANOVA for the N400 peak latency revealed a main effect of Condition ($F(3, 57) = 7.94, p < .001, \varepsilon = 0.29$), which was associated with the N400 peaking later in the C condition compared to each of the Incorrect conditions. There were no differences in the peak latency of the N400 amongst the Incorrect conditions (Table 6). The main effect of Site was also significant ($F(14, 266) = 5.18, p < .001, \varepsilon = .21$), with the response peaking later over frontal and central locations. This finding likely reflects the general anterior distribution of the component across the four experimental conditions. The interaction of Condition x Site was not significant ($p = .08$).

Table 6

Mean Amplitude (μV) and Peak Latency (ms) of the N400 in the Correct (C), Wrong Consonant Deleted (WC), Consonant Cluster Deleted (CC), and Irrelevant Word (IW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	3.65 (0.82)	468 (2.06)
WC	1.50 (0.85)	457 (4.60)
CC	2.30 (0.80)	455 (5.01)
IW	0.056 (0.55)	459 (4.87)

2.5. DISCUSSION

The results of this experiment demonstrated that the PMN is sensitive to the phonological processing required in the phoneme deletion task used here. Participants were required to delete the initial phoneme from a target word (e.g., *clap*) and then judge whether the subsequently presented test item was the correct (e.g., *lap*) or an incorrect (e.g., *ap*) answer. More specifically, the elicitation of the PMN in this classic task requires phoneme awareness and associated phonological processing (Rosner & Simon, 1971) but no explicit semantic processing. In confirmation of previous findings (Connolly, Byrne, & Dywan, 1995; Connolly et al., 2001; Hagoort & Brown, 2000; van den Brink et al., 2001), the PMN was significantly larger to targets violating expectations. Furthermore, the response characteristics of the PMN were visibly and statistically indistinguishable across incorrect answers. If the phonological priming by top-down information were dependent on phonological relatedness, then one would have anticipated gradations in the PMN across incorrect conditions. In other words, smaller amplitudes should have been observed in those conditions that shared more phonemes or phonetic features in common with the prime (WC and CC), compared to those whose phonological structure was completely unrelated (IW).

These results suggest that the expected answer helps a phonological stage of word recognition so long as the incoming acoustic information matches that of the template based on the prime. A mismatch, in this case at the initial phoneme, appears to terminate the matching process involving that particular template and augments the PMN. However, it has been suggested that the PMN is invoked in the course of phonological

processing generally, as required by a matching process between phonemes and acoustic cues, and not simply in response to violations of phonological expectancy (Connolly & Phillips, 1994; Connolly et al., 1992; Connolly et al., 2001; van den Brink et al., 2001; Hagoort & Brown, 2000). The early onset of the P300 in the correct condition makes it difficult to interpret the presence or absence of the PMN in the correct condition. However, as has been reported in the studies cited above, the apparent negative activation over bilateral fronto-temporal regions in the correct condition is suggestive of PMN activity seen in the Incorrect conditions. Together, these results are not incompatible with the suggestion that the PMN reflects a compulsory stage of word (nonword) recognition, but is nonetheless influenced by top-down phonological expectations.

The latency of the N100 and the amplitude and latency of the P200 varied across conditions. However, there is no pattern to the conditional variations observed. While the N100 peaked earlier in the WC and CC conditions, the P200 peaked earlier in the C condition and was larger in the CC compared to the IW condition. These differences are likely due to variations in the acoustic properties (voice onset time, nasality) of the speech signal, which were not controlled for in this experiment. For instance, the initial phoneme in the correct condition was invariably unvoiced as it was preceded by a voiced consonant, whereas the initial phoneme in the CC condition was always voiced. Future studies employing controlled manipulations of such acoustic properties may reveal some interesting effects with regard to early attentional/sensory processes as reflected by the N100 and P200 responses.

In the present study, the P300 in the Correct condition (e.g., *lap*) reflected a

recognition memory function comparing the presented test item with the subject's mental model (Polich & Kok, 1995). Differences in the proportion of Correct (25%) vs Incorrect (75%) choices does not appear to have induced biased response strategies that contributed to the amplitude and/or latency of the P300. Latency was not modulated by condition, and a P300 was observed in both the correct and incorrect conditions. Furthermore, the RT data do not suggest a bias towards making NO-responses, since RTs were faster for infrequent items than for frequent items. Unlike the PMN, the P300 did show gradations across conditions. The P300 was largest in the C condition but was clearly seen in the CC condition. The fact that sizeable P300s were elicited in the CC condition may reflect the CC condition's close phonological approximation to the correct choice. The closeness between these two, combined with the general difficulty in isolating a consonant from a consonant cluster (Trieman, Salasoo, Slowiaczek, & Pisoni, 1982) would increase processing demands, and hence influence the amplitude of the P300 (Johnson, 1986). Indeed, a few participants did show discrepancies in accuracy between the CC and the other conditions.

An N400 differentiated the IW conditions from all other conditions at parietal sites. This response may be similar to what Praamstra and colleagues (Praamstra & Stegeman, 1993; Praamstra, Meyer, & Levelt, 1994) and Dumay et al. (2001) refer to as an N400, or to what Rugg (1984a, 1985b) referred to as a N450. In these studies, the N400/N450 was augmented to items that were phonologically dissimilar to the anticipated response. The same situation applied to the findings presented here, as the largest N400 was observed to phonologically unrelated items. The timing of the N400

suggests that it is related to the N400 seen in those previous studies. However, it is not believed to be the same as the semantic N400, as no semantic processing was required in the phoneme deletion task. Rather, it would seem more appropriate to refer to this response as a phonological N400 or N400-like response. It is hypothesized that the phonological N400 response may represent a phonological congruency test that operates at the level of the whole item. In other words, the amplitude of the phonological N400 response reflects the degree to which a phonological form has been primed by the prompt. That is, the prompt (e.g., *clap without the /k/*) may act as a prime to pre-activate phonological representations of the target. Due to the pre-activation of the target's rime (e.g., *ap*), the phonological N400 is attenuated in the CC and WC conditions. This argument is consistent with evidence from previous studies, in which a response peaking at 400 ms has been attributed to phonological processes in the visual (Lovrich et al., 1997; Rugg, 1984a, 1984b) and auditory modalities (Connolly et al. 2001; Dumay et al., 2001; Kujala et al. 2003; Praamstra et al., 1994).

The findings of experiment 1 contradict interpretations that the PMN is modulated by early semantic influences on word recognition (Hagoort & Brown, 2000, van den Brink et al., 2001). The occurrence of the PMN to both word and nonword responses is evidence that semantic access was not a factor in the processing demands of this task. The absence of any semantic processing requirements in this experiment also undermines interpretations of the PMN as being an early onset N400 (Van Petten et al., 1999). Instead, further support is obtained for explanations of the PMN as reflecting a phonological stage of word recognition (Connolly & Phillips, 1994; Connolly et al., 1990,

1992, 2001) that may be initially at the level of translating an acoustic signal into a phonological sequence preceding the setting up of a short list (Norris, 1994) or cohort (Marslen-Wilson, 1987) of lexical candidates. If the merging of top-down phonemic expectations with bottom-up cues is able to continue without obstacle (i.e., the incoming information matches expectations) the PMN is attenuated. If, on the other hand, a mismatch is encountered, then the PMN is augmented since phonological expectations are rendered useless and new hypotheses must be generated.

CHAPTER 3 – LEXICAL INFLUENCES ON THE PMN

3.1. SUMMARY

ERPs were recorded during a phoneme deletion task in order to determine whether the PMN is dependent on lexical mechanisms. Participants were presented with a word/nonword prompt with the instruction to delete the initial sound (e.g., *snap, /s/; snoth, /s/*) and determine the resulting segment. Following the prompt, a word/nonword response that matched/mismatched expectations (e.g., *nap/tap; noth/toth*) was presented. The PMN, distributed over fronto-central regions, was largest to mismatching responses. Consistent with the view that the PMN is not influenced by lexical access mechanisms, there was no difference between the Mismatch Word and Mismatch Nonword conditions. A centro-partietally distributed P300 was elicited to matching items, and was larger to Match Words than to Match Nonwords. An N400-like response differentiated Mismatch Words from Nonwords over central and parietal regions. The differentiation of words and nonwords by the P300 and the N400-like is proposed to reflect lexical selection mechanisms.

3.2. INTRODUCTION

To date two experiments have examined lexical influences on the PMN. The first, conducted by Connolly et al. (2001) involved a cross-modal priming task. Participants were presented with a visual word/nonword (e.g., *cat*) that was followed by the presentation of a prime letter (e.g., *h*). Participants were told to anticipate the auditory word/nonword that would begin with the same letter as the visual prime and rhyme with the visual item (e.g., *hat*). Thus, matching trials consisted of auditory targets that rhymed with the visual word form (e.g., *house, m: mouse* or *telk, w: welk*), while mismatch trials consisted of auditory targets that did not rhyme with the visual word form (e.g., *house, m: barn*). The PMN was elicited in all trials, but was largest to auditory items that mismatched expectations formed by the visual prime. Importantly, there were no significant differences in the amplitude or latency of the PMN on the basis of whether the stimuli were words or nonwords, suggesting that the PMN is not subject to lexical influences.

The second study examining lexical influences on the PMN employed the same task as in Connolly et al. (2001), but used high resolution MEG recordings in order to localize the neural generators of the PMNm. The results of Kujala et al. (2003) were in line with those reported by Connolly et al. (2001). A PMNm was largest to mismatching items, and was localized to the anterior portions of the left temporal cortex. Although differences in the PMNm latency for words and nonwords were observed, such differences were not significant for those participants displaying PMNm responses to both words and nonwords (n=4). Similar to the findings of Connolly et al. (2001), Kujala

et al. (2003) observed an N400m-like response to mismatching items. The source of the N400m was located posterior to the PMNm in the left hemisphere, providing further support for the distinctiveness of the PMN from the N400.

The findings of Connolly et al. (2001) and Kujala et al. (2003) suggest that the PMN (and PMNm) occurs independently of lexical mechanisms. However, further investigation is warranted on the basis of the relatively small response evoked in Connolly et al. (2001), as well as on the apparent latency differences reported by Kujala et al. (2003). The phoneme deletion task employed in experiment 1 has been proven to elicit a much larger PMN response than has been previously reported in the literature (Brown & Hagoort, 2000; Connolly and Phillips, 1994; Connolly et al., 2001). The reason for this finding likely reflects the explicit requirement of phonological analysis in the phoneme deletion task. Thus, in order to clarify lexical influences on the PMN, the present study employed a phoneme deletion task in which the lexicality of stimuli was manipulated. Participants were instructed to delete the initial consonant from a CCVC word or nonword (e.g., *snap/snoth, /s/*), followed by presentation of the correct choice (e.g., *nap/noth*) or an incorrect choice that contained a mismatch at the initial phoneme (e.g., *tap/toth*). Generally, it was hypothesized that the PMN would be maximal to mismatch items. Further, if the PMN occurs independently from lexical mechanisms, then no differences in response characteristics (latency, amplitude) should be found for word and nonword mismatches.

3.3. MATERIALS AND METHODS

Participants

Fourteen right-handed English-speaking participants (M = 23.5 [SD = 6.90; Range = 19-39]; 13 females) volunteered in this study. All participants reported normal hearing and were screened with a self-report health questionnaire for a history of neurological, audiological and/or psychological problems. Participants were screened for reading ability and phonemic awareness using the Word Attack and Word Identification subtests of the Woodcock Diagnostic Reading Battery (Woodcock, 1998), and the Elision Subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen & Rashotte, 1999). No participants were excluded on the basis of their behavioral data. All participants provided informed consent, and the responsible ethics board approved the study.

Stimuli and Procedures

One hundred and sixty monosyllabic CCVC items (80 words, 80 nonwords), were aurally presented to participants along with the sound of the initial phoneme that was to be deleted (e.g. *snap, /s/*). A delay of 1 second separated the presentation of the target item from that of the target phoneme. Following an interstimulus interval (ISI) of 2 seconds, participants heard a correct (C) (e.g., *nap*) answer that matched or an incorrect (e.g., *tap*) answer that mismatched the anticipated response at the initial phoneme. Responses always consisted of a CVC format. For the 160 target stimuli, there were 160 possible answers divided into 4 categories (i.e., 40 Match Word (MW) + 40 Match Nonword (MNW) + 40 Mismatch Word (MMW) + 40 Mismatch Nonword (MMNW).

See Appendix B for a list of experiment stimuli. Items were differentially randomized for each participant.

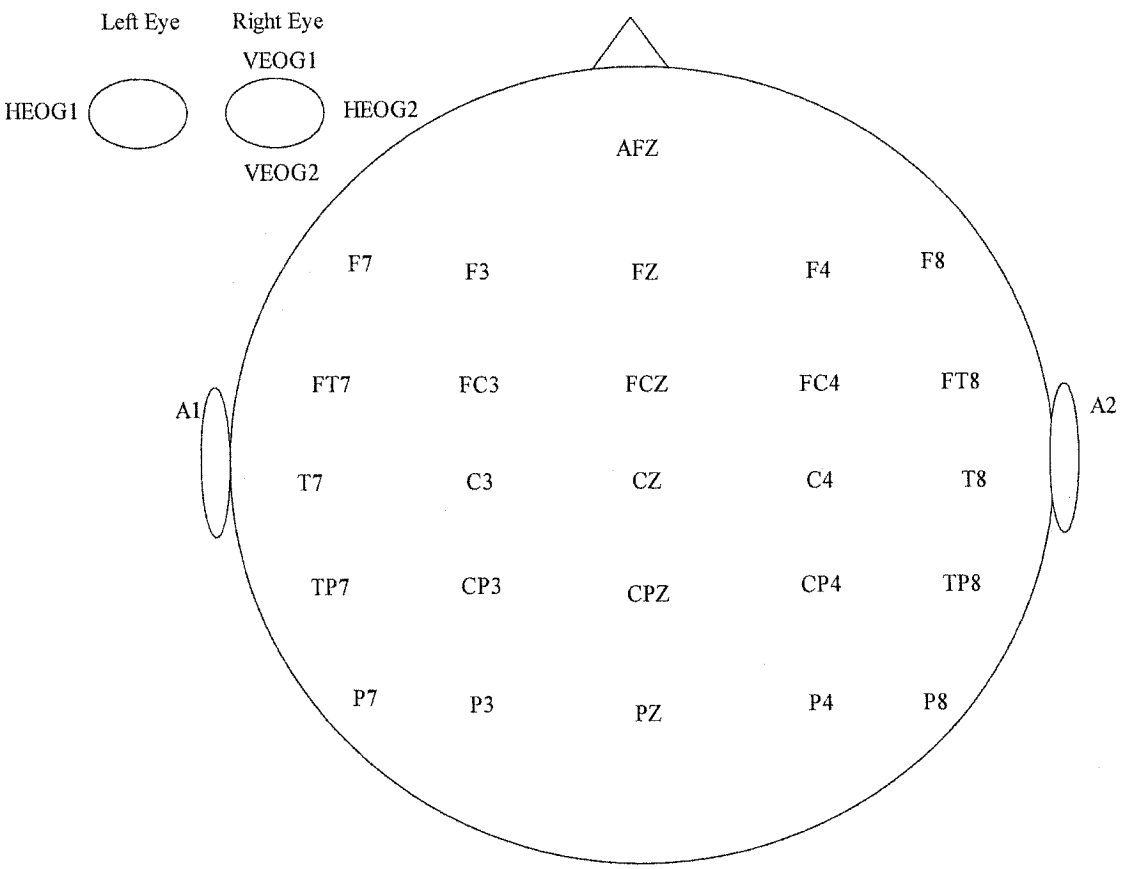
EEG recording took place in a sound attenuated room. As in experiment 1, participants were instructed to determine the resulting segment once the initial consonant had been removed. They were given a two-button response pad and instructed to press the right button to segments that matched their expectations and the left button for those that did not match their expectations. Accuracy was emphasized over reaction time in order to reduce the number of trials that would have to be discarded as a result of behavioral errors. As well, participants were asked to wait until the whole item had been heard in order to reduce motor-related artifacts. Thus, RT data may not provide meaningful information. Button presses were counterbalanced across participants. All stimuli were spoken by a female voice, recorded with Cool Edit 2.0 program digitized at 20,050 Hz and presented binaurally through headphones at 75 dB.

Electrophysiological Recording

EEG activity was recorded at 25 sites (F3, Fz, F4, F7, F8, FC3, FCz, FC4, FT7, FT8, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4, TP7, TP8, T3, T4, T5, T6) using sintered Ag/AgCl electrodes embedded in a NeuroScan Quick-Cap. EEG was referenced to linked ears according to the American Electroencephalographic Society (1991), which is based on the international 10-20 system (Jasper, 1958). The electrooculogram (EOG) was recorded with electrodes placed above and below the right eye (vertical), and on the outer canthus of each eye (horizontal), and an electrode embedded in the Quick-cap (i.e., AFz) served as ground. See Figure 7 for a diagram of the EEG and EOG electrode positions.

Figure 7

The diagram below illustrates the approximate positions of the 25 channels of EEG activity that were recorded in experiment 2 (and the third experiment). These positions are based on the American Electroencephalographic Society (1991), which is an extension of the international 10-20 system (Jasper, 1958). The positions of the horizontal electrooculogram (HEOG) and vertical electrooculogram (VEOG) are illustrated in the top left hand corner of the figure. A1 and A2 refer to the linked ear reference.



Impedance was kept at or below 5 kΩ. EEG was amplified by a Sensorium EPA-5 amplifier and acquired and processed with BrainProducts' Brain Vision software. Stimuli and trigger codes were delivered by Neurobehavioral's Presentation program. EEG was recorded continuously with a bandpass of 0.1 to 100 Hz and sampled at 500 Hz. Data were epoched off-line from -100 to 800 ms post-stimulus onset. Data were digitally filtered offline with a low pass filter setting of 20 Hz. Trials contaminated with EOG activity greater than +/- 75 microvolts (μV) were rejected from the analysis. EEG data on trials that participants responded to correctly were averaged separately across the four conditions. Fourteen percent of trials were excluded from further analyses due to artifacts and/or behavioral errors.

Data Analysis

The amplitude of each component was measured in two ways: first, by deriving the average integrated amplitude relative to baseline within specified time intervals for each component, and second, by peak scoring the most negative (or positive for the P300) peak within a defined latency window. Peak latency was defined as the time from stimulus onset to the peak amplitude of each response. For both scoring methods, the N100 was scored between 100 ms and 160 ms, the P200 between 160 and 240, the PMN between 260 and 320 ms, the P300 between 320 and 380 ms, and the N400-like response between 380-480. The mean amplitude and the peak latency recorded in each condition will be presented in tables for all components listed above. However, only information pertaining to the PMN scalp distribution will be presented in tables, as it is the focus of this thesis.

Repeated measures analysis of variance (ANOVA) using conservative degrees of freedom (Greenhouse & Geisser, 1959) was conducted for each component analysis. Each ANOVA consisted of three factors, Lexicality (Word, Nonword), Congruency (Match, Mismatch), and Site (25 electrode locations). In situations where either the Lexicality or Congruency factor interacted with Site, a second analysis was conducted in order to further investigate the component's scalp topography. In this secondary analysis, the Site factor was divided into two factors, Region (Frontal, Central, Temporal, Parietal Occipital) and Hemisphere (Left, Right). Each Region x Hemisphere combination was linearly derived from a combination of two sites: left frontal (F3, FC3), right frontal (F4, FC4), left central (C3, CP3), right central (C4, CP4), left temporal (T7, FT7), right temporal (T8, FT8), left parietal (P3, P7), and right parietal (P4, P8). Results of the peak amplitude analysis are only discussed if they provide new information over and above that provided by the average amplitude analysis. For all analyses, post-hoc comparisons were conducted using the Tukey honestly significant difference (HSD) test, with $p < .05$ as the required level of significance.

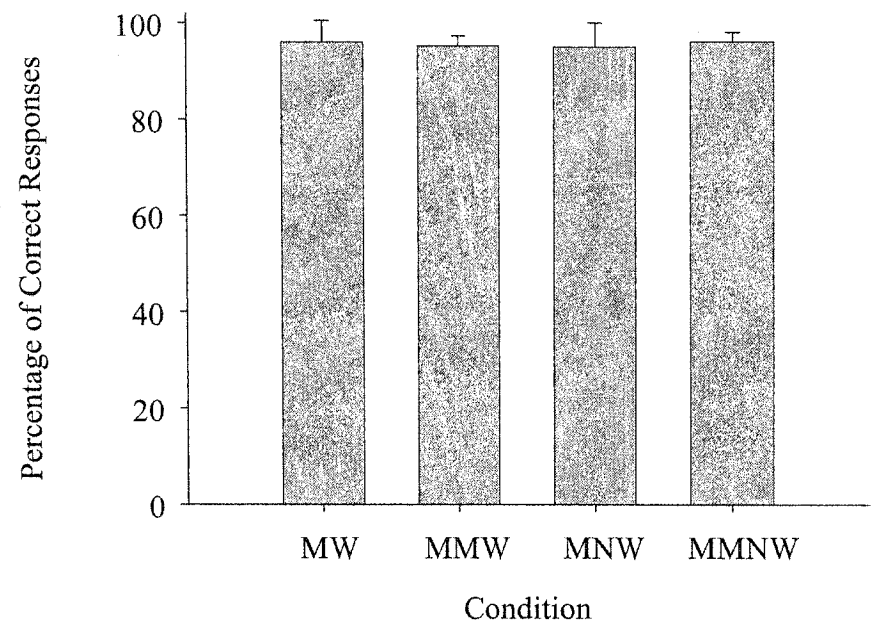
3.4. RESULTS

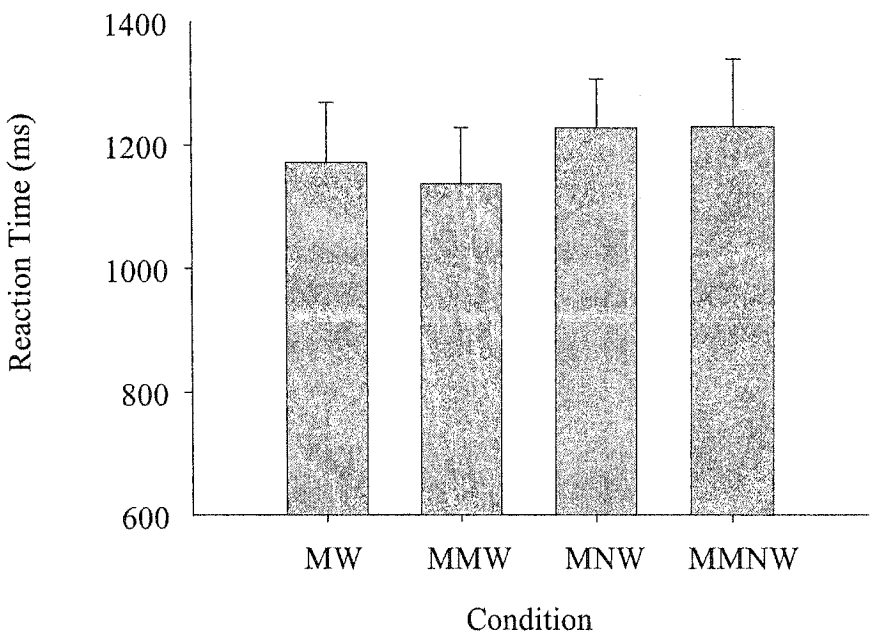
Behavioral Results

Accuracy and RT data were available for 13 out of the 14 participants. Data from one participant was not available due to a technical problem. Lexicality (Word, Nonword) and Congruency (Match, Mismatch) were factors in a repeated measures ANOVA to analyze accuracy and RT data. No significant effects were observed for the analysis of accuracy data. Participants performed at near ceiling levels with an overall accuracy rate of 95.6 % (Figure 8). For the analysis of RT data, there was a significant main effect of Lexicality ($F(1,12) = 12.73, p < 01, \varepsilon = 0.52$), as Words (1154 ms) were responded to faster than Nonwords (1230 ms) (Figure 8). No other effects were significant. The long response times are explained by two factors. Fist, accuracy was emphasized over response time in order to reduce the number of trials that would have to be rejected due to behavioral errors. Second, participants were encouraged to wait until the entire item had been presented before responding in order to reduce the number of trials rejected due to movement and/or ocular artifacts.

Figure 8

Accuracy (top) and Reaction Time (bottom) as a function of Lexicality and Congruency





Electrophysiological Findings

Figure 9 illustrates the grand average waveforms for words and nonwords that matched or mismatched the anticipated answer primed by the prompt. Figure 10 displays the grand average waveforms recorded at Cz for ease of inspection. The N100 does not appear sensitive to the task manipulation, while the P200 appears largest to MW. MM items evoked an anterior to central PMN, which does not appear to differentiate words from nonwords. Although a PMN peak is identifiable in the M conditions, the most prominent component in the M conditions is a P300. Finally, an N400-like response differentiates MMW items from MMNW, as well MW and MNW items over central and posterior sites.

Figure 9 - Caption

Grand average ERPs (N = 14) to target words/nonwords in the Match Word (MW, red dashed line), Mismatch Word (MMW, red solid line), Match Nonword (MNW, black dashed line), and Mismatch Nonword (MMNW, black solid line) conditions for three midline sites (Fz, Cz, Pz), and eight regions [left and right frontal (LF, RF), central (LC, RC), temporal (LT, RT), and parietal (LP, RP) regions]. The PMN (†) was largest to MM items, while the P300 (*) was largest to M items (denoted at Pz). An N400-like response (‡) differentiated MMW from MMNW. Time (ms) is on the x-axis and amplitude (μV) is on the y-axis. Negative is up.

Figure 9

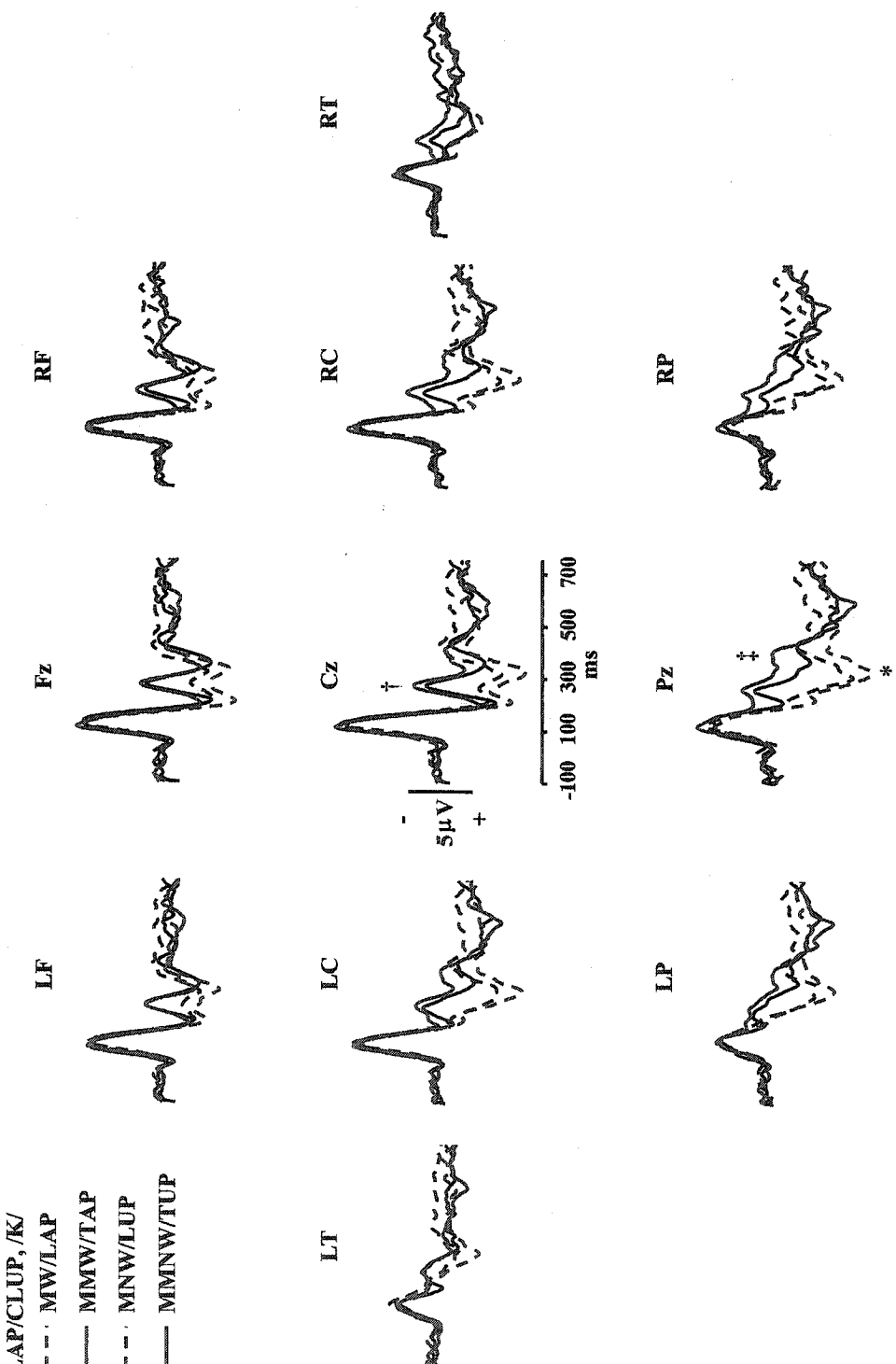
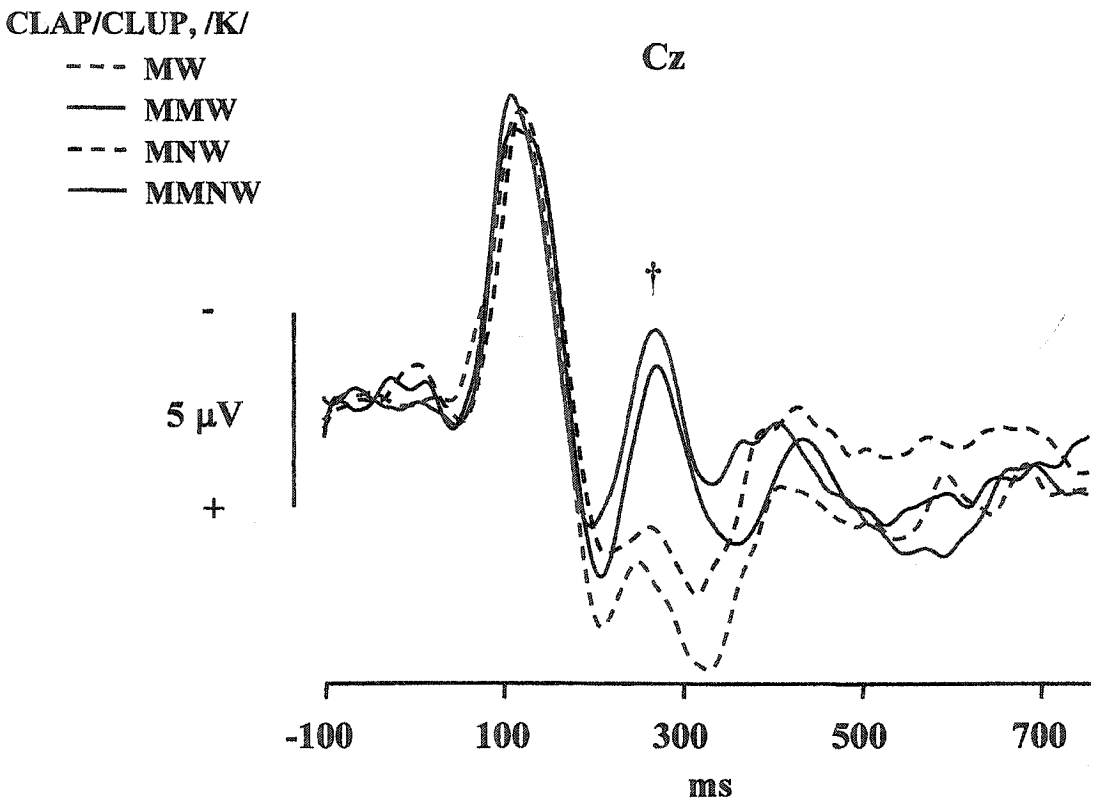

CLAP/CLUP, /K/
MW/LAP
MMW/TAP
MNW/LUP
MMNW/TUP
LF
Fz
RF
LC
Cz
RC
LT
RT
LP
Pz
RP
†
‡
*
5 µV
-
+
-100 100 300 500 700
ms

Figure 10

Enlarged version of Cz presented in Figure 9. All details as in Figure 9.



N100 and P200

The amplitude of the N100 did not vary significantly for either the Congruency or the Lexicality factor (MW = -2.98 μV, MNW = -2.88 μV, MMW = -3.28 μV, MMNW = -3.11 μV; Table 7); however, the main effect of Site was significant ($F(24,312,) = 24.17$, $p < .001$, $\varepsilon = 0.66$). As is typical of the N100, amplitudes were larger over central-parietal sites. None of the interactions involving N100 amplitude were significant.

The peak latency of the N100 was not modulated by the Congruency and Lexicality factors or by their interaction (MW = 137 ms, MNW = 143 ms, MMW = 138 ms, MMNW = 136 ms; Table 7). The peak latency of the N100 was modulated by the Site factor ($F(24,312) = 9.12$, $p < .001$, $\varepsilon = 0.41$), with amplitudes peaking later over lateral frontal (F7), lateral fronto-temporal (FT7), lateral temporal (T7), and lateral temporal parietal (TP7) sites.

The Congruency x Site effect was also significant ($F(24,312) = 3.34$, $p < .001$, $\varepsilon = 0.21$). A subsequent region/hemisphere analysis revealed a significant Region effect ($F(3,39) = 16.54$, $p < .001$, $\varepsilon = 0.56$), which reflected the later peaking N100 in temporal and parietal regions. While the Congruency x Region ($p = .08$) and Lexicality x Region ($p = .08$) approached significance, the interaction of Congruency x Hemisphere achieved significance ($F(1,13) = 8.46$, $p < .01$, $\varepsilon = 0.39$). The origin of this interaction was the later peaking N100 response over the left hemisphere for the M items (143 ms), relative to the N100 recorded over the right hemisphere for M items (136 ms).

Table 7

Mean Amplitude (μV) and Peak Latency (ms) of the N100 in the Match Word (MW), Match Nonword (MW), Mismatch Word (MMW), and Mismatch Nonword (MMNW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
MW	-2.98 (0.39)	137 (1.65)
MNW	-2.88 (0.43)	143 (3.99)
MMW	-3.28 (0.31)	138 (2.69)
MMNW	-3.11 (0.48)	136 (2.10)

P200 Response

For the analysis of P200 amplitude, the main effects of Congruency ($F(1,13) = 8.34, p < .01, \varepsilon = 0.39$) and Site were significant ($F(24,312) = 12.52, p < .001, \varepsilon = 0.49$). Subsequent post hoc analyses attributed the Congruency effect to larger P200 amplitudes recorded in the M conditions (0.96 μV; collapsed across Lexicality) compared to the MM conditions (0.15 μV; see Table 8 for Congruency x Lexicality). The main effect of Site was due to the fronto-central distribution of the P200. The interaction of Congruency x Site was significant ($F(24,312) = 3.87, p < .03, \varepsilon = 0.23$), so a Congruency (2) x Lexicality (2) x Region (4) x Hemisphere (2), was conducted. As in the omnibus analysis, the effect of Congruency was significant ($F(1,13) = 8.62, p < .01, \varepsilon = 0.40$), and was once again due to larger P200 responses elicited in the M conditions relative to the MM conditions. The main effect of Region was significant ($F(3,39) = 10.51, p < .001, \varepsilon = 0.45$) and was attributable to larger amplitudes recorded over the frontal region. The interaction of Congruency x Region was not significant; however, the interaction of Congruency x Hemisphere was significant ($F(1,13) = 7.37, p < .02, \varepsilon = 0.36$), with P200 responses to M items displaying a right hemispheric asymmetry. The interaction of Region x Hemisphere was also significant ($F(3,39) = 4.18, p < .03, \varepsilon = 0.24$), and was associated with larger P200 responses recorded over the left and right frontal regions. The only region displaying a hemispheric asymmetry was the temporal region, in which responses in the right temporal region were larger than those in the left temporal region.

For the analysis of P200 latency, a marginally significant 3-way interaction of Lexicality x Congruency x Site ($F(24,312) = 2.42, p = 0.47, \varepsilon = 0.16$) was obtained. In

order to further investigate the latency distribution across the scalp, a Lexicality x Congruency x Region x Hemisphere analysis was conducted. For this analysis, the only main effect to reach significance was that of Region ($F(13,39) = 4.58, p < .025, \varepsilon = 0.26$), and was produced by the earlier peaking P200 response in the temporal region. The 3-way interaction involving Congruency x Lexicality x Hemisphere ($F(1,13) = 4.50, p < .05, \varepsilon = 0.26$) was also significant. In order to simplify this interaction, 2-way ANOVAs with Congruency and Lexicality as factors were conducted for the left and right hemisphere separately. The interaction of Lexicality x Congruency was significant only for the right hemisphere ($F(1,13) = 7.00, p < .02, \varepsilon = 0.35$). Further analyses of responses recorded over the right hemisphere revealed that responses in the MMW condition peaked earlier than those in the MMW condition, and earlier than those in the MNW and MMNW conditions.

Table 8

Mean Amplitude (μV) and Peak Latency (ms) of the P200 in the Match Word (MW), Match Nonword (MW), Mismatch Word (MMW), and Mismatch Nonword (MMNW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
MW	1.34 (0.50)	225 (2.14)
MNW	0.57 (0.32)	223 (2.18)
MMW	-0.10 (0.53)	224 (2.58)
MMNW	0.42 (0.49)	216 (3.56)

PMN

Visual inspection of the grand average waveforms reveals that the MM conditions produced larger PMN responses than did the M conditions, regardless of the lexicality of the presented items (Figure 9). The ANOVA conducted on the PMN data revealed a significant effect of Congruency ($F(1,13) = 41.10, p < .001, \varepsilon = 0.76$), reflecting the fact that PMN amplitudes in the MM conditions (-0.64 μV) were larger (more negative) than responses elicited in the M conditions (2.54 μV). No other main effects were significant, although the Site effect approached significance ($p = .057$). Importantly, neither the main effect of Lexicality, nor the Interaction of Lexicality x Congruency was significant, indicating that the PMN was not sensitive to the manipulation of lexicality (Table 9).

The Congruency x Site Interaction was significant ($F(24,312) = 10.71, p < .001, \varepsilon = 0.45$). A secondary analysis was conducted with Lexicality (2) x Congruency (2) x Region (4) x Hemisphere (2) as factors in order to examine differences in scalp topography. As in the omnibus analysis, the region/hemisphere analysis revealed that the PMN was largest in the MM conditions. The interaction of Lexicality x Region was significant ($F(3,39) = 4.16, p < .03, \varepsilon = 0.24$), and was produced by more positive amplitudes recorded over the central region for nonwords compared to words (Table 10). Word amplitudes in the central region, although not differing from nonwords in the central region, were more positive than amplitudes in the temporal region. The positive amplitudes recorded in the central region likely reflect the onset of the P300 over centro-parietal locations (the central region consisted of the average of C3, C4, Cp3, Cp4). The interaction of Congruency x Region was significant ($F(3,39) = 11.71, p < .002, \varepsilon = 0.47$),

and further analyses showed that PMN amplitudes in the MM conditions, although not varying across regions, were more negative than those in the M conditions (Table 11). This interaction was again influenced by the onset of the P300, as M items were more positive over the central region relative to the other three regions.

Table 9

Mean Amplitude (μV) and Peak Latency (ms) of the PMN in the Match Word (MW), Match Nonword (MW), Mismatch Word (MMW), and Mismatch Nonword (MMNW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
MW	2.88 (0.66)	278 (4.65)
MNW	2.19 (0.68)	277 (3.47)
MMW	-0.96 (0.74)	288 (2.76)
MMNW	-0.33 (0.83)	288 (2.71)

Table 10

Mean Amplitudes (μV) of the PMN for the Lexicality x Region interaction. Standard Error is presented in parentheses.

Region	Lexicality	Mean Amplitude
Frontal	**W**	1.03 (0.74)
	NW	0.73 (0.97)
Central	**W**	1.18 (0.77)
	NW	1.30 (0.72)
Temporal	**W**	0.41 (0.47)
	NW	0.12 (0.51)
Parietal	**W**	0.76 (0.64)
	NW	1.12 (0.55)

Table 11

Mean Amplitudes (μV) of the PMN for the Congruency x Region interaction. Standard Error is presented in parentheses.

Region	Congruency	Mean Amplitude
Frontal	**M**	2.45 (0.84)
	MM	-0.69 (0.86)
Central	**M**	3.46 (.67)
	MM	-0.92 (0.93)
Temporal	**M**	1.12 (0.43)
	MM	-0.58 (0.52)
Parietal	**M**	2.53 (0.53)
	MM	-0.64 (0.76)

Due to the overlapping time course of the PMN with that of the P300, it is useful to report the peak amplitude analysis for the PMN response, which is less sensitive to the onset of the positive component. As in the interval analysis, the main effect of Congruency was significant ($F(1,13) = 30.90, p < .001, \varepsilon = 0.70$), with the PMN being larger (most negative) in the MM conditions (-1.80 μV) relative to the M conditions (0.97 μV). Neither the Lexicality factor, nor the interaction of Lexicality x Congruency was significant. The interaction of Congruency x Site was significant ($F(24,313) = 7.67, p < .01, \varepsilon = 0.37$) and is once again best interpreted by the Region/Hemisphere analysis. In contrast to the interval analysis, the interaction of Lexicality x Region was not significant ($p = .11$), indicating that the onset of the P300 was the driving factor behind the significant Lexicality x Region interaction apparent for the interval analysis.

A significant Congruency x Region effect ($F(3,39) = 8.63, p < .006\ \varepsilon = 0.40$) did not clarify the regional distribution of the PMN in the MM conditions. Amplitudes in each of the regions in the MM conditions, although not differing from each other, were more negative than those in the M conditions. More positive amplitudes were recorded in frontal, central and parietal regions compared to the temporal region in the M conditions. It is clear from Figures 7 and 8 that the morphology of the PMN is most apparent at frontal and fronto-central locations. The failure for this observation to be confirmed by data analysis likely reflects the influence of the frontally distributed P200. The trough to peak distance for the P200/PMN complex is greater over frontal sites relative to parietal locations and as a result, the PMN amplitude relative to baseline is equivocal across the scalp.

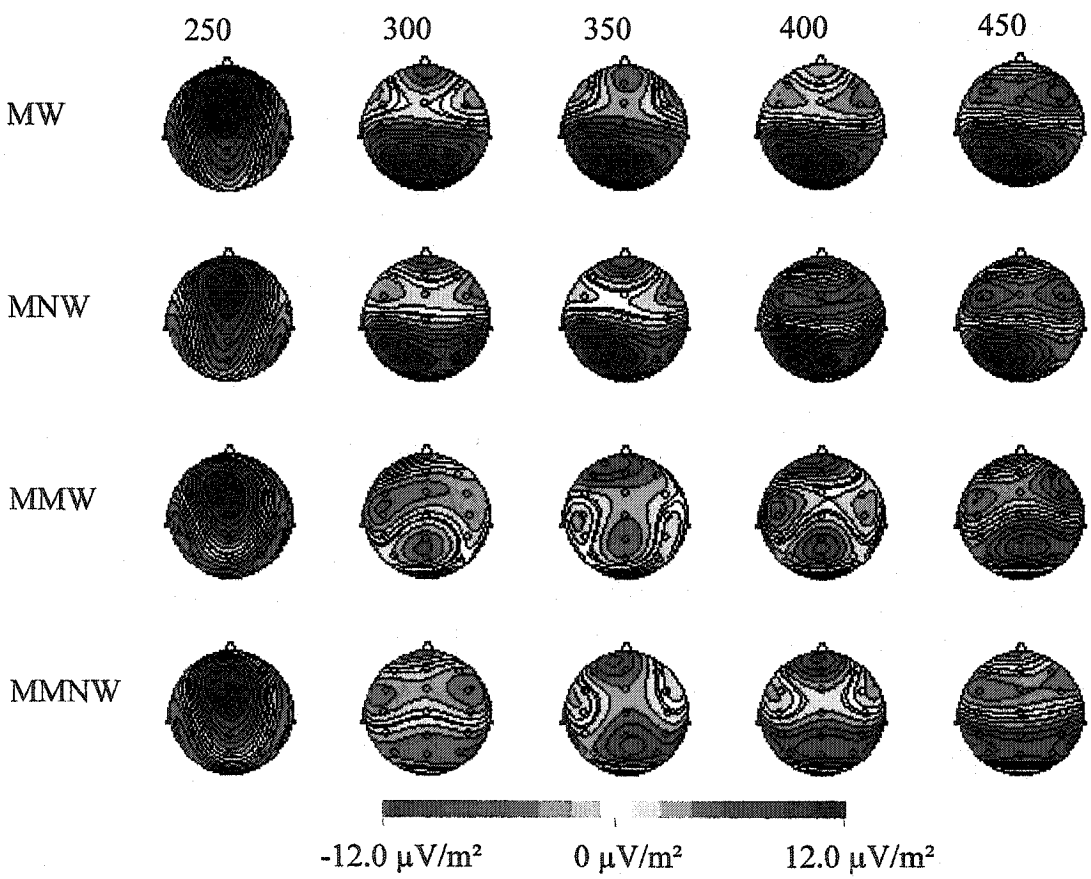
Observations of the scalp current source density maps (CSD) (Figure 11) illustrate the scalp distribution of the PMN. The CSD maps were constructed using the spherical spline method (Perrin, Pernier, Bertrand, & Echallier, 1989). CSD maps preserve information regarding the location of the intracranial current generators that would be otherwise lost due to volume conduction and distortion by the skull. The CSD maps illustrate neuronal depolarization (e.g. current sink) as negative activity, and neuronal hyperpolarization (e.g., current source) as positive activity (Picton et al., 1995). The scalp topography maps for the MMW and MMNW conditions depict a frontally distributed negative activation corresponding to the time course of the PMN (map 300 ms). Similarly, the CSD maps show an anterior current sink corresponding to PMN activation in the M conditions (map 300 ms). The topographic maps also illustrate the influence of the P300 activation on PMN amplitude. Activation associated with the P300 in the M conditions overlaps with activation corresponding to the PMN in M conditions (map 300 ms).

The analysis of PMN latency revealed a significant effect of Congruency ($F(1,13) = 12.87, p < .003, \varepsilon = 0.50$), with the PMN peaking later in the MM conditions (288 ms) than in the M conditions (277 ms). A significant effect of Site ($F(24,351) = 4.16, p < .003, \varepsilon = 0.24$), was associated with the PMN peaking earlier over parietal locations. The latency of the PMN was not modulated by the Lexicality Factor or by the interaction of Congruency x Lexicality (Table 9). The fact that the PMN peaked earlier in the M relative to the MM conditions simply reflects the reduced amplitude in the former condition.

Figure 11 - Caption

Current source density (CSD) maps presented in 50 ms intervals from 250 to 450 ms. The iso-contour lines are separated by 1.2 μV. Blue regions represent negative activation and red regions represent positive activation. The CSD maps for the PMN interval show a anterior distribution that is most prominent at map 300 ms. Increased anterior activation occurs in the MMW and MMNW conditions; however, a similar pattern is observed in the MW and MNW conditions. Activation corresponding to the P300 elicited in the MW and MNW conditions is most prominent over central to parietal regions at maps 300 and 350 ms. Activation corresponding to the N400-like response is distributed over anterior regions in all conditions (maps 400 ms and 450 ms).

Figure 11



P300

The grand average waveforms illustrate the sensitivity of the P300 to the congruency manipulation. The ANOVA for P300 amplitude resulted in a significant effect of Congruency ($F(1,13) = 13.65, p < .003, \varepsilon = .51$), which was associated with larger P300 responses elicited in the M (3.83 μV) condition compared to the MM Conditions (1.31 μV). A significant effect of Site ($F(24,312) = 5.10, p < .004, \varepsilon = 0.28$) was attributable to larger P300 responses recorded over midline central and parietal sites (Cz, Pz, CPz) as well as over lateral central and parietal sites. The interaction of Congruency x Lexicality was significant ($F(1,13) = 5.33, p < .04, \varepsilon = 0.29$). Further analyses revealed that words (4.50 μV) in the M condition produced a larger P300 than nonwords (3.16 μV) in the M condition. Words (0.94V) and nonwords (1.68 μV) in the MM conditions did not differ significantly from each other, but produced smaller P300 responses than items in the M conditions (Table 12). The interaction of Congruency x Site was significant ($F(24,312) = 9.20, p < .001, \varepsilon = 0.41$), and is best interpreted by conducting a regional analysis.

Results of the regional analysis replicated those findings of the omnibus analysis with regard to the Congruency effect ($F(1,13) = 14.27, p < .002, \varepsilon = 0.52$). Items in the M conditions elicited larger P300 responses than those in the MM conditions. A significant Congruency x Lexicality interaction ($F(1,13) = 5.13, p < .04, \varepsilon = 0.29$) was once again associated with larger P300 responses for words in the M condition relative to nonwords in the M condition. Items in the MM conditions did not differ significantly from each other, although P300 responses to words and nonwords in the MM conditions were

smaller than those recorded for words and nonwords in the M conditions. A significant Congruency x Region interaction ($F(3,39) = 14.29, p < .001, \varepsilon = 0.52$) was attributable to the centro-parietal distribution of the P300 response in the M conditions. There were no significant effects involving P300 latency (Table 12).

Table 12

Mean Amplitude (μV) and Peak Latency (ms) of the P300 in the Match Word (MW), Match Nonword (MW), Mismatch Word (MMW), and Mismatch Nonword (MMNW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
MW	4.50 (0.61)	334 (3.02)
MNW	3.16 (0.98)	345 (4.50)
MMW	0.94 (0.89)	340 (3.97)
MMNW	1.68 (0.74)	342 (4.42)

N400-like Response

As depicted in Figures 7 and 8, the PMN is followed by a negative-going wave peaking at approximately 440 ms. This response is seen at all sites in the frontal regions; however, it appears to differentiate the MMW from the MMNW condition at central and-parietal locations. Analysis of the 380-480 interval revealed a significant Site effect ($F(24,312) = 6.0, p < .01, \varepsilon = 0.32$), which reflects the larger negativities recorded over frontal and central regions compared to temporal and parietal regions. The CSD maps highlight the anterior distribution of the N400-like response (Figure 11). A significant Lexicality x Congruency effect ($F(1,13) = 7.89, p < .05, \varepsilon = 0.38$), was attributable to larger negative amplitudes recorded in the MMW condition compared to the MW condition (Table 13). Although amplitudes recorded in the MMW were more negative than amplitudes in the MMNW, this difference did not achieve significance. The interaction of Condition x Site displayed a non-significant trend ($p = .056$). A subsequent regional analysis did not provide any new information pertaining to the modulation of the N400-like response.

Analysis of the peak latency of the N400-like response revealed a significant main effect of Site ($F(24,312) = 7.99, p < .01, \varepsilon = 0.36$). This was due to the response peaking earlier over parietal locations compared to frontal and central locations. A significant Lexicality x Congruency effect ($F(1,13) = 7.65, p < .05, \varepsilon = 0.25$), was attributable to the response peaking earlier in the MMW condition compared to the other conditions (Table 13).

In order to further investigate the apparent differentiation of the MMW from the

MMNW an analysis was conducted that limited the Site factor to central and parietal locations (C3, Cz, C4, Cp3, Cpz, Cp4, P3, Pz, P4). The results of this analysis revealed a significant Lexicality x Congruency interaction ($F(1,13) = 8.69, p < .01, \varepsilon = .40$). Post hoc analysis revealed that MMW items were more negative than all other items. No other effects were significant (Table 14).

Table 13

Mean Amplitude (μV) and Peak Latency (ms) of the N400-like response in the Match Word (MW), Match Nonword (MW), Mismatch Word (MMW), and Mismatch Nonword (MMNW) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
MW	2.40 (0.60)	450 (3.03)
MNW	1.10 (0.68)	449 (3.62)
MMW	0.87 (0.73)	430 (4.45)
MMNW	1.75 (0.67)	452 (2.98)

Table 14

Mean Amplitude (μV) of the N400-like response in the Match Word (MW), Match Nonword (MW), Mismatch Word (MMW), and Mismatch Nonword (MMNW) conditions collapsed across central and parietal locations. Standard error is presented in parentheses.

Condition	Mean Amplitude
MW	3.89 (0.86)
MNW	2.20 (0.79)
MMW	0.99 (1.07)
MMNW	2.48 (0.93)

Difference Waves

In order to isolate the PMN, Word and Nonword difference waveforms were derived by subtracting Match items (collapsed across Lexicality) from the Word and Nonword Mismatch conditions. Match items were collapsed across Lexicality due to differences in P300 amplitude between Match Word and Match Nonword conditions. If these data were not integrated then effects seen for the resulting difference waves could be attributed either to differences in the P300 or the N400-like response. The grand average ERP difference waves depicted in Figure 12 do not distinguish words from nonwords over the frontal and temporal regions. However, differences between words and nonwords emerge over central and parietal sites and likely correspond to the N400-like response that distinguished the MMW from the MMNW condition over posterior locations. The CSD maps derived from the grand average difference waveforms show evidence of a posterior sink that is slightly enhanced in the Word condition relative to the Nonword condition (Figure 13).

In order to characterize the modulation of the PMN as well as that of the N400-like response, the mean amplitude for Word and Nonword items was calculated for two intervals (250-350, 350-450) at Left and Right Frontal, Central, Temporal and Parietal Regions (Table 15). For the first interval (250-350), all regions with the exception of the Left Temporal region differed significantly from baseline ($t(13) > -2.16$). However, for the second interval (350-450), only Word items at Central and Parietal regions differed significantly from baseline ($t(13) > 2.16$). These results support the hypothesis that while

the PMN is not sensitive to Lexicality, the N400-like response is modulated by lexical selection.

Figure 12 - Caption

Grand Average (N=14) difference waveforms for Word (red) and Nonword (black) items at left and right frontal (LF, RF), left and right central (LC, RC), left and right temporal (LT, RT) and left and right posterior (LP, RP) regions. Word difference waves were derived by subtracting the M (collapsed across Lexicality) from the MMW condition, and Nonword difference waves were derived from subtracting the M (collapsed across Lexicality) from the MMNW condition. Both subtractions effectively isolated the PMN, and show how similar the PMN is for Word and Nonword conditions. The differentiation of Word from Nonword Mismatches by the N400-like response is apparent over parietal regions. Time (ms) is on the x-axis and amplitude (in μV) is on the y-axis. Negative is up.

Figure 12

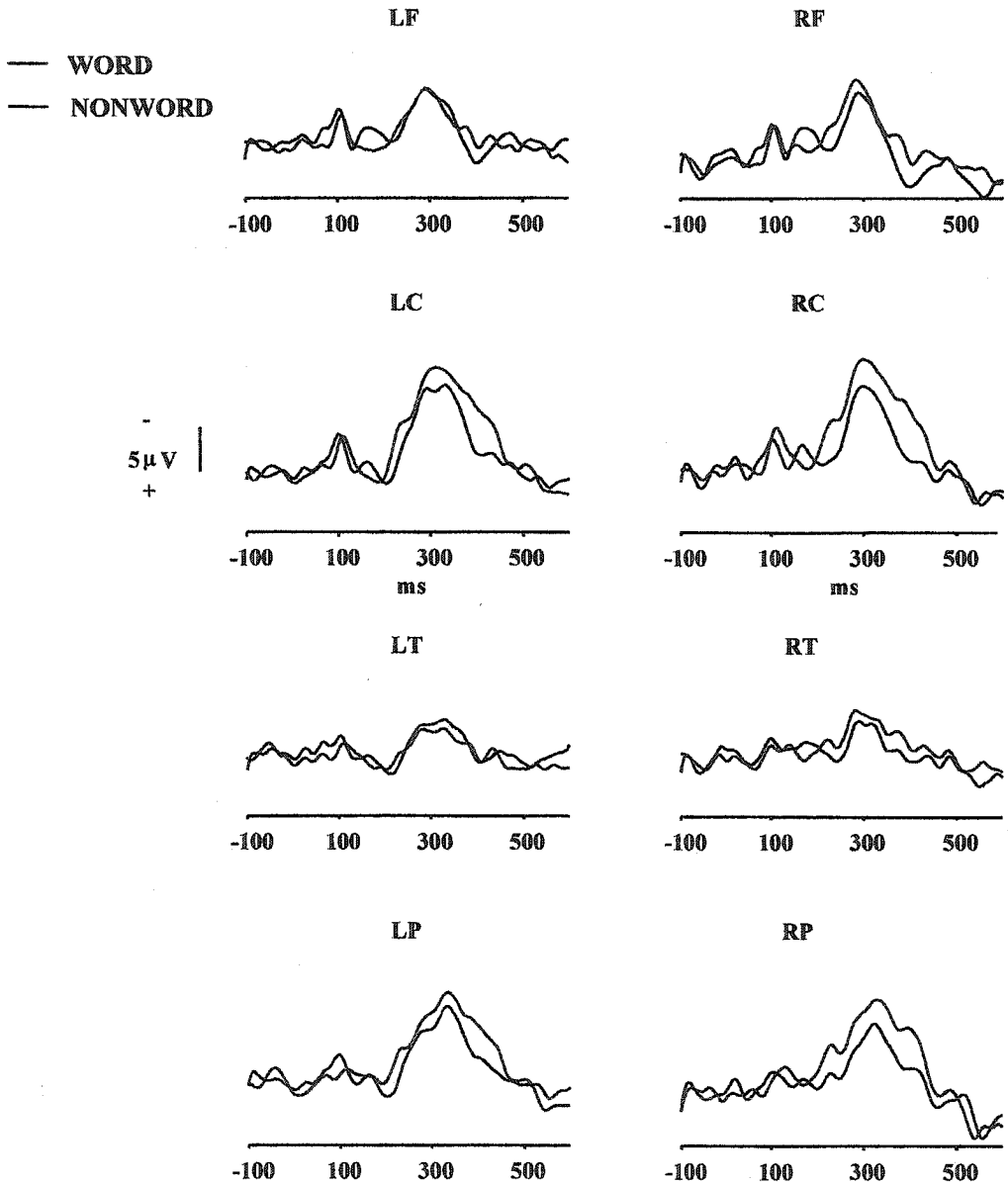


Figure 13

Current source density maps derived from the Word and Nonword difference waveforms presented in Figure 12. Maps are presented in 50 ms intervals from 250 to 500 ms. Iso-contour lines are separated by 1.5 μV. Blue regions represent negative activation and red regions represent positive activation. Activation corresponding to the PMN is most prominent at map 300 ms. It is noteworthy that a parietal sink overlaps with the PMN activation and continues throughout the rest of the interval. This parietal sink, which appears to show increased activation for Words compared to Nonwords, likely reflects the N400-like response apparent in the grand average waveforms.

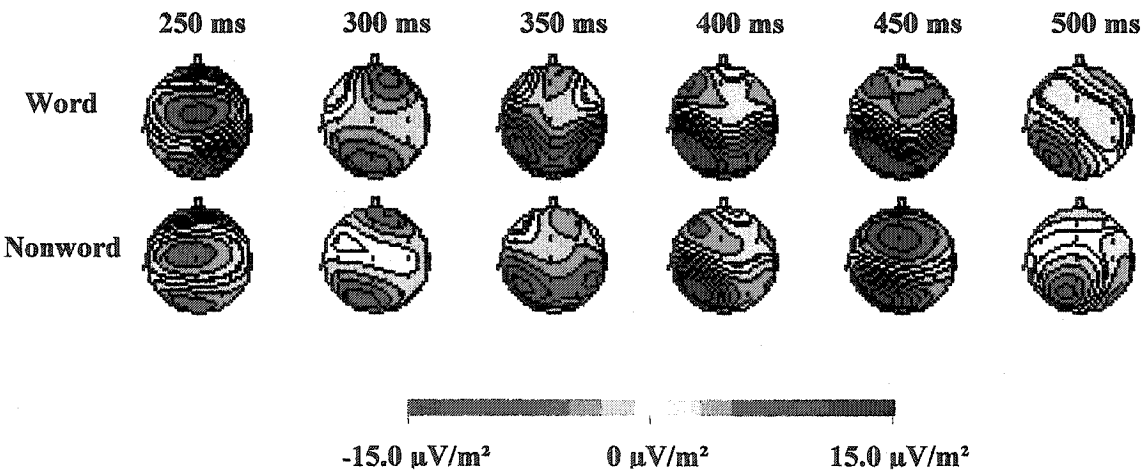


Table 15

Mean Amplitude (μV) from baseline for the 250-350 ms and 350-450 ms intervals for Word (W) and Nonword (NW) items at 8 scalp regions. Standard Error is presented in parentheses.

	Interval 250-350	**Interval 350-450**
LF W	-2.45 (0.96)	-.055 (0.87)
RF W	-3.23 (0.66)	-.0.79 (0.67)
LF NW	-2.54 (0.83)	0.10 (0.94)
RF NW	-2.66 (0.74)	0.42 (0.86)
LC W	-4.52 (1.2)	-3.39 (1.29)
RC W	-4.90 (0.96)	-3.02 (1.13)
LC NW	-3.79 (1.0)	-1.75 (1.13)
RC NW	-3.56 (1.1)	-1.01 (1.09)
LT W	-1.02 (0.64)	-.199 (0.55)
RT W	-2.03 (0.35)	-0.96 (0.41)
LT NW	-1.41 (0.45)	-0.24 (0.58)
RT NW	-1.39 (0.45)	-0.25 (0.58)
LP W	-3.33 (0.92)	-2.77 (1.09)
RP NW	-3.83 (0.80)	-2.85 (0.95)
LP NW	-2.76 (0.86)	-1.41 (0.98)
RP NW	-2.52 (0.99)	-1.26 (1.04)

3.5. DISCUSSION

The aim of this experiment was to investigate lexical influences on the PMN during a phoneme deletion task. As in experiment 1, the PMN was elicited to items that mismatched expectations primed by the task context. The amplitude and latency of the PMN did not differentiate between word and nonword mismatches. In addition, the CSD maps for the PMN interval did not distinguish between the scalp distribution of the PMN in the MMW and MMNW conditions (Figure 11). These results are in line with the findings of Connolly et al. (2001), who showed that the PMN did not differentiate between words and nonword targets that failed to match primed expectations. In a parallel MEG experiment to Connolly et al. (2001), Kujala et al, (2003) reported latency differences in the PMNm response between words and nonwords. Although this difference was not significant for the participants who showed the response to words and nonwords, the issue warranted further investigation. In the present experiment, the latency of the PMN for words and nonwords was indistinguishable, peaking at 288 ms for both mismatching words and nonwords. Thus, these results offer the most compelling evidence to data that the PMN is not subject to lexical influences.

An N400-like response differentiated MMW from MMNW items. Previous research showed that an N400-like response differentiated phonologically unrelated words from phonologically unrelated nonwords (Praamstra & Stegeman, 1993; Praamstra et al., 1994 experiment 1, Dumay et al. 2001). Dumay et al (2001) attributed their finding to a phonological priming mechanism that was modulated by lexical selection. Since phonologically unrelated items were not included in the present experiment, it is not clear

whether the same explanation can be applied to the findings seen here. An alternative explanation to account for the differentiation between words and nonwords is that lexical access was constrained in the MMNW condition, because participants are able to predict the lexicality of the target. That is, in the present experiment nonword prompts are always paired with nonword targets, allowing participants to predict whether the target is a word or nonword. Praamstra et al. (1994) offered a similar explanation in order to account for the failure of priming effects to develop for nonwords. In their study, nonwords began with an illegal consonant cluster, thereby terminating lexical access mechanisms prematurely. However, this hypothesis is not supported by the findings of Connolly et al. (2001) and Kujala et al. (2003), who observed an N400-like response to both word and nonword mismatches, despite the fact that participants could have predicted the lexicality of items (i.e., words were always paired with words). One way to test for strategic effects on lexical access would be to mix the pairing of word prompts with nonword targets and vice versa (e.g., */snop/* without */s/ - *mop*). Future studies will need to be conducted in order to clarify the functional role of this N400-like response.

In experiment 1, the P300 made it difficult to interpret the presence of the PMN in the correct condition. In this experiment, however, a distinct PMN peak is visible in the correct (e.g., Matching) conditions (Figures 7 and 8). In addition, the CSD maps reveal an anterior negative activation in the MW and MNW conditions during the PMN interval that is similar to that observed in the MM conditions (Figure 11). These observations offer additional support for the proposal that the PMN represents an obligatory response that is nevertheless augmented by a mismatch (Connolly et al., 2001).

As in experiment 1, a P300 was observed to correct responses (i.e., Match conditions), reflecting a recognition memory function (Polich & Kok, 1995). Unlike the PMN, the P300 did differentiate between words and nonwords. The P300 in the MW condition was significantly larger than that in the MMW condition. This apparent lexicality effect may reflect the process of lexical selection. However, it is also plausible that the P300 is being modulated by the preceding P200. Although the P200 appears largest in the MW condition, the Word x Congruency effect failed to reach significance ($p = .11$).

The findings in this experiment also help to clarify a potential confound that was present in experiment 1. There was concern that the disproportion of incorrect (75%) relative to correct (25%) choices could have produced biased response strategies that contributed to the amplitude and/or latency of the P300. The appearance of the P300 in this experiment, in which the proportion of correct and incorrect choices were evenly balanced, is further confirmation that the results obtained in experiment 1 were not attributable to biased response strategies.

In summary, the findings of this experiment offer unequivocal support for the proposal that the PMN is not dependent on lexical mechanisms. These findings offer confirmatory evidence for the findings of Connolly and colleagues (1992, 1994, 2001), and argue against interpretations of the PMN as representing early lexical selection mechanisms (Hagoort and Brown, 2000; van den Brink et al., 2001). Instead, findings indicate that the PMN serves as a neural measure operating at a perceptual stage of spoken word recognition preceding lexical selection. That is, the PMN reflects the

mapping of speech input onto a phonological template consisting of phoneme candidates derived from the task context.

CHAPTER 4 - INITIAL VERSUS FINAL CONSONANT MISMATCH EFFECTS ON THE PHONOLOGICAL MISMATCH NEGATIVITY

4.1. SUMMARY

Event-related brain potentials were measured as the position of phoneme mismatch was manipulated during a phoneme deletion task. Following a CCVC nonword prompt (e.g., *smoob, /s/*), participants were presented with a CVC response that matched expectations (e.g., *moob*), or one that mismatched expectations. The position at which the first phoneme deviated from expectations was manipulated, occurring at either the initial (e.g., ***f**oob*) or final phoneme (e.g., *moo**p***) position. A final response mismatched expectations at all three phoneme positions (e.g., ***t**i**v***). A PMN was most apparent in the initial and all mismatch (IM, AM) conditions; however, a clear peak was also evident over frontal regions in the correct (C) and final mismatch (FM) conditions. The distribution of scalp activation, as inferred by CSD mapping, was highly similar across all four conditions during the PMN time interval, suggesting that the PMN is not merely associated with initial phoneme mismatches. The C and FM conditions produced a Late Negativity (peaking at ~ 520 ms) that appeared to overlap with the PMN. The fronto-central distribution of this component combined with the fact that it was augmented by a mismatch in phoneme expectations (in this case at the final position), suggests that it is involved in monitoring the position of phoneme mismatch. However, latency and scalp variations of this Late Negativity offer preliminary support for the presence of two distinct processes: one related to mapping speech input against a phonological template (i.e., PMN-like) and the second reflecting whole-item phonological analysis (N400-like).

4.2. INTRODUCTION

Models of speech recognition converge on the assumption that activation and selection of a target word is determined by the goodness of fit between the lexical form representation of a given word and the sensory input (Marslen-Wilson, 1980, 1987; Norris, 1994). Mismatching sensory information causes a candidate to be eliminated from the candidate set, thus making way for target selection. However, models differ with regard to how words mismatching sensory input are dropped from the candidate set. For instance, in the original Cohort model (Marlsen-Wilson & Welsh, 1978), mismatching sensory information causes a candidate word to be immediately eliminated from the candidate set (or cohort). However, more recent versions of the Cohort (Marlsen-Wilson, 1987) as well as Shortlist (Norris, 1994) models incorporate a more graded form of bottom-up inhibition. That is, these models are more tolerant of mismatching sensory information and take into account the phonological distance of the sensory information from the lexical form representation. In TRACE (McClelland & Elman, 1986), candidate words receiving less activation are inhibited by more strongly activated words (i.e., lateral inhibition), causing them to be deactivated. The purpose of graded bottom-up inhibition and lateral inhibition are meant to deal with distorted sensory input, such as mispronounced words.

Studies designed to address lexical selection mechanisms typically introduce mismatches in sensory input and determine if lexical candidates remain active (Connine et al., 1993; Frauenfelder et al., 2001). These studies have shown that mismatches beyond the initial phoneme, including medial as well as final mismatches, cause candidates to be

dropped from the candidate set. Evidence such as this highlights the importance of bottom-up information in lexical access and selection.

The sensitivity of the PMN to mismatching sensory information has been well documented in this thesis and in previous work (Connolly and Phillips, 1994; Connolly et al., 2001; Hagoort and Brown, 2000). These findings suggest that the PMN may serve as a useful tool for measuring competition among lexical candidates. In doing so, the PMN could potentially provide evidence with regard to whether lexical selection involves bottom-up versus lateral inhibition. However, whether or not the PMN monitors speech input beyond the initial phoneme has not been explicitly evaluated. In previous experiments, incorrect responses began with an unexpected phoneme; therefore, the first obstacle in the matching process was always encountered at the initial phoneme position and the matching process was likely aborted. In one of the experimental conditions in Connolly and Phillips (1994), the position of the first encountered phoneme mismatch was manipulated, albeit not systematically. In the phoneme-match/semantic-mismatch condition, terminal words began with the expected phoneme, but mismatched expectations at a later phoneme position signaling the violation of expectancies (e.g., *The gambler had a bad streak of luggage (luck)*; where /g/ is the first unexpected phoneme). Despite the presence of mismatching information, a PMN was not observed. Yet, if the process represented by the PMN operates beyond the initial speech input, then one would have expected a PMN to be emitted at the point at which incoming information mismatched phonological expectations. However, as Connolly and Phillips (1994) point out, the position of the initial deviation varied across terminal words (e.g., *He mailed the*

letter without a stampede. [stamp] vs *The gambler had a bad streak of luggage. [luck]*). Since ERPs were time-locked to the onset of the terminal word, inconsistency in the position of phoneme mismatch would have induced variability in the PMN response latency, and in turn attenuate its amplitude.

In order to measure whether the PMN is sensitive to mismatches beyond the initial speech input, the position of phoneme mismatch was systematically manipulated in the present experiment. As in experiment 1, participants heard instructions requiring them to delete the initial phoneme from a target item, in this case, a CCVC nonword (e.g., *smoob without the /s/*). The prompt was followed by a response that either matched expectations of the correct answer, (e.g., *moob*) or mismatched (e.g., *moop, foob, tiv*) those expectations. The position of phoneme mismatch was manipulated for incorrect responses, occurring at either the initial (e.g., ***f**oob*) or the final (e.g., *moo**p***) position of the CVC. In the third incorrect condition, all phonemes mismatched the correct response (e.g., ***tiv***). It was hypothesized that the PMN will monitor the position of mismatch, and will therefore be delayed in the FM condition relative to the IM and AM conditions.

4.3. MATERIALS AND METHODS

Participants

Eighteen healthy, right-handed English-speaking subjects (M = 22.8 [SD = 7.56; Range = 18-42], 13 females) participated in this study. All participants reported normal hearing and were screened with a self-report health questionnaire for a history of neurological, audiological and/or psychological problems. Participants were screened for reading ability and phonemic awareness using the Word Attack and Word Identification subtests of the Woodcock Diagnostic Reading Battery (Woodcock, 1998), and the Elision Subtest of the CTOPP (Wagner, Torgesen & Rashotte, 1999). One male participant was excluded from the analysis based on below average scores on the screening measures. In addition, the data from another male participant were excluded from subsequent analysis based on excessive EEG noise. Thus, the following discussion will be based on the behavioral and ERP data from 16 individuals. Informed consent was obtained from all participants and the responsible ethics board approved the study.

Stimuli and Procedures

Two hundred and forty monosyllabic nonwords (see Appendix C for a list of stimuli), all beginning with a consonant cluster, were aurally presented to participants along with the sound of the initial phoneme that was to be deleted (e.g., *smoob, /s/*). A delay of 1 second separated the presentation of the target item from that of the target phoneme. Following an interstimulus interval (ISI) of 2 seconds, participants heard a correct (C) (e.g., *moob*) or incorrect (e.g., *moop*) answer. Incorrect answers fell into three categories: Initial Phoneme (IM) Mismatch (e.g., *foob*), Final Phoneme (FM) Mismatch

(e.g., *moop*) or all Phoneme (AM) Mismatch (e.g., ***biv***). All response items in the 4 conditions were CVC nonwords.

Participants were seated in a sound attenuated room. As in previous experiments, participants were instructed to determine the resulting segment once the initial consonant had been removed. They were given a two-button response pad and instructed to press one button to segments that matched their expectations and the other for those that did not. Button presses were counterbalanced across participants. Participants were instructed to wait until they heard the entire response before pressing the button, in order to avoid increased errors resulting from participants basing decisions on the initial sound. Thus, response time data may not provide meaningful information. Participants were given a break at the mid point of the experiment. For the 240 target nonwords, there were 240 possible answers divided into 4 categories (i.e., 120 C + 40 IM + 40 FM + 40 AM). Items were differentially randomized for each participant. All stimuli were spoken by a female voice, recorded with Cool Edit 2.0 program digitized at 20,050 Hz and presented binaurally through headphones at 75 dB.

Electrophysiological Recording

EEG activity was recorded at 25 sites (F3, Fz, F4, F7, F8, FC3, FCz, FC4, FT7, FT8, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4, TP7, TP8, T3, T4, T5, T6) using sintered Ag/AgCl electrodes referenced to linked ears (see Figure 7 in Chapter 3). Electrodes were embedded in a NeuroScan Quick-Cap with positions based on the American Electroencephalographic Society (1991), an extension of the international 10-20 system (Jasper, 1958). The electrooculogram (EOG) was recorded with electrodes placed above

and below the right eye (vertical), and on the outer canthus of each eye (horizontal), and an electrode embedded in the Quick-Cap (i.e., AFz) served as ground. Impedance was kept at or below 5 kΩ. EEG was amplified by a Sensorium EPA-5 amplifier and acquired and processed with BrainProducts' Brain Vision software. Stimuli and trigger codes were delivered by Neurobehavioral's Presentation program. EEG was recorded continuously with a bandpass of .1 to 100 Hz and sampled at 500 Hz. An ERP trigger was located at the onset of each response. Data were epoched off-line from -100 to 800 ms post-stimulus onset. Data were digitally filtered offline with a low pass filter setting of 20 Hz. Trials contaminated with EOG activity greater than +/- 75 microvolts (μV) were rejected from the analysis. Twenty one percent of trials were rejected (including those rejected due to errors), with no differences in the percentage of rejected trials across conditions. EEG data on trials that participants responded to correctly were averaged separately across the four conditions.

Data Analysis

The amplitude of each component was measured by calculating the average integrated amplitude relative to baseline within specified time intervals for each component. The N100 was scored as the mean amplitude between 90 ms and 170 ms, the P200 between 170 ms and 230 ms, the PMN between 250 ms and 350 ms, and the Late Negativity between 425 and 575 ms. A wider range was chosen for the Late Negativity because visual inspection of the waveforms indicated that the response was broader in comparison to the earlier responses. The peak amplitude for each component was determined by scoring the most negative component within the latency ranges specified

above. Peak latency was defined as the time from stimulus onset to the peak amplitude of each component. Tables displaying the mean amplitude and peak latency as a function of condition will be presented for all components. However, only information that assists in clarifying the topography of the PMN will be presented in tables.

In the results presented below, only a third (40 items) of the Correct items were included in the ERP data analysis. These 40 trials were chosen randomly from the total number of trials (120), so as to equate the signal-to-noise ratio across conditions[4]. All items were included in the behavioral analysis.

A repeated measures analysis of variance (ANOVA) using conservative degrees of freedom (Greenhouse & Geisser, 1959) was conducted for the amplitude and latency of each component. Each ANOVA assessing amplitude consisted of two factors, Condition (C, IM, FM, AM) and Site (25 levels). A secondary regional analysis following the grouping method implemented in Experiment 2 was conducted in the case of a significant Condition x Site interaction. Post-hoc comparisons were conducted using the Tukey HSD test, with $p < .05$ as the required level of significance

---

[4] Results of an ANOVA including all Correct condition items did not change any of the results reported here. The amplitude of the Late Negativity decreased (became less negative) as a result of increasing the signal-to-noise ratio (including all trials), and thus made the difference between the C and FM condition larger. However, it seems more appropriate to compare waveforms that have more or less equivalent trial numbers; therefore, amplitude and latency data for the Correct condition are based on a randomly selected subset of trials.

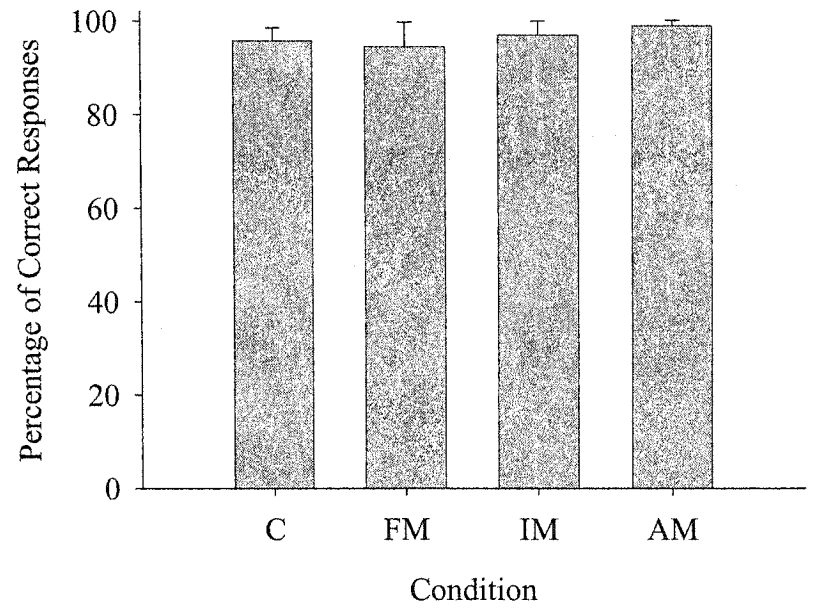
4.4. RESULTS

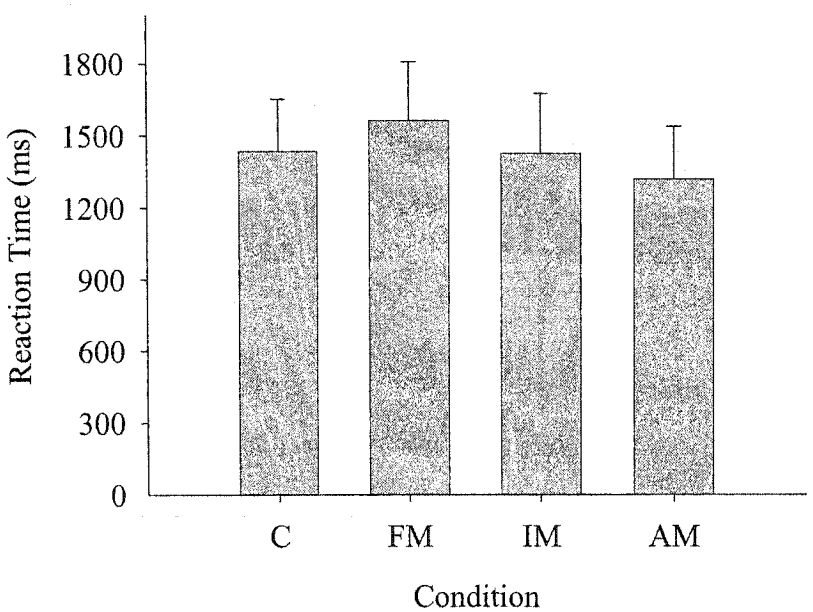
Behavioral Results

Accuracy and RT data were analyzed with a repeated measure ANOVA. Overall accuracy was high (96.5 %); however, the main effect of condition was significant ($F(3,45) = 5.52$, $p < .01$, $\varepsilon = 0.27$). Post hoc analysis indicated that accuracy in the AM and IM conditions was higher than in the C and FM conditions (Figure 14). For the analysis of RT data, a significant main effect of condition ($F(3,45) = 14.38$, $p < .001$, $\varepsilon = 0.49$), resulted from slower RTs in the FM condition than in all other conditions. Furthermore, RTs in the C and IM condition were slower than those recorded in the AM condition (Figure 14). As in experiment 2, the RTs are quite long as participants were asked to wait until they heard the entire item before making their button press. This was a necessary constraint in order to reduce the number of trials that were responded to incorrectly.

Figure 14

Accuracy (top) and reaction time (bottom) data as a function of condition.





Electrophysiological Results

Visual inspection of the grand average waveforms presented in Figure 15 and Figure 16 shows four distinct components, the N100, P200, PMN, and a Late Negativity. The N100/P200 complex is visible in all conditions, and appears relatively unaffected by experimental manipulation. The PMN begins at about 200 ms and peaks at approximately 300 ms in the IM and AM conditions. In those conditions sharing the expected initial phonemes (i.e., C and FM), a broad negativity begins at about 200 ms, peaks at approximately 500 ms, and appears larger in the FM condition. An important feature of the waveforms is that the Late Negativity elicited in the C and FM condition onsets at the same time as the PMN in the IM and AM condition. Despite this overlapping response, a distinct peak corresponding to the PMN is apparent in the FM and to a lesser extent in the C condition, particularly over frontal and central locations.

Figure 15 - Caption

Grand average ERPs (N=16) for the Correct (C, ····), Final Mismatch (FM, —), Initial Mismatch (IM, ---), and All Mismatch (AM, -·-) conditions at five midline sites and eight regions. The PMN (†) is visible in the IM and AM conditions, but a clear peak is also apparent in the FM condition at frontal locations. The Late Negativity (‡) differentiates the FM from the C condition, and appears maximal over frontal and central locations. Time (ms) is on the x-axis and amplitude (μV) is on the y-axis. Negative is up.

Figure 15

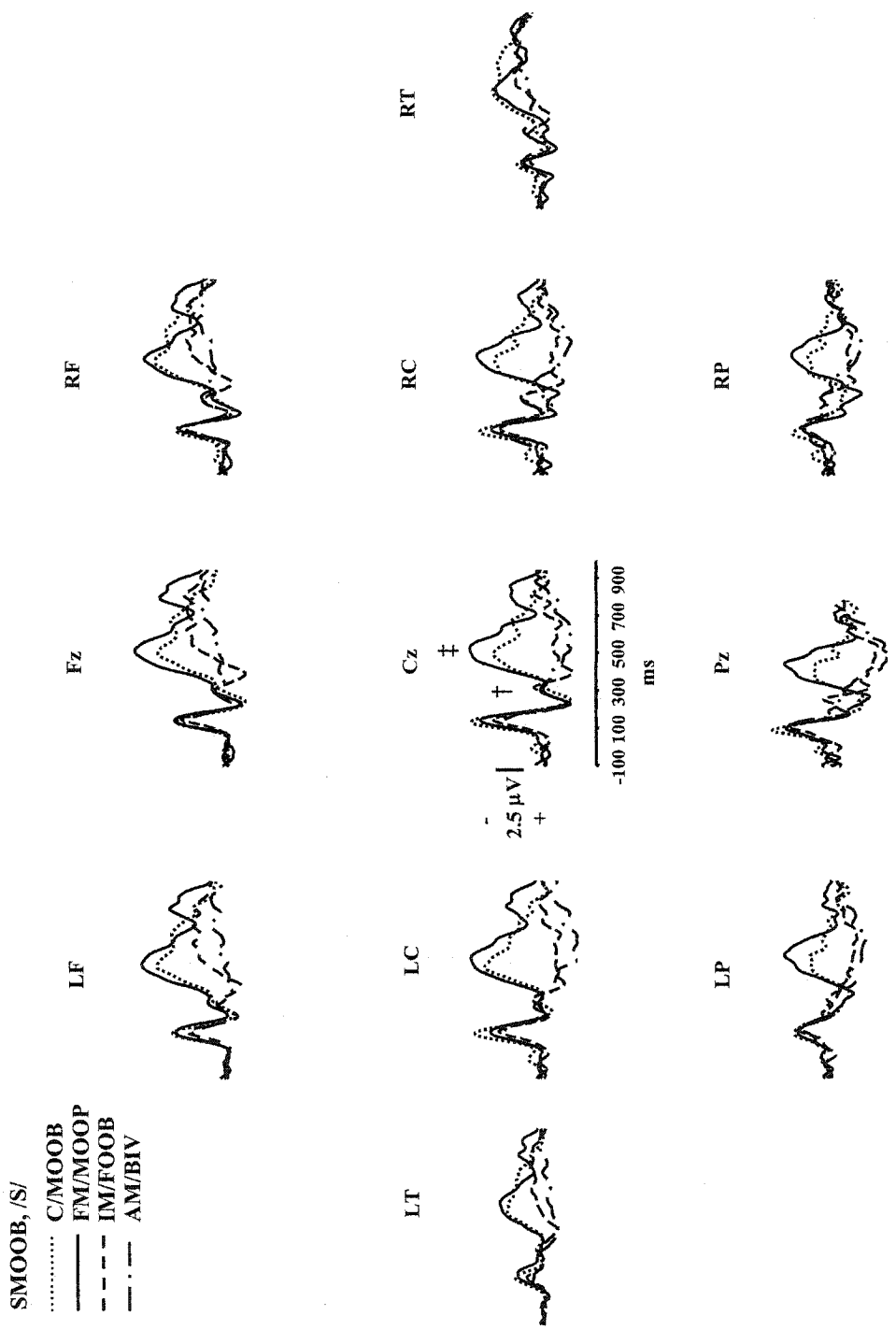
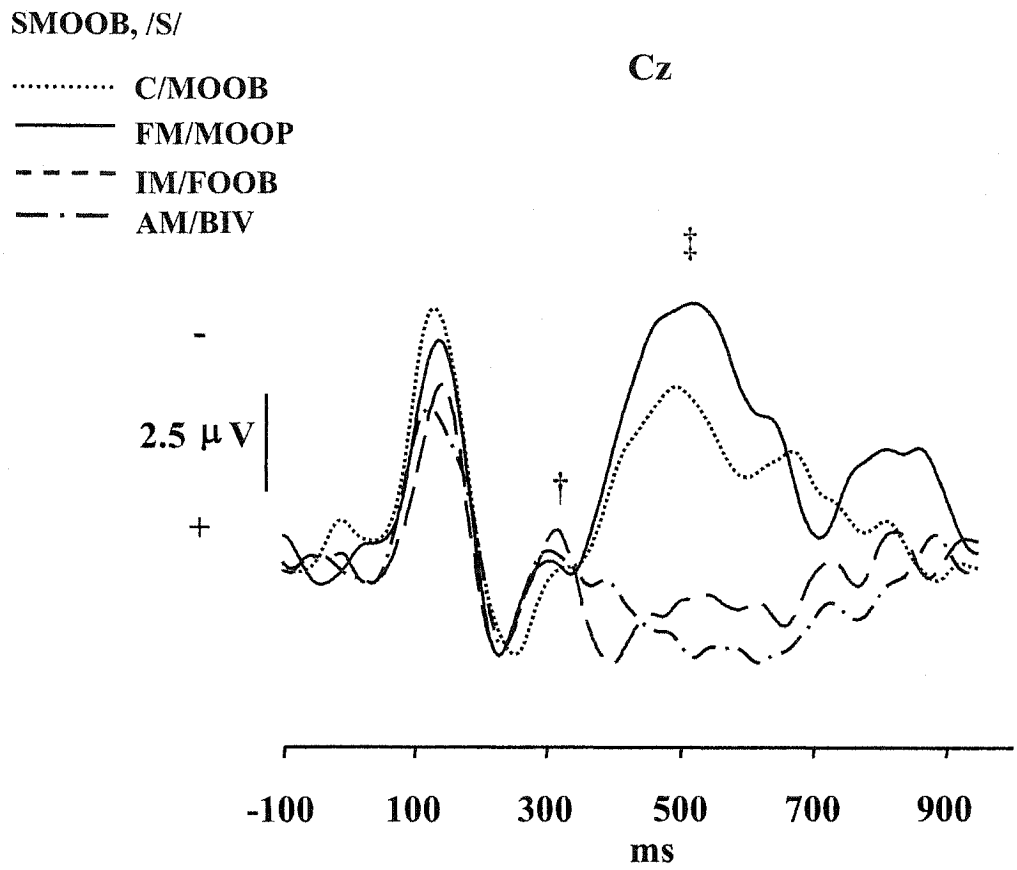

SMOOB, /S/
C/MOOB
FM/MOOP
IM/FOOB
AM/BIV
LF
Fz
RF
LC
Cz
RC
LT
RT
LP
Pz
RP
2.5 µV
-100 100 300 500 700 900
ms

Figure 16

Enlarged version of Cz in Figure 15. All details as in Figure 15.



N100 and P200

The amplitude of the N100 varied significantly ($F(3,45) = 32.34$, $p < .04$, $\varepsilon = 0.18$) across conditions. Post hoc analysis indicated that amplitudes in the C (-2.74 μV) condition were larger (more negative) than those in the IM (-1.53 μV) condition. Amplitudes in the FM (-2.20 μV) and AM (-1.85 μV) conditions, did not differ significantly from each other or from the C or FM conditions (Table 16). The distribution of the N100 over midline and central-parietal sites, accounted for the significant Site main effect ($F(24,369) = 25.3$, $p < .001$, $\varepsilon = 0.63$). The peak latency of the N100 (C = 139 ms, FM = 141 ms, IM = 147 ms, AM = 140 ms; Table 16) was not sensitive to the Condition factor ($p = .34$). The N100 peaked earlier at Cz than over left temporal and lateral parietal sites (P7/P8).

The amplitude of the P200 was not modulated ($p = .81$) by the Condition factor (C = 0.61 μV, FM = 0.70 μV, IM = 0.43 μV, AM = 0.30 μV; Table 17). The main effect of Site approached significance ($p = .056$), as amplitudes over midline and lateral central sites were more positive than those over lateral frontal, lateral temporal and lateral parietal locations. The interaction of Condition x Site was not significant ($p = .10$). P200 latency was not influenced by the conditional manipulation (C = 242 ms, FM = 231 ms, IM = 232 ms, AM = 232 ms; Table 17); however, P200 latency did vary significantly across sites ($F(24,360) = 4.75$, $p < .01$, $\varepsilon = 0.24$). The P200 peaked earliest at lateral frontal (F7/F8) and fronto-temporal locations (FT7/FT8). The Condition x Site interaction was also significant ($F(72,1080) = 2.93$, $p < .01$, $\varepsilon = 0.16$). A subsequent Condition x Region x Hemisphere interaction revealed a significant main effect of Region ($F(3,45) =$

9.87, $p < .001$, $\varepsilon = 0.38$), as responses peaked earlier in the frontal than in the parietal region, and earlier in the temporal than in the central and parietal regions. A significant Condition x Region interaction ($F(9,135) = 3.40$, $p < .01$, $\varepsilon = .18$) was attributable to the P200 in the C condition peaking later over the central and parietal region.

Table 16

Mean Amplitude (μV) and Peak Latency (ms) of the N100 in the Correct (C), Final Mismatch (FM), Initial Mismatch (IM), and All Mismatch (AM) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	-2.74 (0.34)	139 (3.18)
FM	-2.20 (0.35)	141 (3.84)
IM	-1.53 (0.38)	147 (4.19)
AM	-1.85 (0.29)	140 (4.27)

Table 17

Mean Amplitude (μV) and Peak Latency (ms) of the P200 in the Correct (C), Final Mismatch (FM), Initial Mismatch (IM), and All Mismatch (AM) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	0.61 (0.50)	242 (3.50)
FM	0.70 (0.45)	231 (4.67)
IM	0.43 (0.42)	232 (5.28)
AM	0.30 (0.40)	232 (3.54)

PMN

Analysis of PMN amplitudes revealed no Condition main effect (C = 0.70 μV, FM = 0.83 μV, IM = 0.025 μV, AM = 0.034 μV; Table 18). A significant Site effect ($F(24,360) = 3.42, p < .03, \varepsilon = 0.19$), was attributable to the PMN fronto-central scalp distribution. The CSD maps further highlight the anterior distribution of the PMN across all four conditions (Figure 17). Due to the significant interaction of Condition x Site ($F(72,1080) = 3.20, p < .01, \varepsilon = 17$), a Condition x Region x Hemisphere analysis was performed. In this analysis, the interaction of Condition x Region was significant ($F(9,135) = 3.70, p < .01, \varepsilon = 0.20$). Post hoc analyses attributed the interaction to more positive amplitudes recorded in the central and parietal regions for the C and FM condition (Table 19). The PMN in the IM and AM condition was statistically equivalent in amplitude across regions. The positive amplitudes in the C and FM condition over central and parietal regions are the result of the positive-going waveform that overlaps with the PMN in the IM and AM conditions. A significant Condition x Hemisphere interaction ($F(3,45) = 3.99, p < .02, \varepsilon = 0.21$) was invoked by the right hemispheric asymmetry recorded in the IM and AM conditions. The PMN appears more prominent over the right hemisphere compared to the left hemisphere in the grand average waveforms (Figures 15, 16), as well as in the CSD maps (Figure 17).

The latency of the PMN did not vary across incorrect conditions (C = 300 ms, FM = 297 ms, IM = 302 ms, AM = 296 ms; Table 18). A significant Site effect ($F(24,360) = 8.62, p < .001, \varepsilon = 36$) indicated that the PMN peaked earliest at central and parietal locations.

Table 18

Mean Amplitude (μV) and Peak Latency (ms) of the PMN in the Correct (C), Final Mismatch (FM), Initial Mismatch (IM), and All Mismatch (AM) collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	0.70 (0.51)	300 (7.17)
FM	0.83 (0.55)	297 (5.84)
IM	0.025 (0.50)	302 (3.96)
AM	0.034 (0.47)	296 (6.54)

Figure 17 - Caption

Current source density (CSD) maps presented in 50 ms intervals from 200 ms to 400 ms (top) and from 450 ms to 650 ms (bottom). Iso-contour lines are separated by 1.5 μV. Blue regions represent negative activation (i.e., a sink) and red regions represent positive activation (i.e., a source). Activation corresponding to the PMN appears to onset over anterior regions beginning at 300 ms and is sustained for the length of the interval shown. In the IM and AM conditions, this activation displays a right hemispheric asymmetry. The sustained negative activation is the basis of the Late Negativity that is elicited in the C and FM condition. The negative activation appears similar in all conditions, particularly in the 450 ms to 650 ms interval; however, the source of this activation is different. In the FM, IM and AM conditions, a parietal source (red activation) located in the right hemisphere accounts for the anterior sink observed, while a left sided parietal source underlies the anterior activation observed in the C and FM conditions.

Figure 17

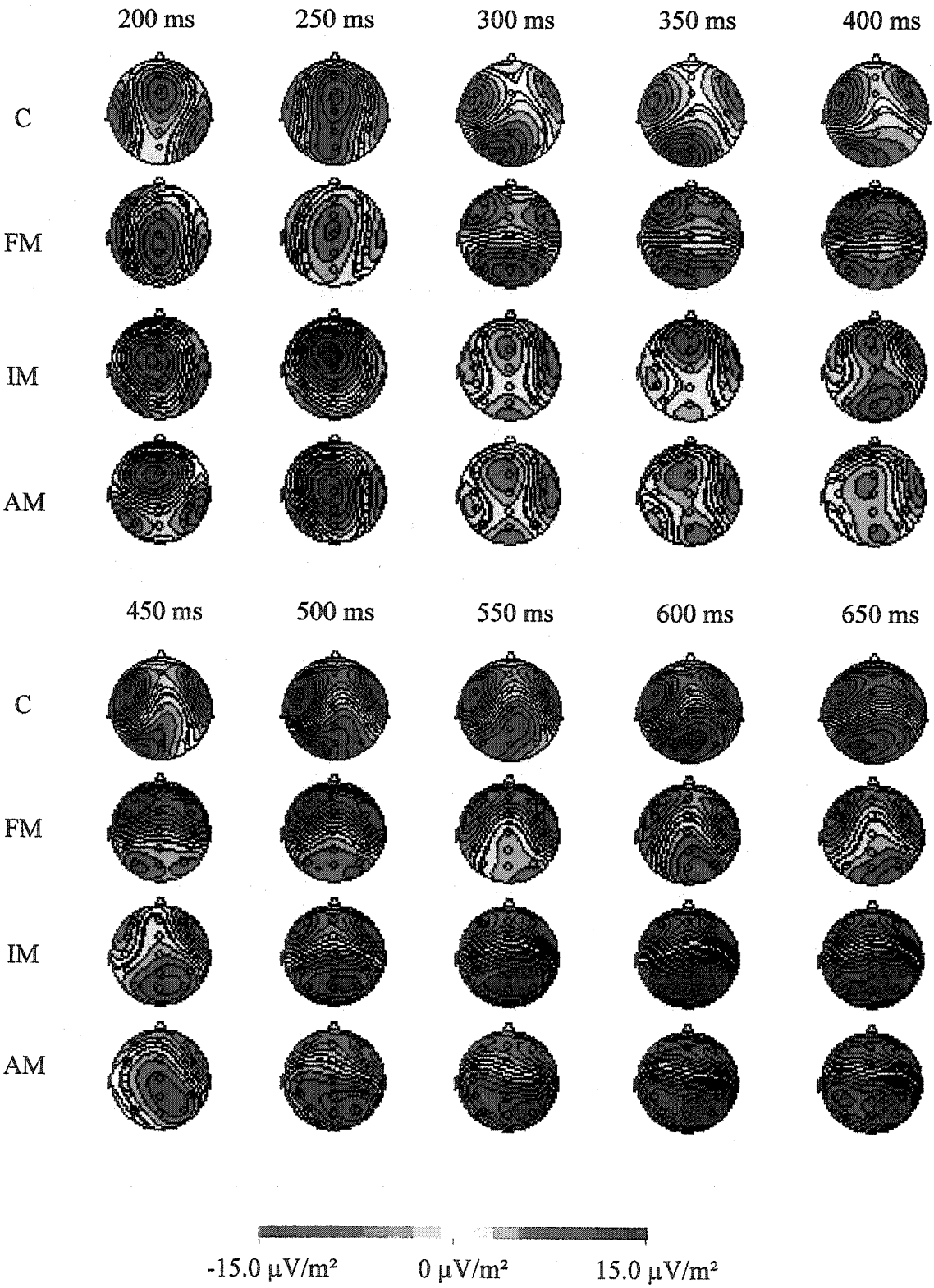

200 ms
250 ms
300 ms
350 ms
400 ms
C
FM
IM
AM
450 ms
500 ms
550 ms
600 ms
650 ms
C
FM
IM
AM
-15.0 μV/m²
0 μV/m²
15.0 μV/m²

Table 19

Mean Amplitudes (μV) and Standard Error of the PMN for the Condition x Region interaction.

Region	Type	Mean Amplitude
Frontal	C	-0.22 (0.76)
	FM	-0.56 (0.69)
	IM	-0.37 (0.61)
	AM	-0.43 (0.54)
Central	C	0.89 (0.63)
	FM	1.82 (0.86)
	IM	-0.21 (0.69)
	AM	-0.21 (0.76)
Temporal	C	-0.10 (0.48)
	FM	0.13 (0.47)
	IM	-0.09 (0.38)
	AM	-0.19 (0.37)
Parietal	C	1.81 (0.44)
	FM	1.95 (0.63)
	IM	0.22 (0.59)
	AM	0.35 (0.71)

Late Negativity

As is clear in Figures 13 and 14, a Late Negativity differentiated the C and FM condition from the IM and AM conditions. The significant Condition effect ($F(3,45) = 30.99, p < .001, \varepsilon = 0.67$) indicated that amplitudes in the C (-2.91 μV) and FM (-4.20 μV) condition were larger (more negative) than amplitudes in the IM (0.90 μV) and AM (1.62 μV) conditions, which did not differ from each other (Table 20). Amplitudes in the FM condition appear more negative than those in the C condition; however, this effect did not reach significance ($p = .06$) in the interval analysis. Nevertheless, when the peak amplitude analysis of the Late Negativity was examined, the amplitude of the Late Negativity was larger (more negative) in the FM (-6.13 μV) compared to the C (-3.85 μV). For the interval analysis, a significant Site effect ($F(24,360) = 10.46, p < .001, \varepsilon = 0.41$) indicated that amplitudes were maximal over frontal electrode locations. The Condition x Site effect was also significant ($F(72,1080) = 5.05, p < .001, \varepsilon = 0.25$). A subsequent regional analysis replicated the Condition main effect ($F(3,45) = 31.50, p < .001, \varepsilon = 0.67$) and also showed main effects of Region ($F(3,45) = 12.63, p < .001, \varepsilon = 0.46$) and Hemisphere ($F(1,15) = 8.99, p < .01, \varepsilon = 0.38$). Subsequent post-hoc analyses indicated that amplitudes were maximal over the frontal region and were augmented in the central region relative to the parietal region. The Hemisphere interaction was attributable to a right hemispheric asymmetry (-1.50 μV compared to 0.97 μV for the left hemisphere). The Condition x Region interaction was significant ($F(9,135) = 6.32, p < .004, \varepsilon = 0.30$). Further analyses indicated that amplitudes in the FM condition were significantly larger than those in the C condition over the frontal region (FM = -6.54 μV

versus C = -4.96 μV). Amplitudes in the central region, although smaller than those recorded in the frontal region, were larger in the FM (-4.85 μV) condition compared to the C (-3.18 μV) condition (Table 21). FM amplitudes in the parietal region appeared larger than those in the C condition; however, this comparison was not significant (p = .07). The CSD maps show anterior activation corresponding to the Late Negativity in the C and FM condition (Figure 17).

Table 20

Mean Amplitude (μV) and Peak Latency (ms) of the Late Negativity in the Correct (C), Final Mismatch (FM), Initial Mismatch (IM), and All Mismatch (AM) conditions collapsed across the Site factor. Standard error is presented in parentheses.

Condition	Mean Amplitude	Peak Latency
C	2.91 (0.58)	510 (8.07)
FM	-4.20 (0.64)	522 (6.65)
IM	0.90 (0.70)	513 (6.17)
AM	1.62 (0.63)	490 (7.89)

Table 21

Mean Amplitudes (μV) of the Late Negativity for the Condition x Region interaction. Standard Error is presented in parentheses.

Region	Type	Mean
Frontal	**C**	-4.97 (0.79)
	FM	-6.54 (0.97)
	IM	-1.15 (0.74)
	AM	0.13 (0.76)
Central	**C**	-3.18 (0.69)
	FM	-4.85 (0.77)
	IM	1.89 (1.01)
	AM	2.66 (0.95)
Temporal	**C**	-3.00 (0.52)
	FM	-3.31 (0.54)
	IM	-0.17 (0.49)
	AM	0.42 (0.49)
Parietal	**C**	-0.92 (0.63)
	FM	-2.28 (0.74)
	IM	2.59 (0.98)
	AM	2.95 (1.07)

Difference Waves

Difference waveforms were obtained in order to clarify the relationship between the C and FM condition. Difference waves will isolate any component(s) occurring in the FM condition that does not occur in the C condition. As seen in Figure 18, the procedure successfully separated out a Late Negativity. The mean amplitude of the Late Negativity was calculated for left and right frontal, central, temporal and parietal regions (Table 22). One sample t-tests revealed that the Late Negativity differed significantly from baseline at all regions with the exception of the left temporal region ($t(15) > 2.13$).

It appears from Figure 18 that the Late Negativity peaks earlier over frontal regions than it does over parietal regions. The CSD maps derived from the difference waves implies that this apparent latency modulation across the scalp may actually reflect the presence of two distinct neural generators (Figure 19). An anterior sink is apparent during the early portion of the Late Negativity interval (maps 400 ms - 500 ms), while a posterior sink emerges during the later portion of the Late Negativity interval (map 550 ms). A repeated measures ANOVA with Interval (425-525, 525-625), Region (Frontal, Central, Temporal, Parietal), and Hemisphere (Left, Right) as factors confirmed these observations. A significant Interval x Region interaction ($F(3,45) = 13.02$, $p < .001$, $= 0.46$) was attributable to larger amplitudes recorded over the frontal region in the first interval and over the parietal region in the second interval (Table 23). Amplitudes over the frontal region did not differ between the two intervals; however, amplitudes over the parietal region were more negative in the second interval compared to the first. Amplitudes in the central region were more negative in the second interval compared to

the first, and amplitudes in the temporal region did not differ between the two intervals.

Figure 18 - Caption

Grand average (N = 16) difference waveforms at midline and lateral regions derived by subtracting the C condition from the FM condition. The subtraction isolated a Late Negativity that was broadly distributed. The time scale extending from 300-700 ms highlights the development of this Late Negativity, which peaks approximately 75 ms earlier over anterior regions compared to posterior conditions. Time (ms) is on the x-axis and amplitude (μV) is on the y-axis. Negative is up.

Figure 18

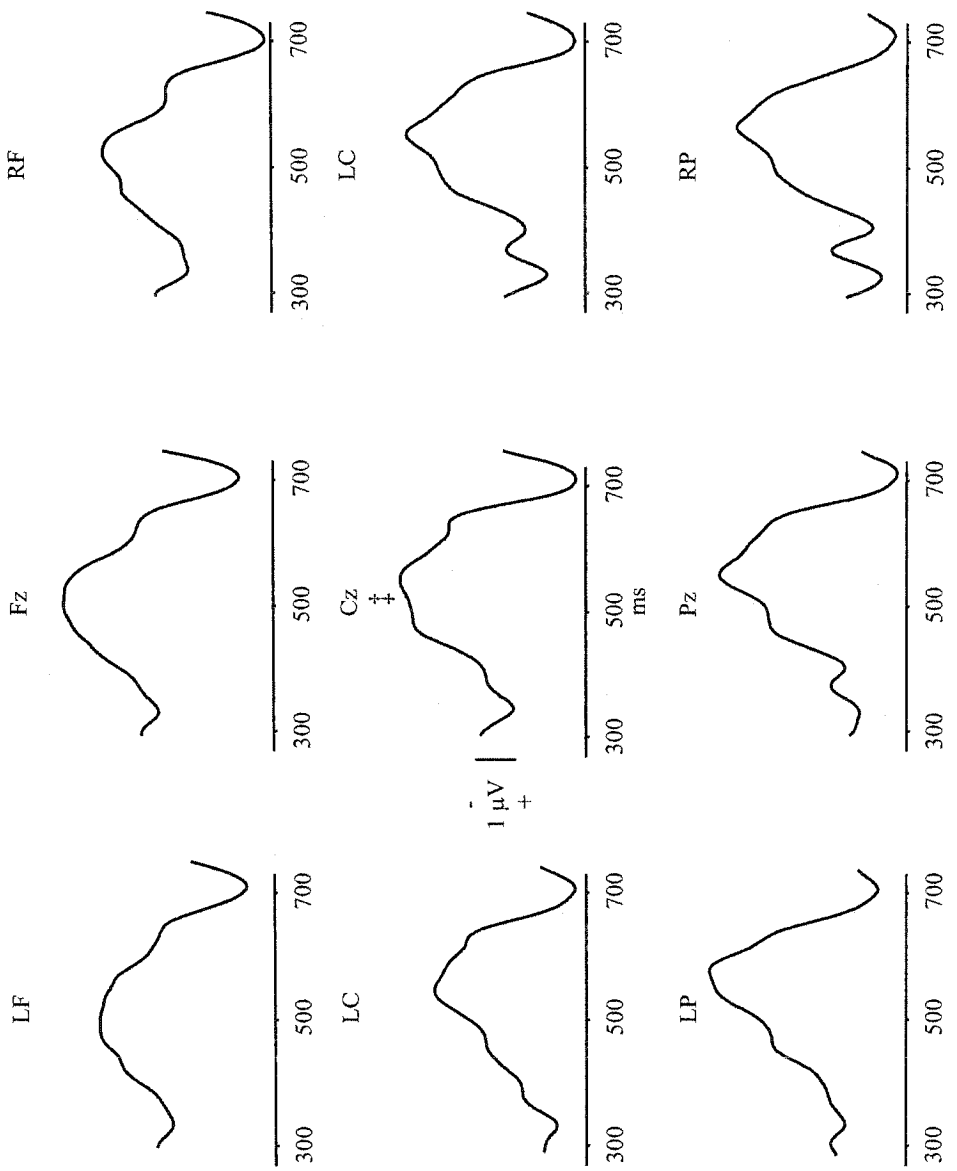


Figure 19

CSD maps derived from the difference waveforms presented in figure 18. Maps are presented in 50 ms intervals, and are separated by 1 μV iso-contour lines. Blue regions correspond to negative activation and red regions to positive activation. Anterior activation reminiscent of the PMN is apparent from 300 ms to 500 ms, perhaps reflecting the continued phonological mapping necessitated by the manipulation of phoneme mismatch. A parietal sink emerges at 550 ms and implies that two distinct components underlie the broad Late Negativity apparent in the grand average waveforms.

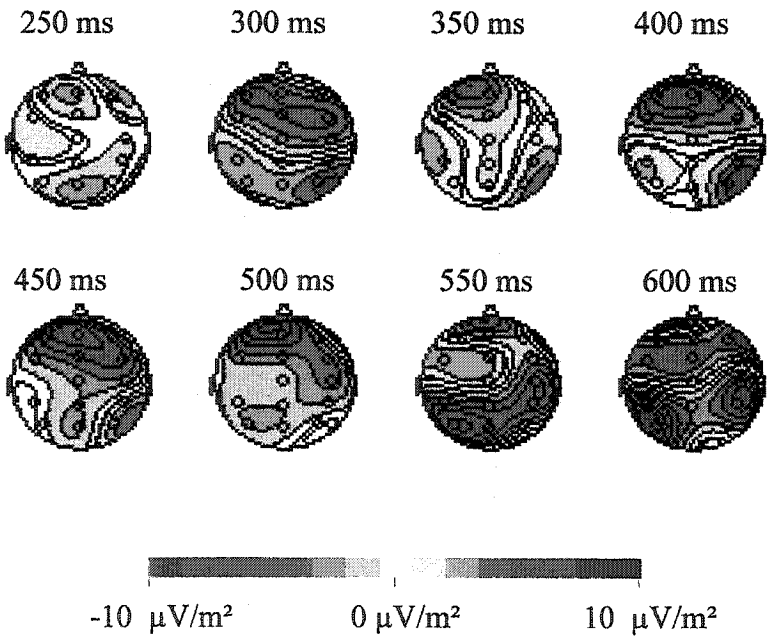


Table 22

Mean Amplitude (in μV) of the Late Negativity from baseline at 8 scalp regions (Left and Right Frontal, Central, Temporal and Parietal). Standard Error is presented in parentheses.

Region	Mean Amplitude
Left Frontal	-1.96 (0.54)
Right Frontal	-1.73 (0.37)
Left Central	-2.10 (0.43)
Right Central	-1.91 (0.29)
Left Temporal	-.0.83 (0.33)
Right Temporal	-0.49 (0.27)
Left Parietal	-1.63 (0.30)
Right Parietal	-1.32 (0.29)

Table 23

Mean Amplitude (μV) of the Late Negativity isolated in the difference waves for both the first (425-525ms) and second (525-625 ms) interval at 4 scalp regions (Frontal, Central Temporal, and Parietal). Standard error is presented in parentheses.

Region	First Interval	Second Interval
Frontal	-1.82 (0.50)	-1.38 (0.51)
Central	-0.68 (0.31)	0.71 (0.71)
Temporal	-0.52 (0.51)	-0.68 (0.30)
Parietal	-1.05 (0.29)	-2.27 (0.38)

4.5. DISCUSSION

As in previous experiments reported in this thesis, a PMN response was elicited to violations in the expectedness of the initial phoneme. Figure 15 shows a distinct component in the IM and AM conditions, where the initial phoneme violated expectations developed by the prompt. However, a peak is also identifiable in those conditions that matched initial phoneme expectations (i.e., the FM and C conditions), particularly at left frontal, Fz and Cz locations (Figures 15, 16). The apparent elicitation of the PMN in conditions which meet phonological expectations is further support for proposals that the PMN represents phonological processing generally and is not solely attributable to mismatches in the initial phoneme (Connolly et al., 2001; Hagoort & Brown, 2001).

The occurrence of a Late Negativity in the C and FM conditions may be indicative of the on-going phonological processing requirements necessitated by the cognitive demands of the task. It is hypothesized that this Late Negativity is related to the PMN for several reasons. First, the scalp distributions of the PMN and the Late Negativity are quite similar; such is not the case for the N400 or N400-like response which has been shown to display a distinct topography from that of the PMN (Connolly and Phillips, 1994; Connolly et al., 2001; Hagoort and Brown, 2000). The similarity in distribution between the PMN and the Late negativity is particularly evident in the CSD maps derived from the difference waveforms (Figure 19), in which anterior activation is sustained from the time point corresponding to the PMN (~300 ms) to the peak of the Late Negativity (~500 ms). The sustained activation over frontal regions is reminiscent of the continual anterior activation attributed to phonological processing in recent work employing high-resolution

montages (Connolly et al., 2001; D'Arcy et al., in press). Second, the Late Negativity appears sensitive to the same cognitive mechanisms that underlie the PMN, namely mapping speech input onto a phonological template. Since both the C and FM conditions began with the expected phonological sequence, participants had to continue mapping phonetic/phonemic cues against a template of phonological expectations until the nature of the final phoneme was revealed. The continuation of phonological processing beyond the initial phoneme is manifested in the elicitation of the Late Negativity in both the C and FM conditions. Third, in line with previous interpretations of the PMN, a mismatch between speech input and phonological expectations resulted in the augmentation of the Late Negativity in the FM condition.

The Late Negativity is not thought to be exclusively related to the N400-like response seen in experiments 1 and 2. If the Late Negativity reflected a phonological incongruency effect as proposed in experiments 1 and 2, then one would have also predicted its manifestation in the IM and AM conditions. The absence of the response in the IM and AM condition suggests that further phonological analysis was terminated due to the mismatching sensory information encountered at the initial phoneme. Furthermore, there was no evidence of a Late Negativity elicited to anticipated items in experiments 1 and 2, whereas a clear Late Negativity was evoked in the C condition in this experiment.

There is reason to speculate that the Late Negativity observed here may in fact represent the co-occurrence of two components, and thus two distinct cognitive mechanisms. The CSD maps derived from subtracting the C from the FM condition, illustrate an anterior sink corresponding to PMN-like activation, as well as a later onset

parietal sink that may correspond to the N400-like responses observed previously (Experiments 1 and 2 this thesis; Connolly et al., 2001; Dumay et al., 2001; Praamstra & Stegeman, 1993; Praamstra et al., 1994). Although it is speculation at this point, it is hypothesized that the earlier portion of the waveform is related to the PMN and is involved in the continued mapping of speech input to phoneme candidates, while the later portion of the waveform is involved in whole-item phonological analysis.

The current experiment provides evidence that the neural mechanisms responsible for eliciting the PMN are involved in mapping sensory input against a phonological form representation in a continuous fashion. Future studies will time-lock the onset of ERP recording to the point at which coarticulatory cues specify the presence of a mismatch in expectations. This will allow for a more accurate picture of the consequences of phonetic mismatches on the response characteristics of the PMN. If the PMN or a PMN-like process does prove to monitor speech input in a continuous fashion, then we can begin to address issues pertaining to lexical selection mechanisms.

CHAPTER 5: FUNCTIONAL INTERPRETATION OF THE PMN

5.1. INCORPORATION OF THE PMN INTO MODELS OF SPOKEN WORD RECOGNITION

The primary objective of this thesis was to clarify functional interpretations of the PMN. As outlined in the introduction, there was debate as to whether the PMN reflects a pre-lexical versus a lexical/semantic stage of spoken word recognition. In order to dissociate levels of processing, a phoneme deletion task, which engages metacognitive skills independently of lexical/semantic influences, was developed. Findings showed that the PMN is largest to items that mismatch expectations primed by the task context (i.e., the prompt). These results provide support for the hypothesis that the anticipated answer facilitates a phonological stage of word recognition so long as the incoming speech information corresponds to the primed template. A matching process between that particular template and the incoming speech information operates beyond the initial phoneme. A mismatch, regardless of position, appears to terminate this comparison process, and augments the PMN. However, the matching process, regardless of outcome appears to invoke the PMN. This view is based on observation of the response to correct answers and not simply in response to deviations between the template and acoustic cues. This proposal is supported by previous work (Connolly & Phillips, 1994; Connolly et al., 2001; Connolly et al., 1992; Hagoort & Brown, 2000; van den Brink et al., 2001), which observed a PMN response in correct contexts.

The early onset of a large P300 in experiment 1 made it difficult to interpret the

presence or absence of the PMN in the C condition (Figure 3) and yet, the negative activation over anterior regions in the C condition was reminiscent of PMN activity seen in incorrect conditions (Figure 5). The strongest evidence for the obligatory activation of the PMN during phonological processing was presented in experiments 2 and 3. The PMN response observed for matching items in the grand average waveforms in experiment 2 were unambiguous (Figure 9) and the scalp activity corresponding to the PMN was similar to that observed for mismatching items (Figure 11). Even in experiment 3, where a Late Negativity overlapped with the PMN, a distinct peak is apparent in the C and FM conditions (Figure 15). Furthermore, the scalp activity in the C and FM conditions was analogous to that observed in the IM AM match conditions (Figure 17). Taken together, these results indicate that the PMN reflects a compulsory stage of speech recognition and is not merely a response associated with initial phoneme mismatches.

The statistically equivalent PMN responses observed for both words and nonwords is evidence that lexical access is not a factor in its occurrence and function, and thus does not support the hypothesis that the PMN reflects early lexical influences on speech perception (Hagoort and Brown, 2000; van den brink et al., 2001). The independence of the PMN from an N400-like response also challenges interpretations of the PMN as being an early onset N400 (Van Petten et al., 1999). Although an N400-like response was observed in experiments 1 and 2, it did not interfere with the PMN. In fact, in experiments 1 and 2, the PMN appears more robust than the N400 response (Figure 3, Figure 9). Finally, the apparent sensitivity of a PMN-like response to positional mismatches suggests that the PMN operates in a continuous fashion.

Together, these results offer further evidence for the proposal that the PMN reflects a phonological stage of word recognition that may be initially at the level of translating the speech signal into a phonological sequence prior to setting up a shortlist (Norris, 1994) or cohort (Marslen-Wilson, 1987) of lexical candidates. Subsequently, this list of lexical candidates, influenced by top-down phonemic expectations, is continuously matched to acoustic-phonetic cues present in the incoming speech information. If this merging process continues without obstacle (i.e., the incoming information matches expectations) the PMN is attenuated. If, on the other hand, a mismatch is encountered, then the PMN is augmented since phonological expectations are rendered useless and new hypotheses must be generated.

This account of the functionality of the PMN can most easily be incorporated into the MERGE model of speech recognition proposed by Norris, McQueen, and Cutler (2000). MERGE proposes that phonological information is analyzed in a continuous bottom-up fashion and receives no direct feedback from lexical representations. The present results can be understood in a model that includes a phonological stage involving phoneme cohorts developed from incoming acoustic information and selection between phoneme candidates. This development and selection process appears to be influenced by top-down phonological expectations that are created by linguistic and task context. Thus, results of this experiment propose that the PMN reflects the merging of phonological top-down information with pre-phonological representations. As in MERGE, expectations are not thought to affect bottom-up processing, in this case of the speech signal, but rather decisions at a higher level, in this case concerning phonological interpretation.

5.2. THE PMN AND ITS RELATIONSHIP TO OTHER ERP COMPONENTS

Studies presented here clearly support the dissociation of the PMN from the mismatch negativity (MMN) and the N2 response. The MMN is an ERP response observed for oddball items in sequences of repeated auditory stimuli (Näätänen, 1990). An experimental manipulation that is critical for eliciting mismatch negativities is the presence of infrequently occurring stimuli (Näätänen, 1990). In experiment 1, the PMN could be seen in all conditions but was largest in incorrect conditions, which accounted for 75% (25% each) of the total number of trials presented. This experimental design is exactly the opposite of oddball paradigms needed to elicit the mismatch negativity (i.e., the MMN responds to the few deviant stimuli presented in the context of standard stimuli). In contrast to paradigms that elicit an MMN, in which participants' attention is typically directed away from eliciting stimuli, participants consciously process stimuli in paradigms that elicit the PMN. Unlike the MMN, eliciting an N2 does require that participants attend to stimuli. However, the N2 is similar to the MMN in that it occurs to infrequent stimuli.

The explicit requirement of phonemic analysis in this study effectively isolated the PMN from other language related components. Specifically, the N400 related to semantic processing, which occurs in close temporal proximity to the PMN and, in some paradigms, can mask it (e.g., Connolly & Phillips, 1994; Hagoort & Brown, 2000; van den Brink et al., 2001). Although a later negativity was apparent in all three experiments, a robust PMN peak was observed over fronto-central scalp regions, a distribution which is consistent with that observed in recent investigations employing high-resolution

montages (Connolly et al., 2001; D'Arcy et al., in press; Kujala et al., 2003). Inconsistencies in the PMN scalp topography may be related to overlapping negativities seen in previous experiments. Hagoort and Brown (2000) observed a centro-parietal distribution, while Connolly and Phillips (1994) reported an equal distribution across the major anterior to posterior sites. Visual inspection of the waveforms of previous investigations (Holcomb & Neville, 1991; Praamstra et al., 1994) shows that an early negativity was most distinct from the later N400 at centro-parietal electrode locations. However, it is possible that the PMN was obscured at frontal locations by the later negativity (i.e., the N400), which was maximal at fronto-central locations[5]. The ability to isolate the PMN from other components is important for elucidating the cortical regions involved in phonemic analysis, using source localization techniques.

[5] Differences between related and unrelated stimuli were largest at centro-parietal locations; however, negative waveform seen to both types of stimuli had a fronto-central maximum.

5.3. POTENTIAL CLINICAL APPLICATIONS OF THE PMN

Most ERP studies focusing on phonological processing have employed rhyme judgment tasks (Lovrich, Cheng, Velting, & Kazmerski, 1997; Praamstra & Stegeman, 1993; Praamstra et al., 1994; Rugg, 1984a, 1984b). As already discussed above, non-rhyming targets are associated with an N450 or N400-like response. To my knowledge, the experiments presented in this thesis represent the first ERP studies that have necessitated the engagement of more advanced forms of phonological awareness skills, defined as the ability to identify and manipulate the sound structure of language (Ellis, 1993). The phoneme deletion task employed here requires the ability to manipulate individual phonemes (i.e., phoneme awareness), which is considered a higher level of phonological awareness compared to, for instance, the ability to detect rhymes (Anthony, Lonigan, Burgess et al., 2002; Hesketh, Adams, & Nightingale, 2000). Typically, the hierarchy of phonological awareness skills follows a developmental course whereby children are sensitive to rhyme before they are sensitive to intrasyllabic units (i.e., onsets and rimes), and are sensitive to intrasyllabic units before they are sensitive to individual phonemes (Anthony, Lonigan, Burgess, et al., 2002; Liberman, Shankweiler, Fisher, & Carter, 1974). The development of phonological awareness skills, and in particular the development of phoneme awareness, is pivotal to reading acquisition, for it is knowledge of the properties of spoken language that shape the basis for a child's ability to map print onto spoken words (Liberman, 1998). An extensive literature shows that efficient reading skills are dependent on the attainment of phonological awareness (Bradley & Bryant, 1983; Wagner & Torgensen, 1987), that the core problem underlying reading disabilities

is a deficit in phonological awareness skills (Fletcher, Shaywitz, Shankweiler, et al, 1994; Stanovich & Siegel, 1994), and that measures of phonemic awareness skills are among the best predictors of reading achievement (Muter, Hulme, Snowling, & Taylor, 1997, 1998; Stanovich, Cunningham, & Cramer, 1984; Wagner, Torgesen, Rashotte, et al, 1997).

Neuroimaging studies employing different imaging methods (i.e., PET, MEG, fMRI) and different tasks (i.e., auditory rhyme, visual word/nonword rhyme, letter rhyme) have pinpointed the involvement of the left temporo-parietal region in phonological processing, and its dysfunction in dyslexic adults (Paulesu, Frith, Snowling, et al, 1996; Rumsey, Andreason, Zametkin, et al, 1992; Shaywitz, Shaywitz, Pugh, et al, 1998; for reviews see Pugh, Mencl, Jenner, et al, 2001 and Temple, 2002). Although initial reports were based on observations of reading impaired adults, subsequent research has shown similar disruptions in the left temporo-parietal region in children (Shaywitz, Shaywitz, Pugh, et al, 2002; Simos, Breier, Fletcher, Bergman & Papanicolaou, 2000; Temple, Poldrack, Salidis, et al, 2001).

The studies reported above illustrate dysfunctions in the spatial profile of reading impaired individuals. However, a number of studies have reported neurophysiological disruptions in the time course of orthographic and phonological processes in reading impaired adults (Helenius, Salmelin, Service, & Connolly, 1999; Salmelin, Service, Kiesilä, Uutela, & Salonen, 1996) and children (Kraus, McGee, Carrell, Zecker, Nicol, & Koch, 1996; Taylor & Keenan, 1999). Recently, our lab has found abnormalities in the time course of phonological processing in children with reading disabilities (Newman et

al, in preparation). Specifically, we have found that the PMN is attenuated and/or delayed in adults and children with reading disabilities. This finding serves as further support for the role of the PMN in a phonological processing stage of spoken word recognition. The relative absence of the PMN in a group of reading disabilities children likely reflects disruptions in the underlying brain circuitry responsible for phonological processing. It is possible that the absence of the PMN in dyslexic children is related to the left temporo-parietal dysfunction reported in those studies reported above. This hypothesis is supported by the recent localization of the PMNm to the anterior region of the left temporal cortex in a group of normal-reading adults (Kujala et al., 2003).

It has been shown that intervention methods emphasizing the attainment of phonemic awareness skills produce the best outcomes in terms of remediation (Ball & Blachman, 1991; Foorman, Francis, Fletcher, Schatschneider, & Mehta, 1998; Torgesen, Rashotte, & MacPhee, 2001). However, the neural systems underlying such improvements are still not fully understood. For instance, do remediation programs re-train the cognitive network to function as it does in so-called normal readers, or do they teach successful methods of compensation? One of our on-going research projects attempts to address this question by monitoring reading impaired adults and children as they progress through a reading intervention program. The intervention program, Spell Read P.A.T., focuses on improving reading skills through intensive instruction in phonological processing skills. In our work, the effects of training are evaluated by neuropsychological and ERP measurements, administered before training and at various times during training. The results have been remarkable. We have seen the appearance of

the PMN in poor readers for whom the PMN was initially absent, as well as an earlier latency in those readers who had initially showed the response but for whom it had been significantly delayed (Newman, Connolly, MacDonald, & Arnold, 2001; Connolly & Newman, in preparation). These manifestations of neural plasticity in poor readers have been observed before any behavioral improvement is observed. Furthermore, evidence of neural plasticity have been observed in both children and adults indicating that changes in the neural systems underling phonological processing are not solely due to on-going developmental processes.

Our remediation results are in line with those from a handful of studies employing MEG, ERP, and fMRI techniques (Kujala, Karma, Ceponiene, et al, 2001; Simos, Fletcher, Bergman, et al, 2002; Temple, Deutsch, Poldrack, et al, 2003). In a recent fMRI study, Temple et al. (2003) measured children's brain activity with fMRI before and after they underwent behavioral remediation with the Fast ForWord Language program (Merzenich, Jenkins, Johnston, et al, 1996). Before training, children showed decreased activation in left temporo-parietal regions, a finding that is consistent with previous fMRI studies conducted on reading disabled adults and children (for reviews see Pugh et al., 2001 and Temple, 2002). However, following training, children showed increased activation in left temporo-parietal areas as well as in the left inferior frontal gyrus. Importantly, these increases were correlated with improvements in oral language skills. These findings suggest that behavioral remediation brings neural activation in reading impaired children closer to what is seen in normal-reading children. Aside from increases in these areas, the right inferior and superior frontal gyri, and right middle temporal gyrus

also showed increased activity. Temple et al. (2003) attributed increases in these right hemisphere homologues to compensatory mechanisms. Whether such regions will diminish in activation as reading skills continue to improve will require follow-up studies of these children.

In a MEG study of brain changes during remediation, Simos et al. (2002) reported that the brain activation profiles of young dyslexic readers become normal following effective intervention. In their study, magnetic source imaging scans were obtained during a nonword reading task from children aged 7-17 years before and after receiving 80 hours of instruction emphasizing the development of phonological processing skills. Prior to instruction, the profile of brain activation in these children was distinctively different from a group of controls with no history of reading impairment. In the dyslexic readers, the left posterior superior temporal gyrus showed reduced activation, while the corresponding area in the right hemisphere showed increased activation. Following remediation, an improvement in reading skills was highlighted by increased activation in the left posterior superior temporal gyrus. These findings, like those by Temple et al. (2003), suggest that intervention normalizes the reading profile of previously deficient readers.

5.4. FUTURE DIRECTIONS

The findings described above are an important part of the knowledge base that must be developed in order to understand the neural basis of reading disabilities. However, one question that will be of great interest in the future is why the brain systems failed to develop normally. That is, if remediation programs cause underlying brain mechanisms to operate "normally" rather than in a compensatory fashion, why were the normal neural pathways not functioning correctly in the first place? We can begin to answer these questions by combining various behavioral and neuroimaging methodologies to study the development of phonological processing skills from infancy to adulthood. The observation of the PMN in a group of normally developing children is an important first step, as it makes way for cross-sectional and longitudinal investigations of the neurodevelopment of phonological processing skills. It is not yet known whether the PMN can be evoked in pre-literate children. Current tasks used to study the PMN must be made age appropriate before the response can be studied in such a population. In addition, the use of a variety of behavioral and neuroimaging methods to study reading disabilities and their remediation is underscored by the fact that not all individuals with normal phonological processing skills elicit a PMN. Assuming that an appropriate paradigm was employed and that all technical considerations were met (i.e., sufficient signal-to-noise, minimal artifacts), it is possible that those healthy individuals who fail to show a PMN are using different strategies to complete the task. It is also possible that the PMN is in fact present, but obscured by the presence of other components such as the N400 or the P300. Future work will aim to identify the sensitivity and specificity of the

PMN in healthy children and adults, as well as to uncover what other strategies may be employed in task performance.

There is a great deal of interest in linking neuroanatomical data obtained from fMRI studies with that obtained from ERP/MEG studies. This presents a serious challenge to researchers, as there is not a one-to-one correspondence between electrical (as reflected in ERPs) and hemodynamic responses (i.e., fMRI). In the case of the PMN, the challenge may be more daunting as the PMN reflects a subtle aspect of speech recognition, occurring within a brief temporal window. Furthermore, the PMN is often followed and partially obscured by a response reflecting lexical/semantic processes (Connolly & Phillips, 1994; Hagoort & Brown, 2000). Indeed, until recently, the neural generators for the PMN have not been identified due to the presence of a dominant late negativity (Helenius, Service, Connolly, Leinonen, & Lyytinen, 2002). Kujala et al. (2003) have localized PMNm sources to anterior regions of the left hemisphere. However, D'Arcy et al. (in press) have described a different pattern of PMN sources, locating the PMN to the left inferior frontal region and to the left inferior parietal region.

As discussed in the introduction, discrepancies between these two findings likely reflect the cognitive mechanisms that were engaged by the different tasks employed. Specifically, verbal working memory processes may underlie the activation of the inferior frontal activation observed by D'Arcy et al. (in press). The hypothesis that the PMN may be modulated by the influence of working memory needs to be tested. Nevertheless, it remains a viable explanation to account for differences in the localization of the PMN. The robustness of the PMN in the experiments presented in this thesis, combined with

minimal activation of an N400-like response makes the phoneme deletion task an optimal choice for future investigations aimed at localizing the PMN. The phoneme deletion task may even be adopted for investigating working memory influences on the PMN by employing letter strings of various lengths as prompts, thereby increasing demands on working memory.

5.5. CONCLUSION

The results from the three studies presented in this thesis demonstrate that the PMN occurs independently of lexical/semantic mechanisms. The PMN does not appear to be affected by the degree of phonological similarity between expectations and the heard signal. That is, the deviation of a single phoneme in the acoustic stream is sufficient to increase the PMN amplitude to a level equal to that produced by a stimulus that totally mismatches expectations. The amplitude and latency of the PMN were not modulated by lexicality, suggesting that the PMN is a pre-lexical manifestation of phonological processing during speech perception. Finally, the appearance of a PMN-like response to a final phoneme mismatch suggests that speech input is mapped against a phonological representation in a continuous fashion. Taken together, findings presented in this thesis suggest that the PMN reflects a pre-lexical stage of spoken word recognition, whereby speech input is mapped against a phonological template developed by the linguistic task. This process is compulsory, as is evident by the PMN to items that match expectations. However, insofar as the PMN is augmented by a mismatch between phoneme expectations and a phonological template, the name Phonological Mismatch Negativity, remains an appropriate reference to the functionality of this response.

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Appendix A

Stimuli Presented in Experiment 1

Table A1. Items 1-20 in each Condition

Target C	Response C	Target WC	Response WC	Target CC	Response CC	Target IW	Response IW
blink	link	bleed	beed	black	ack	blow	push
brain	rain	bran	ban	bless	ess	brush	time
break	rake	brat	bat	block	ock	climb	had
bring	ring	bread	bed	bridge	idge	clip	chair
clap	lap	break	bake	bright	ight	clock	dog
click	lick	brute	boot	broom	oom	cluck	sit
cloud	loud	claim	lame	clean	een	crow	bow
cries	rise	clean	keen	click	ick	cry	nose
drink	rink	cramp	camp	clump	ump	flute	has
flash	lash	crane	cane	crack	ack	flies	head
fray	ray	crash	cash	craft	aft	flow	but
glad	lad	drawer	door	crib	ib	fly	gone
globe	lobe	drip	dip	crush	ush	fridge	car
glove	love	dry	die	crust	ust	grip	tell
plate	late	flake	fake	draw	aw	ground	kiss
play	lay	flown	phone	flag	ag	gruff	house
scare	scare	fright	fight	flap	ap	place	dear
sled	led	grain	gane	french	ench	pluck	book
sleeve	leave	great	gate	fruit	oot	plug	give
slept	lept	plane	pane	gray	ay	prize	top

Table A2. Items 21-40 in each Condition

Target C	Response C	Target WC	Response WC	Target CC	Response CC	Target IW	Response IW
small	mall	plot	pot	prince	ince	school	face
smile	mile	praise	pays	scarves	arves	slacks	duck
spill	pill	shred	shed	shrubs	ubs	slap	bit
spit	pit	slip	sip	sleep	eep	slate	push
spot	pot	slow	so	snap	ap	slate	tuck
stable	table	snack	sack	snow	ow	sleeves	watch
stack	tack	snail	sail	sport	ort	slice	tins
stare	tear	snap	sap	star	ar	slid	tale
start	tart	sneeze	seize	stool	ool	spare	keep
stern	turn	spain	sane	stop	op	spout	shoe
stew	two	speak	seek	stub	ub	brim	mean
stick	tick	speed	seed	stuck	uck	stalk	fit
stole	tole	spin	sin	stuff	uf	steak	cup
stone	tone	spoke	soak	swept	ept	still	need
sweat	wet	steam	seam	swing	ing	swear	mouth
sweep	weep	store	sore	swish	ish	swept	might
switch	witch	sweet	seat	train	ain	thread	bad
trace	race	swing	sing	trim	im	throat	goose
track	rack	throw	though	trip	ip	trust	ship
tried	ride	try	tie	troll	ole	twin	pant

Appendix B

Stimuli Presented in Experiment 2

Table B1. Items 1-40 in the Match Word Condition

Prompt	Response	Prompt	Response
praise	raise	bleed	lead
school	cool	brush	rush
stable	table	block	lock
slate	late	brain	rain
slice	lice	bran	ran
slip	lip	clap	lap
small	mall	click	lick
spain	pain	climb	lime
spill	pill	cloud	loud
stalk	talk	cries	rise
stick	tick	ground	round
sweet	wheat	flake	lake
switch	witch	flash	lash
track	rack	flown	loan
trim	rim	fridge	ridge
drink	rink	glove	love
trust	rust	grip	rip
twin	win	plane	lane
trace	race	plot	lot
stub	tub	stone	tone

Table B2. Items 1-40 in the Match Nonword Condition

Prompt	Response	Prompt	Response
bloas	loas	preb	reb
breg	reg	sceeg	ceeg
blig	lig	stoyb	toyb
breet	reet	slith	lith
broop	roop	slibe	libe
clig	lig	slav	lav
clerd	lerd	smoob	moob
clige	lige	spoaf	poaf
cloyf	loyf	spiv	piv
crige	rige	stoym	toym
groke	roke	stoth	toth
flayb	layb	swike	wike
flowp	lowp	swape	wape
floyt	loyt	trup	rup
frike	rike	treb	reb
glige	lige	druk	ruk
gris	ris	truth	ruth
plafe	lafe	twis	wis
plig	lig	trame	rame
stabe	tayb	stup	tup

Table B3. Items 1-40 in the Mismatch Word Condition

Prompt	Response	Prompt	Response
black	tack	plate	mate
bless	guess	globe	robe
blink	think	sneeze	tease
bread	head	snap	tap
break	take	speed	deed
claim	game	spin	thin
clip	dip	sweat	pet
clock	shock	swish	fish
bright	tight	swing	thing
cramp	lamp	slid	bid
crash	dash	smile	tile
prize	size	start	part
flag	tag	steam	theme
flap	cap	slack	pack
fruit	suit	drip	tip
fright	bite	stare	care
grain	sane	bring	sing
great	date	stop	mop
plug	bug	stool	pool
place	case	brim	dim

Table B4. Items 1-40 in the Mismatch Nonword Condition

Prompt	Response	Prompt	Response
blek	thek	ploysh	voysh
blood	tood	glav	tav
bleb	geb	snoth	foth
broash	doash	snid	gid
braf	taf	spishe	fishe
clibe	wibe	spav	dav
clabe	dabe	swabe	gabe
clek	tek	swibe	tibe
bris	fis	swul	rul
crawd	fawd	sloyt	boyt
creeg	teeg	smiv	kiv
pruth	tuth	stath	gath
flayb	rayb	stabe	payb
floas	toas	sleg	feg
freg	neg	dras	fas
frit	jit	stis	fis
grup	mup	brab	fab
greb	seb	stib	gib
pleeg	beeg	stig	nig
plose	fose	brife	tife

Appendix C

Stimuli Presented in Experiment 3

Table C1. Items 1-40 in the Correct Condition

Prompt	Response	Prompt	Response
slert	lert	plerf	lerf
slibe	libe	grook	rook
slowsh	lowsh	greej	reej
sloosh	loosh	groyd	royd
sleeth	leeth	grawf	rawf
sloyb	loyb	gref	ref
slawd	lawd	grashe	rashe
sloas	loas	gret	ret
slabe	labe	gris	ris
slav	lav	groke	roke
slish	lish	grup	rup
slesh	lesh	grige	rige
breg	reg	growf	rowf
brife	rife	clerd	lerd
browf	rowf	cloog	loog
broop	roop	cloyf	loyf
breet	reet	clawf	lawf
broos	roos	clabe	labe
plif	lif	clup	lup
pleb	leb	clis	lis

Table C2. Items 41-80 in the Correct Condition

Prompt	Response	Prompt	Response
clig	lig	twoyf	woyf
clut	lut	twath	wath
clige	lige	twis	wis
clowf	lowf	tweg	weg
cloat	loat	crowsh	rowsh
floog	loog	crith	rith
fleeb	leeb	crige	rige
flawth	lawth	crus	rus
flabe	labe	crep	rep
flav	lav	croash	roash
flib	lib	snoob	noob
flep	lep	sneeg	neeg
flut	lut	snoyk	noyk
flup	lup	snofe	nofe
flus	lus	snate	nate
flup	lup	snawf	nawf
flowp	lowp	sniv	niv
floyt	loyt	snig	nig
twerf	werf	snup	nup
twoog	woog	ployt	loyt

Table C3. Items 81-120 in the Correct Condition

Prompt	Response	Prompt	Response
plig	lig	brabe	rabe
plafe	lafe	brith	rith
troog	roog	bresh	resh
troyf	royf	brawm	rawm
treth	reth	brith	rith
tris	ris	snibe	nibe
trup	rup	snep	nep
tref	ref	snowf	nowf
trowf	rowf	swush	wush
troaf	roaf	swike	wike
trife	rife	swoot	woot
tresh	resh	swoym	woym
truth	ruth	swib	wib
bruk	ruk	sweth	weth
broosh	roosh	swab	wab
broyth	royth	swoth	woth
breeg	reeg	swape	wape
broysh	roysh	sweej	weej
broath	roath	swark	wark
brav	rav	swerg	werg

Table C4. Items 1-40 in the Final Mismatch Condition

Prompt	Response	Prompt	Response
brook	roob	steef	teeg
breej	reet	scib	cip
brawf	rawp	sced	cet
crup	ruk	sceej	ceet
cribe	rige	scoyd	coyt
crowsh	rowd	scabe	cayg
crooth	roog	sceb	cep
smoob	moop	glooj	loog
smeed	meeg	gleet	leeb
smoky	moyp	glawf	lawd
smoaf	moab	glabe	layp
plarb	lart	twul	wup
plert	lerd	twibe	wige
plorf	lort	twooth	woog
plooth	loog	twoyd	woyp
stoog	toop	frook	roop
steeb	teek	freeb	reet
stoyf	toyg	froyt	royb
stawf	tawb	broyd	royg
stoov	toop	frawl	rawp

Table C5. Items 1-40 in the Initial Mismatch Condition

Prompt	Response	Prompt	Response
broash	doash	stib	gib
Brab	fab	stig	lig
Bris	fis	scad	gad
braf	taf	scoof	loof
creeg	teeg	scuth	tuth
croyt	boyt	scishe	fishe
crawd	fawd	scowf	lowf
croas	toas	scood	tood
smayg	dayg	glav	tav
smawf	bawd	gleb	seb
smiv	kiv	glek	thek
smek	lek	glup	mup
pleeg	beeg	twid	gid
ploysh	voysh	twesh	besh
plose	fose	twav	dav
plabe	dabe	swoth	toth
stoag	boag	frabe	tayb
stabe	pabe	fras	fas
stath	gath	frit	jit
stis	fis	freg	neg

Table C6. Items 1-40 in the All Mismatch Condition

Prompt	Response	Prompt	Response
breg	lup	steb	shuf
brup	koof	scowg	thert
brige	sawth	scofe	neth
bworf	feg	scark	thawp
crabe	jop	scerf	toyf
crav	fashe	scorb	feep
crith	bool	glipe	shook
cret	lek	glerf	lert
smup	toaf	glowk	cishe
smife	lowth	gloys	woth
smerd	thaf	twabe	chod
plav	dit	tweeg	thas
plith	wib	tworb	thashe
plesh	dom	smowk	shep
plawf	jep	frud	thowf
steg	looth	frike	weeg
stup	sheg	frowp	shav
stige	cabe	froas	tige
stowf	royn	sceev	paybe
stawth	fert	twerb	gope