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Semantic and phonological priming effects on N400 activation in people who stutter

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Semantic and Phonological Priming Effects on N400 Activation in People Who Stutter

by

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Jessica L. Huffman

ABSTRACT

To date, research on mechanistic aspects of fluency disorders has focused heavily on motor contributions to stuttering. Only recently have researchers begun to explore psycholinguistic contributions to stuttering. Psycholinguistic planning for speech heavily involves the activation and processing of lexical information. We used a neuroscience approach to compare word activation in mental lexicon while completing a picture naming task in people who stutter (PWS) versus fluent individuals (PWNS).

Twenty-eight individuals ranging in age from 19 - 52 years old participated in a picture-word priming task adopted from Jescheniak et al. (2002). Electroencephalogram (EEG) was recorded while participants saw black and white line drawings, followed immediately by an auditory probe word that was either Semantically-Related, Phonologically-Related, or Unrelated to the label of the preceding picture. EEG was also recorded to Filler (naming-only) trials. Averaged ERPs were generated for each condition. Two principal component analyses (PCA) were conducted in order to summarize patterns in the ERP data and test for differences in ERPs elicited by different conditions. One PCA compared Semantically-Related probe word trials, Semantically-Unrelated probe word trials, and Filler trials. The second PCA compared Phonologically-Related probe word trials, Phonologically-Unrelated probe word trials, and Filler trials.

The primary goal of each analysis was to determine whether each probe word condition elicited ERP activity that was different from Filler (naming-only) trials.

Relative to Filler trials, all four types of probe words elicited a series of ERP components, some related to sensory processing of the probe words, and some related to linguistic processing of the probe words including N400-type ERP activity. Crucially, N400 priming was observed for PWNS on Semantically-Related trials, but not for PWS. This result indicates that the activation of semantic word networks on the path to picture naming may operate differently in PWS versus PWNS. In contrast, no differences were found between groups for Phonological N400 priming. Discussion relates these effects to the larger body of existing literature on psycholinguistic ability in PWS. Discussion also focuses on how the activation of semantic word networks may differ in PWS versus PWNS, and how therapy for stuttering might address such differences.

INTRODUCTION

Stuttering is a disorder of fluency that emerges during childhood. The prevalence[1] of stuttering in children is estimated at 5% (Guitar, 2006; Bloodstein, 1995; Andrews et al, 1983), while prevalence in adults is estimated at 1% (Bloodstein, 1995; Andrews et al, 1983; Yairi & Ambrose, 2005). Prevalence rate declines because 20 – 80% of children diagnosed with stuttering spontaneously recover[2] (Bloodstein, 1995; Andrews et al, 1983; Guitar, 2006). Still, at least three million people in the United States stutter persistently into adulthood. Of those people, at least three men stutter for every woman (Bloodstein, 1995). These individuals come from all walks of life (Guitar, 2006).

Historically, stuttering has been conceptualized by speech and language researchers in a number of different ways. Conture (1996) surmised that the best way to define the phenomenon is to describe what happens during moments of stuttering, both in terms of what can be observed behaviorally and what the speaker reports experiencing emotionally. In this spirit, Marcel Wingate (1964) defined stuttering as follows:

1. (a) Disruption in the fluency of verbal expression, which is (b) characterized by involuntary, audible or silent, repetitions or prolongations in the utterance of short speech segments, namely: sound, syllables, and words of one syllable. These disruptions (c) usually occur frequently or are marked in character and (d) are not readily controllable.

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[1] Prevalence is a term used to describe the percentage of people who stutter at any given time period.
[2] Spontaneous recovery is a term used for individuals who recover from stuttering without receiving treatment.

2. Sometimes the disruptions are (e) accompanied by accessory activities involving the speech apparatus, related or unrelated body structures, or stereotyped speech utterances. These activities give the appearance of being a speech-related struggle.

3. Also, there are not infrequently (f) indications or report of the presence of an emotional state, ranging from a general condition of "excitement" or "tension" to more specific emotions of a negative nature such as fear, embarrassment, irritation, or the like. (p.488)

Though broad in scope, Wingate's definition is still limited in the following way: Much of what happens during speech production is not observable behaviorally. Speech production is driven, in large part, by a number of cognitive processes that unfold covertly, in the mind, within the fraction of a second that separates one's initial intention to speak from actual articulation. Some of these processes are psycholinguistic in nature, i.e., involve retrieving and processing linguistic information, while others involve computing speech motor movements. When Wingate's definition was published, little was known about processing linguistic information or computing speech motor movements prior to actual speech production. The purpose of this study was to examine how premotor, psycholinguistic processes operate in adults who stutter (hereafter, PWS), specifically, the activation of word networks on the path to picture naming.

In the sections that follow, we begin by outlining a model of the psycholinguistic and motor mechanisms involved in speech production. The subsequent section discusses speech motor performance in PWS, including consideration of why a purely speech

motor approach fails to account for all symptoms of stuttering. Finally, we review psycholinguistic research in the area of fluency disorders, and outline an innovative neuroscience approach for studying word network activation in PWS.

A Mechanistic Model of Speech Production Planning

Two primary premotor processes drive planning for speech production. One involves generating a linguistic utterance plan. The second involves generating a speech motor plan and program. Each process is outlined below.

Linguistic Utterance Planning

Linguistic utterance planning is the process by which an individual selects words for expressing an intended message, arranges those words into phrase and sentence structures, and retrieves the phonological form of those words (Levelt, 1983). In order to generate a linguistic utterance plan, a speaker must possess two types of linguistic knowledge. At one level, a speaker must have a robust lexicon. Individuals can know as many as 50,000 to 100,000 words by adulthood (Miller, 1991), all of which are stored in a mental lexicon. A speaker must also possess knowledge about the syntactic, phonological, and discourse rules that govern language use. Assuming the speaker has linguistic competence at each level, she must also be able to put to use (i.e., retrieve and process) this knowledge efficiently via a set of psycholinguistic processing activities, outlined next.

As shown in Figure 1, the path to speech production begins with concept formation. Here, the speaker conceptualizes what she wants to say. Next, she

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activates words in her mental lexicon that convey the meaning of her intended message. This process is known as lexical selection. As words are activated in mental lexicon, the speaker grammatically encodes her message, i.e., assigns each word a grammatical function and a position in the utterance. Function words are also retrieved during grammatical encoding. The final process of linguistic utterance planning is phonological encoding, during which the speaker retrieves the segments (phonemes) of each word, and assigns them to specific positions within the syllable structure of the emerging utterance.

Resulting from this process is a linguistic utterance plan, i.e., a set of words, grammatically arranged, and phonologically specified. Before the linguistic utterance plan is sent forward for articulation, an internal monitor checks that semantically- and pragmatically-appropriate words have been selected, grammatical structure properly specified, and phonemes retrieved and correctly assigned positions within the utterance (see Figure 1, lexical monitor, syntax monitor and inner loop, respectively). In rare instances, psycholinguistic speech planning errors go undetected, resulting in overt speech errors (Fromkin, 1973; Cutler, 1982). More often, planning errors are detected internally. In those cases, the internal monitor interrupts speech production and initiates a repair (Levelt, 1983), disrupting fluency. Currently, the frequency of which PWS make speech planning errors, perhaps resulting in disrupted fluency, is unknown. As noted above, of the many psycholinguistic activities outlined here, our aim was to begin to examine how the lexical selection process operates in PWS.

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Figure 1. Model of the Normal Speech Production Process (adopted from Postma, 2000).

Speech Motor Processes

As linguistic utterance plans are generated, the brain translates them into speech motor movements. This involves speech motor planning and programming (van der Meurwe, 1997). Speech motor planning involves establishing a set of movement goals for speech production. These goals dictate where and when the speaker will move the articulators in order to produce the desired speech sounds. Speech motor programming involves generating a set of instructions that specify how the speech muscles will move in order to realize the goals set forth in the speech motor plan. The amount of force, range, and velocity to be used during specific movements is specified in the speech motor program, as are trajectories along which articulators should be moved.

The speaker executes the speech motor program, resulting in a series of controlled, sequenced speech motor movements. As an utterance is articulated, proprioceptive and auditory feedback loops are used to monitor speech motor control (see bottom right of Figure 1). Feedback allows the speaker to determine whether she has reached intended motor targets. If a mistake is detected, the speaker has the ability to adjust the motor program "on-line".

A Heavy Focus on Motor Performance in PWS

The aforementioned processes must operate efficiently in order for speech to be produced fluently. To date, a preponderance of research has been aimed at investigating motor aspects of stuttering, i.e., to determine whether deficient motor skill is what sets the stage for moments of stuttering. There is, at least, face validity for focusing on motor aspects

because PWS sometimes exhibit observable struggle behavior during moments of stuttering. Many PWS report knowing exactly what they want to say, but report having difficulty initiating articulation or transitioning between articulatory targets. A huge body of evidence generated over the last four decades, reviewed by Peters, Hulstijn and Van Lieshout (2000), confirms that impaired motor coordination and timing are persistent factors in the speech motor performance of PWS. For example, researchers have consistently shown that laryngeal reaction times of PWS are longer than those of people who do not stutter (hereafter, PWNS), an effect that becomes more apparent with increased utterance complexity (see Bloodstein, 1995). Such findings are taken to suggest that deficient motor skill has a role in setting the stage for moments of stuttering.

As a result of the heavy focus on motor contributions to stuttering, many of the techniques available today for the treatment of adulthood stuttering are motor-based. Explicit planning of oral motor movements, coupled with prolonged speech techniques and the use of self-imposed contingencies (i.e., rewarding oneself when using these techniques), do appear to alleviate stuttering in adults (Bothe, Davidow, Bramlett, Ingham, 2006). However, stuttering relapse is still very common in adults. Often, treatment helps initially but its effectiveness diminishes over time. One survey by McClure and Yaruss (2003) confirmed that treatment for stuttering is not a one-time solution: 85% of adults who undergo speech therapy report having two or more different treatment experiences, while 31% have five or more different treatment experiences. Such findings lead to the hypothesis that in addition to speech motor difficulty, PWS may have difficulty managing other typically automatic aspects of speech production.

Linguistic Utterance Planning in PWS

In the past 20 years, there has been a shift in focus from motor contributions to stuttering to an examination of whether the covert linguistic processes underlying speech production operate inefficiently in PWS. This new line of research is primarily concerned with how PWS process lexical knowledge. This is because linguistic planning for speech production is driven in large part by the rapid, cognitive processing of lexical knowledge (Dell, 1986; Garrett, 1988; Butterworth, 1989; Dell & O'Seaghdha, 1992; Levelt, Roelofs, & Meyer, 1999); processing that can be elicited experimentally via picture naming. In the fraction of a second that separates picture presentation from articulation of a picture label, words whose meanings relate to the pictured object are activated in mental lexicon. This is called semantic network activation (Levelt et al., 1999). Soon after (in just tens or hundreds of milliseconds), the phoneme constituents of each word become available and, due to the network organization of mental lexicon, activate still other words sharing the same phonemes. This is called phonological network activation (Levelt et al., 1999). The set of potential picture labels and phonologically associated words competes for activation. Some words gain activation strength, and their semantic and phonological properties become available to the speaker, while other words lose activation strength. Efficiency in this process is subserved by 1) the appropriate development and maintenance of network connections between semantically- and phonologically-related words in mental lexicon; as well as 2) limits placed on the degree of activation spreading allowed between words, i.e., too many words should not be able to enter into competition on the path to picture naming (Dell & O'Seaghdha, 1991).

Several modern-day theories attribute moments of stuttering to breakdowns in these processes, specifically at the level of phonological encoding (Wingate, 1988; Perkins, Kent, & Curlee, 1991; Postma & Kolk, 1993; Karniol, 1995). The general premise is that phonological encoding, during which a target word's phonemes are retrieved (Dell, 1986), is delayed in PWS. According to at least one theory, the delay occurs because a clear "winner" in the competition among words for activation does not always emerge in PWS (Postma & Kolk, 1993). The hypothesized result is the undesirably strong activation and subsequent retrieval of phonemes from a semantic or phonological associate of the speaker's intended word. As noted above, when the internal monitor detects an incorrect phoneme, it signals the speaker to initiate a repair. If PWS were to frequently generate phonological planning errors due to inefficient resolution in the competition among word entries, then their internal monitors may frequently trigger the repair process, setting the stage for moments of stuttering (Postma & Kolk, 1993).

Unfortunately, some psycholinguistic research in the area of fluency disorders loses the forest for the trees, focusing exclusively on the time-course of phonological processes (Wijnen & Boers, 1994; Postma & Kolk, 1993). As outlined above, activating the phonological codes of words is inextricably tied to the efficiency with which activation spreads through both semantic and phonological word networks. There does exist a limited body of evidence about how lexical network activation operates in PWS at both semantic and phonological levels. However, as outlined below, much of this evidence has emerged from research using primarily behavioral means, which may not be optimally suited for investigating psycholinguistic processes in PWS.

Semantic Network Activation in PWS

On tests of word association, PWS respond equally fast (Crowe & Kroll, 1991; also see Taylor, Lore, & Waldman, 1970) or faster (Jensen, Markel, & Beverung, 1986) than PWNS. At first glance, this suggests that PWS are equally skilled at accessing semantic word networks. However, on a task requiring participants to monitor sentences for category-specific words (Bosshardt & Fransen, 1996), PWS were slower than PWNS, suggesting difficulty accessing words from specific semantic networks. In addition, PWS have been shown to use fewer synonyms to generate definitions from those produced by PWNS (Wingate, 1988), and word associations vary widely between PWS (Crowe & Kroll, 1991). This may suggest that PWS maximize speed on word association tasks by strategically using less common responses. A different possibility is that less desirable words automatically gain activation strength on par with more desirable words in PWS.

Evidence for this latter effect was reported by Newman and Ratner (2007), who reported that PWS made more errors associated with lower frequency words than PWNS on a confrontation naming task. The PWS, as a group, were shown to produce naming errors that were lower in frequency than errors produced by PWNS, e.g., "androgeny" for "boy". This might be expected if PWS were using word substitutions. A greater number of errors of this type might also point to less restraint on activation spreading in the mental lexicons of PWS. However, this conclusion was challenged recently by Hennessey, Nang, & Beilby (2008), who used a picture naming reaction time (hereafter, RT) task to assess linguistic encoding deficits in PWS. When a probe word appears just before a picture-to-be-named, the picture is named more slowly when the probe word is

semantically related to the picture label (semantic interference) than when the two are

unrelated. Semantic interference was of the same magnitude for PWS and PWNS,

suggesting that semantic network activation is no less restrained for PWS than it is for

PWNS. The studies may not be entirely comparable, however, as Hennessey et al. (2008)

used probe words that were highly related to the picture labels (e.g., baby-child), which

can attenuate semantic interference and even induce priming, versus more distantly

related pairs (e.g., horse-whale, both of which are animate) (Mahon, Costa, Paterson,

Vargas, & Caramazza, 2007). Therefore, the stimuli used may not have been sensitive to

subtle differences in semantic network activation between PWS and PWNS.

The findings reviewed so far tentatively suggest that semantic network activation

is less restrained in PWS. Other findings suggest that semantic network activation is too

restrained in PWS. Wingate (1988) reported that PWS scored lower than PWNS on the

Verbal Scale of the Wechsler Adult Intelligence Scale (hereafter, WAIS), which requires

individuals to define words. PWS used a higher average number of words than PWNS,

but provided poorer definitions, determined in part by the smaller number of synonyms

used. Fewer synonyms indicate, somewhat tentatively, that network connections among

related words are less well-developed in PWS. Results of two other studies help to

substantiate this claim. Prins, Main, and Wampler (1997) reported significantly lower

scores on the Peabody Picture Vocabulary Test (hereafter, PPVT) for PWS than for

PWNS, though it is important to note that the PWS still scored within normal limits. The

PPVT has construct validity as a measure of receptive vocabulary. Scores on this test are

influenced by word frequency and polysemy (Miller & Lee, 1993), the latter of which

reflects an ability to adapt words in one's vocabulary in order to accommodate new meaning. Low-normal PPVT scores may reflect sub-clinical difficulty organizing networks of semantically related words in order to accommodate complex meanings. Another sign of poorer semantic network organization is that PWS have significantly more difficulty than PWNS disambiguating words in confusing sentences (Watson et al., 1994). It is also interesting to note that PWS stutter more on words that are semantically less-predictable from context than on predictable words. One interpretation of this finding posits that PWS have difficulty making lexical decisions at points of uncertainty in sentence planning (Bloodstein, 1995). Though a tentative hypothesis, inefficient access to, or competition among, semantically related words could account for this effect.

Phonological Network Activation in PWS

In addition to semantically-related words, networks of phonologically-related words become activated on the path to speech production. Burger and Wijnen (1999) examined spoken RTs as PWS and PWNS recited lists of phonologically-related words, as well as lists of unrelated words. Facilitation from priming, i.e., the reduction in RTs observed with phonologically-related words versus unrelated word list priming, was equivalent between groups. Hennessey et al. (2008) reported similar results for the phonological manipulation in their picture-word task. When a probe word appears directly after a picture-to-be-named, the picture is named more quickly when the probe word is phonologically-related to the picture label (phonological priming) than when the two are unrelated. RT facilitation from phonological priming was numerically longer for

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PWS than for PWNS, but statistically there was no group difference. The results of both studies suggest that differences in RTs between groups without priming cannot be attributed to disproportionately high competition among phonologically-related words in PWS. Results from other studies run counter to this conclusion.

Weber-Fox, Spencer, Spruill, and Smith (2004) asked PWS and PWNS to judge whether pairs of printed words rhymed. The words were similar orthographically and rhymed; were dissimilar orthographically and did not rhyme; rhymed but were orthographically dissimilar; or were orthographically similar but did not rhyme. PWS were significantly slower than PWNS when judging the latter type of stimulus pairs. Weber-Fox et al. (2004) interpreted this effect as suggesting that PWS are particularly sensitive to increased cognitive load, which here, was elicited by phonologic / orthographic incongruency. However, slower phonological monitoring times have been observed in PWS even without incongruency. In their study, Sasisekaran, De Nil, Smyth, and Johnson (2006), PWS and PWNS monitored internal speech for target phonemes during tacit picture naming. Those participants also completed other tasks designed to assess RTs for simple motor movements, auditory monitoring of tone sequences, and overt naming. The PWS performed on-par with PWNS for all but phoneme monitoring, during which they were significantly slower. Having ruled out motor slowness, auditory monitoring slowness, and naming slowness, Sasisekaran et al. (2006) concluded that PWS are slower in some aspect of the phonological encoding process. One possibility is that activation spreading to, and competition among, phonologically-related words takes longer to resolve in PWS, slowing phoneme monitoring times.

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As noted above, one reason for inefficient lexical activation may be that activation spreading is less restrained. Unrestrained activation spreading at a phonological level may be evident in the occurrence of phoneme errors. In PWNS, phoneme errors occur more often for lower-frequency words than for higher-frequency words (Stemberger & MacWhinney, 1986; Dell, 1990). According to Dell (1990), as the phonemes of a lower-frequency word (e.g., guy) gain activation strength, bottom-up activation from those phonemes to other, higher-frequency words can occur (e.g., activation of /g/ for "guy" could spread bottom-up to the lexical entry "go" which, in turn, spreads activation to /o/ before /ai/ in "guy" can be retrieved, resulting in a phoneme error). This same phenomenon might help to explain why lower-frequency words attract higher rates of stuttering (Bloodstein, 1995). As noted above, phoneme errors (e.g., elicited by lower-frequency words) might be detected internally, disrupting fluency in order to initiate a repair. When access to word form information is artificially sped-up, leaving little or no time for error correction – as with tongue twister tasks – PWS generate more speech sound errors than PWNS (Postma & Kolk, 1990; Eldridge & Felsenfed, 1998). These findings lead us to speculate that activation spreading at a phonological level may be less restrained in PWS versus PWNS.

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A Cognitive Neuroscience Approach to the Study of Lexical Network Activation

A limitation of the work reviewed above is that lexical network activation[3] was assessed offline, using behavioral measures potentially influenced by factors such as the motor abilities, metalinguistic skills, and preferences-for-responding brought about by participants. A dependent variable somewhat immune to these factors is the event-related potential (ERP), generated by the brain automatically (i.e., not under conscious control) as people process information, make decisions, and regulate behavior. Specific ERP components mark the activation of specific cognitive and linguistic processes. Most relevant for our purposes is N400, an ERP component elicited by lexical stimuli (Fischler, 1990), peaking in amplitude at ~ 400 - 550 milliseconds after word onset. Crucially, N400 amplitude is inversely related to a word's activation level in memory (Van Petten & Kutas, 1990). A word whose activation has been primed by a preceding stimulus elicits a relatively small N400, while an unprimed word elicits a relatively large N400.

Weber-Fox and colleagues have used this property to assess lexical activation in PWS. In one study (Weber-Fox, 2001), participants read sentences silently, some of which contained word violations (e.g., "She looked at her watch to check the **rain**."). N400, while expectedly large in response to words semantically incongruous with their sentence contexts in PWNS, was reduced in amplitude in PWS. Weber-Fox and Hampton (2008) reported similar results from an auditory task. Both studies assessed lexical activation as PWS processed sentences, i.e., as comprehenders, and it is unclear to what

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[3] Lexical network activation is used here to describe both the semantic and phonological psycholinguistic aspects of speech production.

extent sentence processing mirrors psycholinguistic planning for speech production. At

least indirectly, attenuated N400 for word comprehension corroborates behavioral

evidence, cited above, that lexical activation operates differently in PWS.

N400 priming can also be used to assess lexical network activation on the path to

picture naming, using a method called picture-word priming (see Jescheniak, Schriefers,

Garrett, & Friederici, 2002). Picture-word priming involves presenting a picture on each

trial, followed by an auditory probe word. Participants are instructed to label the picture,

but not to name it aloud until several hundred milliseconds after the probe word has been

presented (i.e., when prompted by a cue to name the picture). ERPs are measured at the

onset of each auditory probe word. Each probe word elicits ERP activity, including

activation of the N400 component. The general aim of this research design is to

manipulate the amplitude of the N400 by manipulating the relationship between the

picture labels and auditory probe words. If preceding picture label and subsequent probe

word are unrelated, then the N400 activated in response to the probe word should be

relatively large in amplitude. If, on the other hand, preceding picture label and subsequent

probe word are related in some way, N400 amplitude should be attenuated. Jescheniak et

al. (2002) found that both semantic relatedness (e.g., picture of *grass*, followed by probe

word *mower*) and phonological relatedness (e.g., picture of *grass*, followed by probe

word *grab*) attenuated N400 amplitude in typically fluent speakers. These results were

interpreted as reflecting that, when speakers search for picture labels on the path to

picture naming, a set of related words becomes activated in mental lexicon, i.e., via the

spreading activation process described above. Some of those words will be semantically-

related to the target picture label, while others will be phonologically-related to it. When one of those words is presented auditorily, the N400 component is attenuated in amplitude, presumably because it was preactivated during the search for the target picture label. If activation spreading through semantic or phonological word networks operates inefficiently in PWS, then picture-word priming effects on N400 amplitude seen for PWNS should be less robust or absent for the PWS. We adopted this design to investigate the activation of lexical networks in PWS, with some key modifications to the design used by Jescheniak et al. (2002), as described in Appendix A.

Summary and Research Questions

Stuttering is a serious speech disorder that can be described in terms of observable characteristics. Moments of stuttering may be a result of dyscoordination in at least some of the processes that drive normal speech production. To date, research has shown differences in overt motor aspects of speech production for PWS. However, little research exists to determine if other, covert processes involved in speech production differ in PWS. The purpose of this study was to answer two specific research questions. 1) Does picture-naming activate a network of Semantically-Related words in adults who stutter in the same manner as that seen for adults who do not stutter, as evidenced by semantic N400 priming effects in a picture-word priming task? 2) Does picture-naming activate a network of Phonologically-Related words in adults who stutter in the same manner as that seen for adults who do not stutter, as evidenced by phonological N400 priming

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effects in a picture-word priming task? In order to answer these two questions, we used the picture-word priming paradigm created by Jescheniak et al. (2002), outlined above.

At least three possible outcomes were foreseen. First, if the activation of word networks operates normally in PWS then we would expect to see a typical N400 priming effect wherein the N400 would have a decreased amplitude for Semantically- and Phonologically-Related trials versus Filler and Unrelated trials (Jescheniak et al., 2002). If, on the other hand, semantic or phonological competitors undesirably gain activation in PWS on the path to naming, N400 will be larger in amplitude rather than smaller when probe words are related to the picture labels, an indication of uncontrolled competition in mental lexicon. Finally, if activation of semantic or phonological word networks operates typically on a gross scale but is sub-clinically inefficient in PWS (e.g., due to limited network connections), N400 priming should appear but may be reduced in amplitude relative to PWNS. The method used to determine whether or not typical picture-word N400 priming effects are evidenced in PWS is described in further detail below.

METHOD

Participants

In total, 35 individuals were tested: 17 PWS, and 18 PWNS. Of the 17 PWS participating in the study, 14 were included for data analysis (12 men and 2 women, with a mean age of 29.9 years, ranging from 19 to 52 years). Of the 18 PWNS, 14 were included for data analysis (7 men and 7 women, with a mean age of 30.14 years, ranging from 19 to 45 years). All included participants were monolingual English speakers with normal or corrected-to-normal vision, no hearing deficit, and normal language function. None of the participants were taking medications that can affect cognitive function, and none had a history of neurological injury. A speech sample was collected from each of the 14 PWS in order to confirm their diagnosis of stuttering. All participants gave informed consent to participate in the study, completed a medical history questionnaire, and were paid 10 dollars per hour for their participation.

A total of seven individuals were excluded for the following reasons. One PWS was excluded due to nonnative English-speaking status; a second PWS had unilateral hearing loss; and a third PWS took prescription medication that can alter cognitive function. One PWNS was excluded due to suspected head injury; a second PWNS for taking prescription medication that can alter cognitive function; a third PWNS for self-reported Attention Deficit Disorder; and a fourth PWNS whose recorded EEG data were found to be atypically noisy.

<center>**Stimuli**</center>

The study was conducted using thirty-eight simple line drawings of common objects, selected from the IPNP Mini Database Query, a database of normed pictures (Szekely et al., 2004). All objects were depicted as black and white line drawings measuring 2 inches in height by 2 inches in width with similar style and quality (see Figure 2 for an example). The most frequently-used label for each drawing, as determined using norms (gathered as part of the International Picture Naming Project), was a noun with no more than two syllables. The average phoneme length for the labels was 3.9, and the average frequency of the labels was 3.2 tokens per million words. For each picture, two probe words were selected: One being the strongest (semantic) free associate of the picture label but phonologically unrelated to it; a second word semantically unrelated to the picture label but sharing the word-initial phoneme. Semantic associates were found using the University of South Florida Free Association Norms website (Nelson, McEvoy, & Schreiber, 1998). It is important to note that each of the two probe words was also reassigned to a different picture to which it was completely unrelated. Using the example shown in Figure 2, "water" would have been assigned to the picture "fish", as well as to a different picture to which it was completely unrelated. Therefore, "water" would have appeared twice: Once as a word Semantically-Related to its picture, and once as a word Semantically-Unrelated to its picture. Using the same example, "frost" would have been assigned to the picture "fish", as well as to a different picture to which it was completely unrelated. Therefore, "frost" would have appeared twice: Once as a word Phonologically-Related to its picture, and once as a word

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Phonologically-Unrelated to its picture. Appendix B lists each picture label; the Semantically-Related probe word for each picture; the reassignment of each word in the Semantically-Related list to a Semantically-Unrelated picture; the Phonologically-Related probe word for each picture; and the reassignment of each word in the Phonologically-Related list to a Phonologically-Unrelated picture. Word frequency and number-of-phoneme statistics are shown for each word.

Preparation of Auditory Probe Words

The probe words were transformed into a set of auditory stimuli as follows. A female, native speaker of English read aloud each word, several times consecutively. All readings were recorded to digital audiotape, digitized at a sampling rate of 44.1kHz, and then processed using Sony Sound Forge 8.0 editing software. The best-spoken exemplar of each word was selected; its waveform spliced from the original recording and saved as a separate sound file (.WAV format). The loudness of each word was normalized to an RMS amplitude of 15 dB, and a noise gate used to reduce high-frequency noise (hiss).
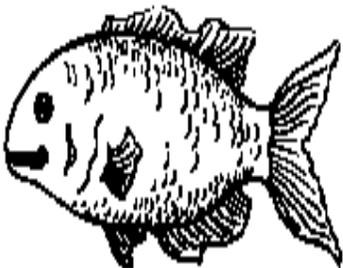
Strongest semantic free associate = water

Word-initial phonological probe word = frost

Figure 2. Illustration of a picture stimulus and its Semantically- and Phonologically-Related auditory probe words.

Procedures

Prior to testing, each participant was asked to familiarize themselves with the black and white line drawings they would be seeing on the computer monitor during the experiment. Instructions were that participants would see a picture appear on the screen, and that they were to name the picture once a naming cue (!!!) appeared on the screen. Participants were told they could proceed to the next trial by pushing any button on a response box. To ensure each participant had a good understanding of the task, they were asked to verbally summarize the task requirements using their own words before testing began. In addition to the main task instructions, participants were asked to minimize movements while participating in the experiment.

Each participant was tested in a single session, during which they received a total of 228 trials (38 Phonologically-Related trials, 38 Phonologically-Unrelated trials, 38 Semantically-Related trials, 38 Semantically-Unrelated trials, and 76 naming-only Filler trials). The experiment consisted of two different trial types: Experimental trials, and Filler trials. As shown in Figure 3, each Experimental trial consisted of a fixation cross ("+") that stayed on the monitor for 550 milliseconds, followed by a black and white line drawing that remained on the monitor for 450 milliseconds, followed by a spoken word (either the Semantically-Related Probe, Phonologically-Related Probe, or Unrelated probe), followed by an articulation cue ("!!!") that remained on the monitor until the participant spoke the label fully and pressed a button for the next trial. Eight hundred milliseconds separated the onset of the spoken word from the visual naming signal.

The second type of item was a filler item. As shown in Figure 4, for Filler trials the participant saw a fixation sign ("+") that remained on the monitor for 550 milliseconds, followed by a black and white line drawing that remained on the monitor for 450 milliseconds, followed by an articulation cue ("!!!"). 1450 milliseconds separated the onset of the picture from the onset of the articulation cue, which stayed on the monitor until the participant pressed the button to begin the next trial.

The 228 items were presented in a single, large block of trials. Trials for each of the five different conditions were presented in random order. Each trial was separated by an intertrial interval of 2100 milliseconds. Each of the 38 pictures appeared a total of six different times during testing: Twice in Filler trials, and once in each of the four probe word conditions. This procedure is closely related to the experimental design used by Jescheniak et al. (2002) (see Appendix A).
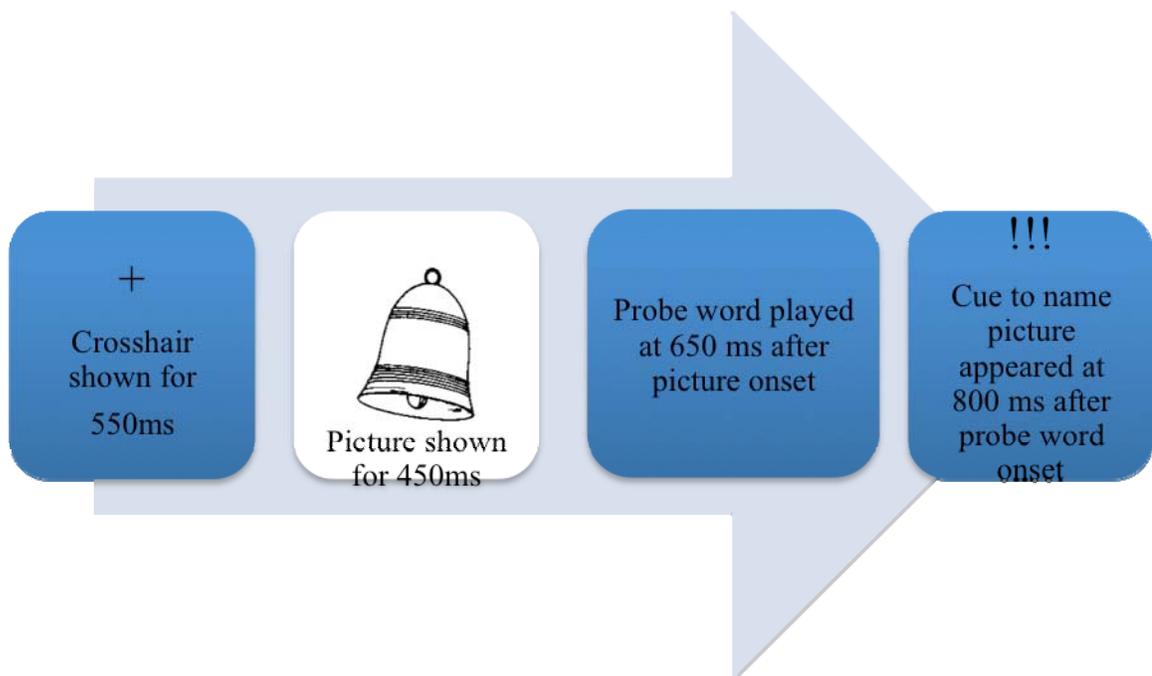
Figure 3.Illustration of procedure for Experimental trials.

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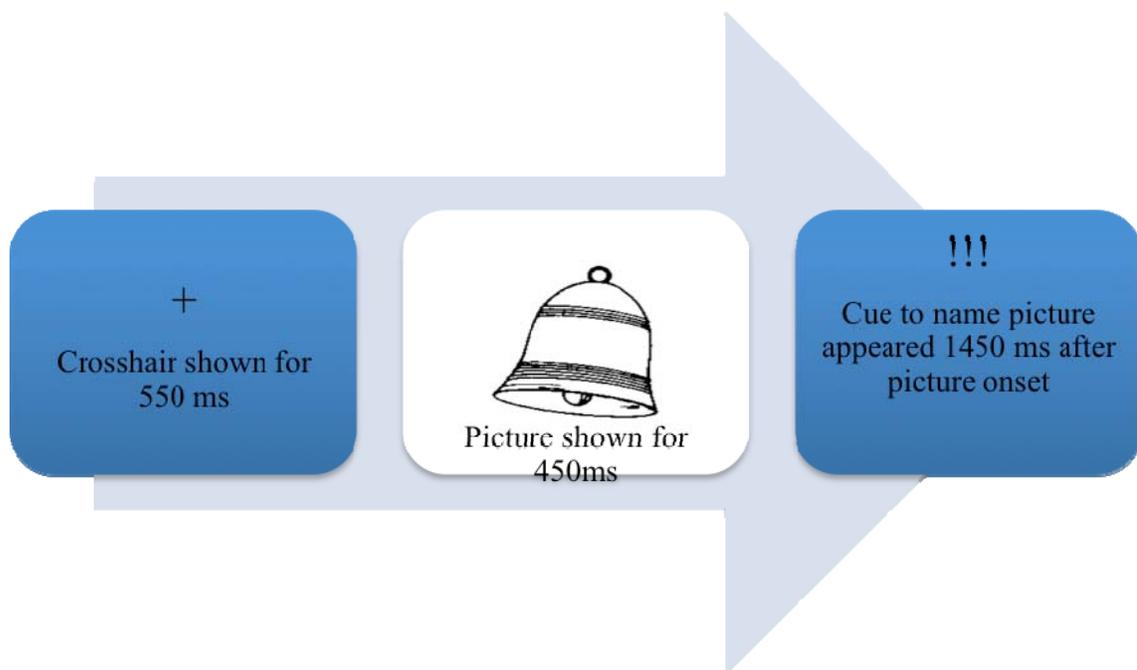
Figure 4. Illustration of procedure for Filler trials.

Apparatus and Recording

Each participant was seated in a dimly lit, sound-attenuating booth, facing a 19-inch LCD computer monitor. The auditory probe words were presented auditorily via high-quality, insert earphones (Etymotic Research, Model E-2). Participants signaled the experimental software (Eprime) to progress from one trial to the next by using a push-button response box (Psychological Software Tools). In addition to behavioral data, continuous EEG was recorded from each participant as follows. During testing, each participant wore a nylon QuikCap (Neuroscan) (see Figure 5). The cap was fitted with a set of 62 active recording electrodes, positioned in a geodesic pattern covering the forehead, top, sides, and back of the head, as well as one reference (midline Cz reference)

and one ground electrode. Four additional electrodes recorded electro-ocular activity. A

recording electrode was also affixed to each mastoid process. The electrodes were

constructed of silver / silver chloride (Ag / AgCl). Conductive electrolyte QuikGel

(Neuroscan) was used as the medium between each electrode and the scalp. Placement of

the cap took between 10 and 30 minutes.

Continuous EEG was recorded from each participant during testing at a sampling

rate of 500 Hz (1 recording every 2 milliseconds from each electrode). SCAN software,

Version 4.3 (Neuroscan), was used to control EEG recording. Electrode impedance was

kept below 30 kOhm (Ferree, Luu, Russell, & Tucker, 2001). The continuous EEG data

were low-pass filtered online, at a corner frequency of 100 Hz. E-Prime experimental

control software (Psychological Software Tools, version 1.1), run on a PC computer, was

used to present the picture stimuli.
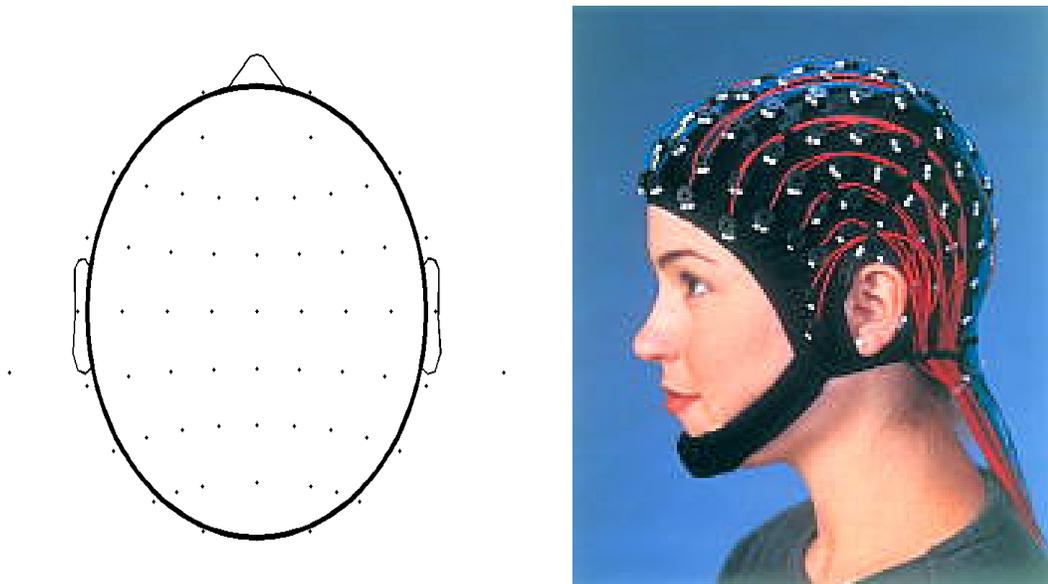
Figure 5. Topographic plot of electrodes on cap (left) and picture of cap (right).

EEG-to-Average-ERP Data Reduction

The continuous EEG record of each participant was segmented into individual epochs. Each epoch was comprised of EEG data that had been recorded, from each of the 66 active recording electrodes, during presentation of the target auditory word in each trial, beginning 300 milliseconds before the onset of the word, and terminating at 1000 milliseconds following the onset of the word. Epochs of the same duration were also created for each Filler trial, beginning 300 milliseconds before a word would have appeared (in non-Filler trials) and terminating 1000 milliseconds later. The epoch length was eventually truncated to a critical interval of ERP activity (-100 to 800 milliseconds relative to stimulus onset) following averaging. However, we began with an extended epoch to ensure that the procedures, described next, would adequately correct or reject artifacts on the leading and trailing edges of this critical time interval.

EEG ocular artifact correction

Inspection of the EEG data recorded revealed that most participants' recordings were contaminated by eye blink artifact. In order to salvage as many trials as possible, we used an ocular artifact correction procedure modified from Dien (2005). The segmented EEG data for each participant were submitted to an Independent Component Analysis (ICA) (Bell & Sejnowski, 1994). After the ICA decomposition of each EEG record into 66 components, the inverse weights (scalp map) of each component were correlated with a blink template generated by averaging at each channel the peak activity of two blink exemplars sampled from each participant. Any component whose inverse weights

matched the blink template (r = .9 or better) was identified as a blink component. The

activity related to each blink component was removed from each trial if it reduced the

overall EEG variance for that trial. At least one blink component was identified for each

participant. On average 195 trials (SD = 23.16) were corrected for blink activity.

EEG trial rejection

After ICA blink correction, channels whose fast-average amplitude exceeded 200

microvolts (large drift) were marked bad; as were channels whose differential amplitude

exceeded 100 microvolts (high-frequency noise). Any EEG trial with more than three bad

channels (5% of the total number of channels) was rejected from further analysis. No

participant lost more than 20% of their trials for any condition, and most participants lost

well under 10% of their trials per condition, due to bad channel artifact.

Final EEG processing

For any accepted trial with channels marked bad (<=3), the EEG activity at those

channels was replaced using spherical spline interpolation (Ferree, 2000). The EEG trials

were averaged together, separately for each condition. As a result, each participant had

five sets of ERP averages: Semantically-Related, Semantically-Unrelated,

Phonologically-Related, Phonologically-Unrelated, and Filler. For each participant, no

fewer than 30 artifact-free trials went into the set of ERP averages for each Related or

Unrelated condition, while no fewer than 69 artifact-free trials went into the set of ERP

averages for the Filler condition. The averaged ERP data were truncated to include only

the critical time window (-100 to 800 milliseconds), rereferenced to left mastoid, and

baseline-corrected (-100 to 0 milliseconds).

ANALYSIS

Behavioral analysis

Participants' naming responses were scored as correct, incorrect, or as no response given. Performance on each trial was scored as "correct" only if the label used was the precisely-spoken one-word label indicated for each picture prior to beginning the experiment (see Procedures above). All other responses were scored as incorrect or as no response given. Incorrect responses included two-word answers (e.g., "match stick" for match), phonological errors (e.g., "cambull" for camel), semantic errors (e.g., "desk" for bed), and unrelated word errors (e.g., "spider" for door). All trials scored as incorrect or no response given were removed from final analysis.

ERP Analysis

Dominant patterns of variance in the ERP data set were identified using Principal Component Analysis (PCA). PCA is a data reduction technique that can be used to summarize large data sets with great efficiency. PCA was used here as an ERP preprocessing step, the results of which were used to describe specific patterns of variance in the ERP data set and to test for experimental effects associated with those patterns of ERP variance.

Temporal-spatial PCA

The ERP data related to the Semantic aspect of the task and, separately, the ERP data related to the Phonological aspect of the task, were submitted to a two-step, covariance-based, temporal-spatial PCA (Spencer, Dien, & Donchin, 2001). For step one of each analysis, the averaged ERP data were combined into a single data matrix comprised of 451 columns (one column for each of the sampling points in the critical time window) and 5,208 rows (the averaged ERP voltages for 28 participants, at each of 62 electrodes, in each of the three conditions). This matrix was used as input to a temporal PCA. The aim of this initial, temporal PCA was to identify distinct windows of time in the ERP averages (hereafter, temporal factors) during which similar voltage variance was registered across consecutive sampling points. As reported below, for the Semantic portion of the task, a total of 11 dominant-variance temporal factors were retained. For the Phonological portion of the task, 13 temporal factors were retained.

For each analysis, a subset of temporal factors was singled-out because their time-course (i.e., peak latency) was consistent with that of the standard N400 effect or sensory-evoked ERPs (e.g., N1, P2, which were targeted to assess whether the auditory probe words were processed at a sensory level in addition to lexical-semantic processing). In step two, a spatial PCA was performed on the factor scores of each selected temporal factor. That is, the scores for each temporal factor (representing the voltage variance within a specific time window) were reconfigured into a matrix with 62 columns (one column per electrode) and 84 rows (scores for the temporal factor, for each of the 28 participants, in each of the three different conditions). This matrix was then

submitted to a spatial PCA, in order to identify topographically coherent regions of voltage activity (hereafter, spatial factors) within the time window represented by each temporal factor.

The following specific procedures were used to conduct each principal component analysis. First, in order to determine how many dominant-variance components were extracted by each PCA, we used Rule M (Preisendorfer & Mobley, 1988). Rule M estimates how many components extracted from a real data set account for more variance than corresponding components extracted from a data set of normally-distributed, randomly-sampled noise having the same dimensions as the real data set. All components meeting this criterion for each PCA were retained and rotated to simple structure using Promax (Hendrickson & White, 1964) with Kaiser normalization and k=2 (Richman, 1986; Tataryn, Wood, & Gorsuch, 1999). All PC analyses and Promax rotations were completed using the Matlab-based PCA Toolbox (Dien, 2005).

In order to test for experimental effects, factor scores summarizing the voltage variance associated with specific pairs of temporal and spatial factors were submitted to a repeated-measures ANOVA with Condition as a within-subjects factor with three levels (Unrelated, Related, Filler) and Group as a between-subjects factor with two levels (Stuttering, Fluent). When the sphericity assumption was violated, the degrees of freedom were corrected (Greenhouse & Geiser, 1959). This correction is reflected in the reported p-values. As noted above, we were particularly interested in identifying temporal-spatial factor combinations whose time-course and scalp topographic distribution, respectively, were consistent with N400 activation or with auditory sensory potentials.

RESULTS

Behavioral Data

Each subject's responses were scored for naming accuracy. All data were assessed quantitatively and qualitatively for similarities and differences among the PWS and PWNS groups. Table 1 below depicts the mean number correct and the standard deviation per trial type for each group in each condition (see Appendix B for individual scores on all trial types).

Table 1. Mean & Standard Deviation for Naming Accuracy in Each of the Five Conditions.[4]

Group	Data Type	Filler Trials	Semantically-Unrelated Trials	Semantically-Related Trials	Phonologically-Unrelated Trials	Phonologically-Related Trials
PWS	Mean	75.36	37.71	37.79	37.64	37.79
	SD	1.15	0.47	0.43	0.63	0.43
PWNS	Mean	75.43	37.86	37.71	37.64	37.86
	SD	1.09	0.36	0.61	0.84	0.36

Quantitatively there were few differences in the mean number of incorrect trials per trial type between groups. As seen in Table 1, PWS had a slightly higher mean for Semantically-Related trials than PWNS. In contrast, PWNS had somewhat higher means for Filler, Semantically-Unrelated, and Phonologically-Related trials than the PWS. Both groups had the same mean on the Phonologically-Unrelated trials. The standard deviation

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[4] A total of 76 items were possible for the Filler condition, while a total of 38 items were possible for each of the four Experimental conditions.

for each trial type also closely resembled one another between groups (see Table 1 above). The PWS had a slightly higher standard deviation on the Filler, Semantically-Unrelated, and Phonologically-Related trials; while, the PWNS had a minimally higher standard deviation on the Semantically-Related and Phonologically-Unrelated trials.

A repeated-measures ANOVA was run, in order to determine whether the subtle differences between groups, noted above, were statistically significant. Trial type was entered as a within-subjects factor with four levels, while group (Fluent versus Stuttering) served as a between-subjects factor. The ANOVA revealed that there was no main effect of Trial Type (F[3,78]=1.15, p=.34), no main effect of Group (F[1,26]=.049, p=.83), and no two-way interaction of Group and Trial Type (F[3,78]=.41, p=.75). Overall, these findings confirm that the pictures were easily recognized and named. Some of the minor naming difficulty encountered (i.e., trials scored as incorrect) seemed to be caused by momentary lapses of attention on trials, and by fatigue toward the end of the task. At least one PWS also occasionally produced exaggerated labels (e.g., "cheese and sausage pizza" for "pizza"), perhaps as a secondary strategy for naming those items fluently.

Naming accuracy was also assessed qualitatively, in order to determine whether the nature of the errors was different for the PWNS versus PWS. Our assessment revealed that some differences, though subtle, could be discerned between groups in terms of different error types and number of subjects who made errors. Of the PWS who made errors, five different error types were observed: No response given, two-word answers instead of one-word answers (e.g., "match stick" for match), phonological errors (e.g., "cambull" for camel), semantic errors (e.g., "desk" for bed), and unrelated word

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errors (e.g., "spider" for door). Of the PWNS who made errors, three different error types

were observed: No response given, semantic errors (e.g., "toad" for frog), and two-word

answers instead of one-word answers (e.g., "swiss cheese" for cheese). It is interesting to

note that in contrast to the PWS, no PWNS made phonological errors. As a whole, the

PWS had seven subjects who made an error of any type, while the PWNS only had five

subjects make errors. The greatest number of errors made by any participant was nine,

with the least number of errors being one. The results of our qualitative analysis reveal

that although both groups made errors the number of PWS who generated errors was

greater than the number of PWNS, and the error patterns were slightly different.

ERP Data

Analysis of Semantic Conditions

Grand average waveforms for both Groups are shown in Figure 6 at midline

electrodes (Fz, Cz, Pz) for Semantically-Unrelated trials, Semantically-Related trials, and

Filler trials. Relative to Filler trials, Semantically-Related and -Unrelated trials elicited a

sequence of ERP activity, beginning with an early negativity, followed by positive-going

activity, and then later negative-going activity. As described above, the data for these

conditions were submitted to a Temporal-Spatial PCA. A total of 11 temporal factors

were identified. That is, 11 different time windows contained distinct, large-variance
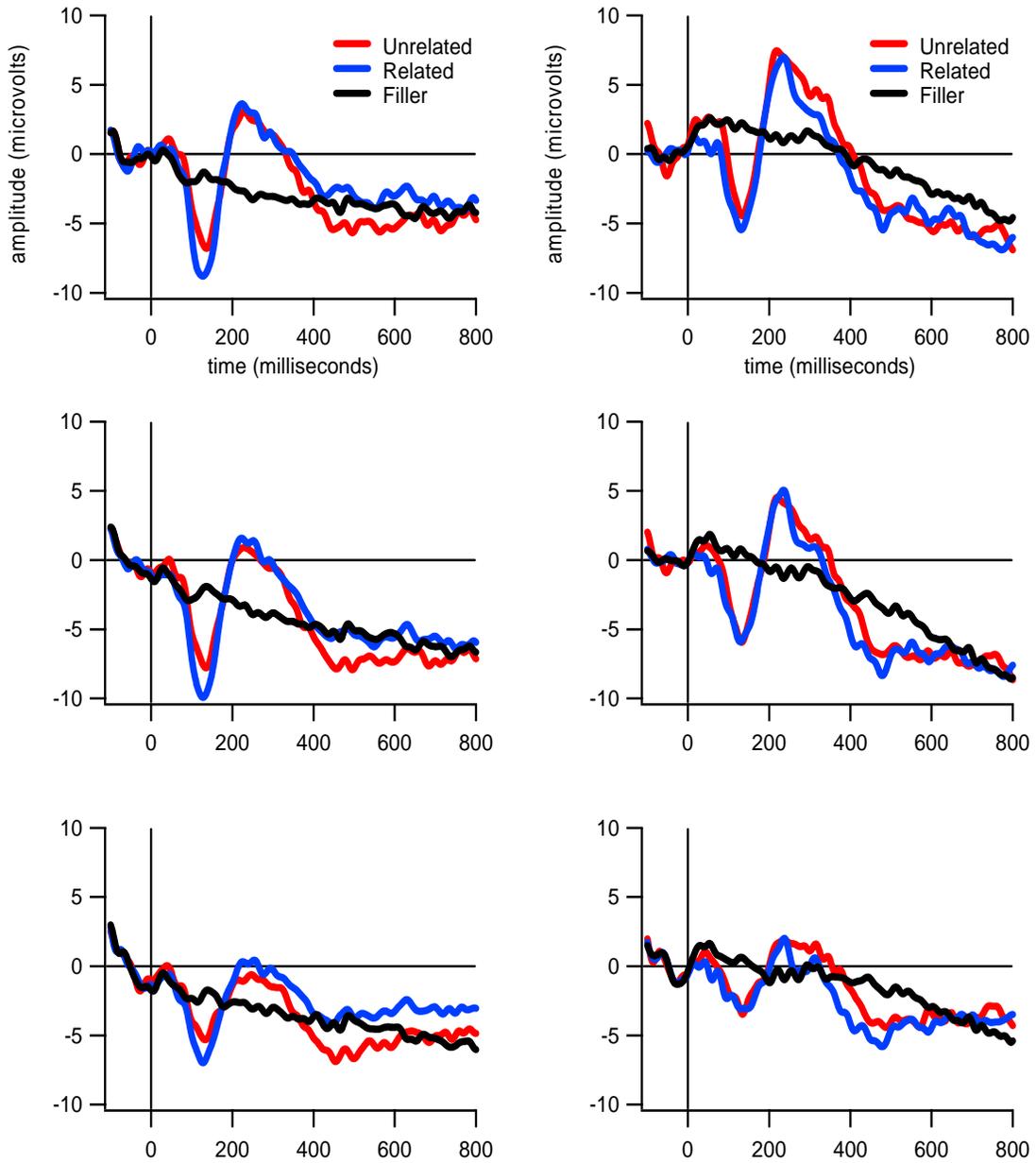
Figure 6. Grand average ERP waveforms for the Fluent Group (left) and Stuttering Group (right) at Fz (top), Cz (middle), Pz (bottom) for Filler Items, Semantically-Unrelated Probe Words, and Semantically-Related Probe Words.

ERP activity. Those 11 temporal factors accounted for 81.23% of the variance in the data set. A spatial PCA was then conducted for the time periods associated with each of the 11 temporal factors, in order to identify topographically coherent regions of ERP activity (spatial factors) within each time window.[5] Factor scores for each temporal-spatial combination were submitted to ANOVA to test for condition effects, group effects, and group-by-condition interactions in the voltage variance within the time window represented by the temporal factor, at the scalp region represented by the spatial factor.

Just four of the 11 time windows yielded spatial factors whose scores were associated with statistically significant effects. Figure 7 shows the factor loadings for each of the four time windows. The largest consecutive factor loadings indicate the sampling points during which a distinct pattern of ERP activity was registered. The peak latency (in milliseconds), given by the highest factor loading, is labeled for each time window. Each time window will, hereafter, be labeled using its peak latency (T126, T204, T306, and T476, respectively). Figure 8 shows the spatial factors, within each time window, at which statistically significant ERP effects were detected. The largest factor loadings indicate the electrode sites primarily defining each spatial factor.

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[5] Eleven separate spatial PCA's were conducted, one for each of the 11 temporal factors.
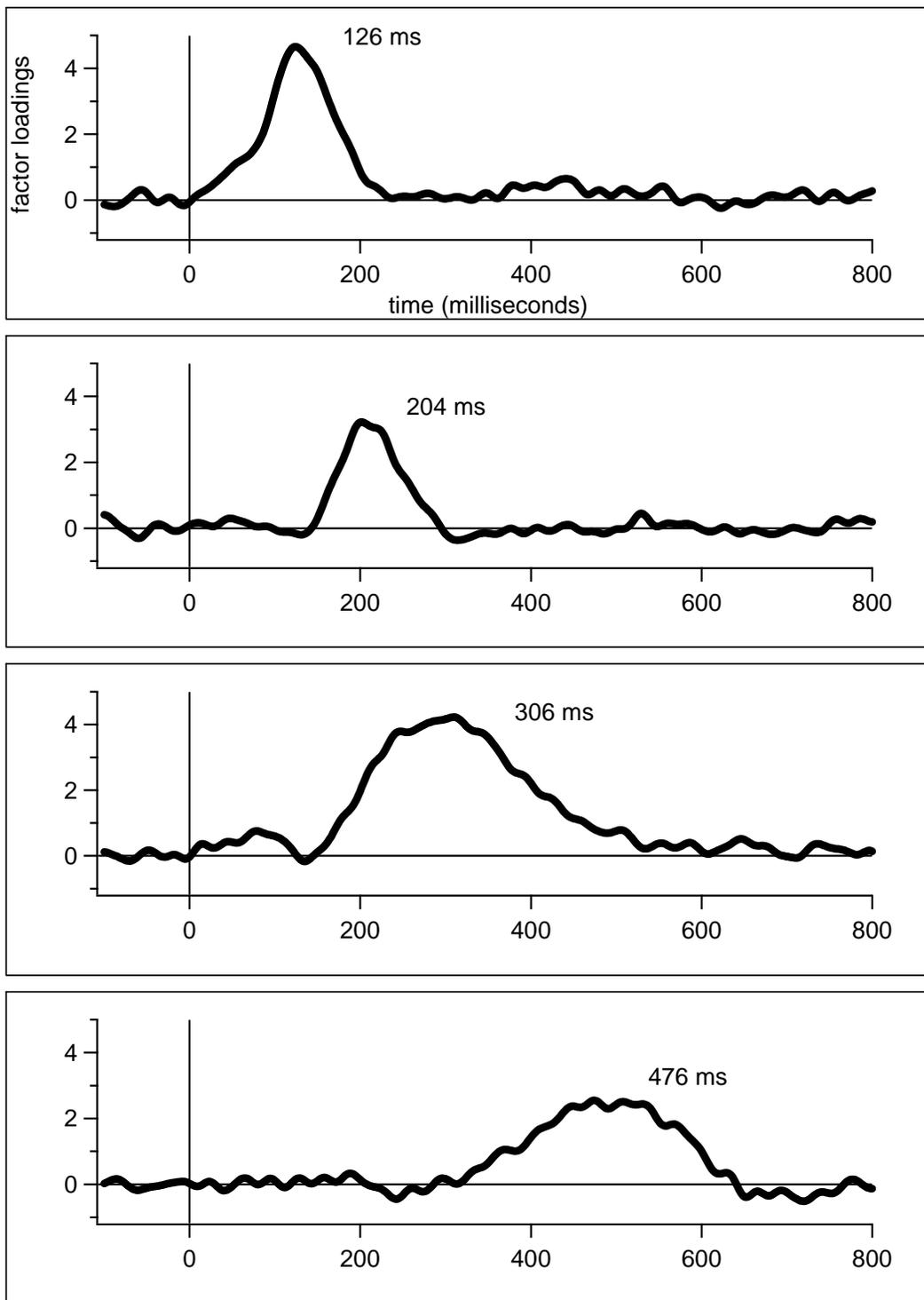
Figure 7. Factor loadings of four relevant temporal factors, each capturing a time window

during which distinct ERP activity was detected.

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Frontal				
Posterior				
Time Window	T126	T204	T306	T476
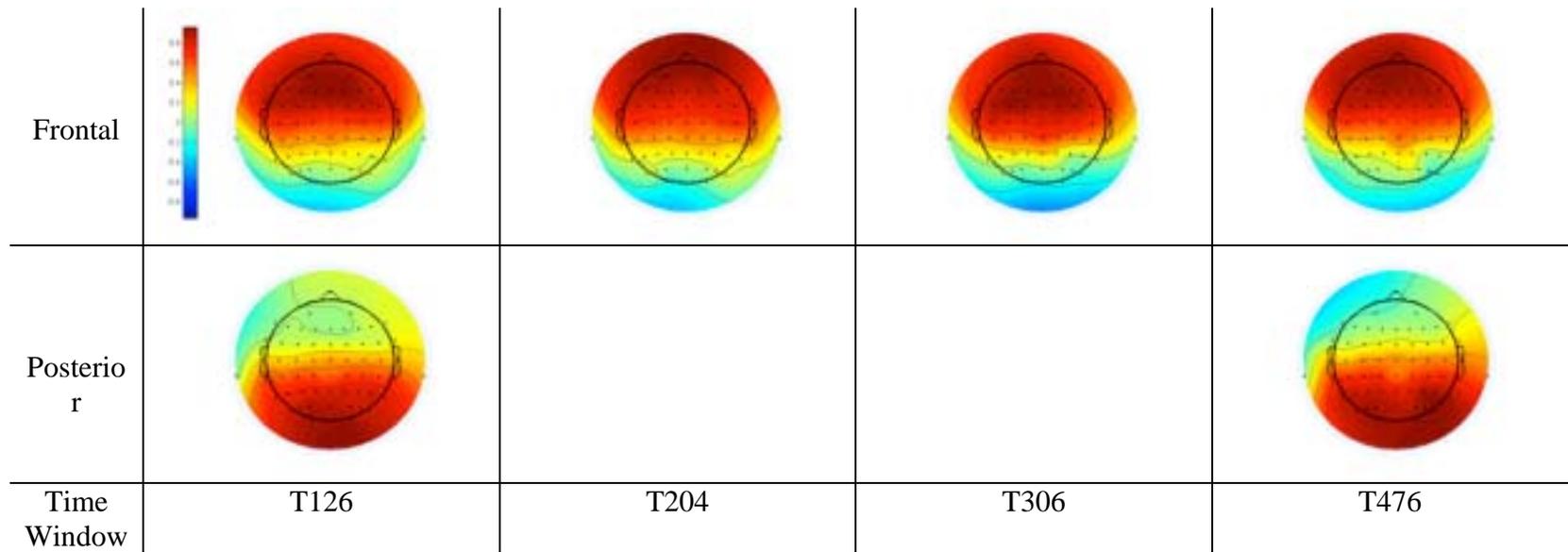
Figure 8. Spatial factors associated with statistically significant experimental effects within each of four critical time windows.

Several of the temporal-spatial combinations captured ERP activity that differentiated both the Semantically-Related and Semantically-Unrelated probe word trials from the Filler trials. For example, both conditions elicited ERP activity more negative in amplitude than Fillers at the posterior region of the scalp during T126 (see Figure 8) (main effect of condition, $F(2,52)=9.57$, $p=.000$; Semantically-Related versus Filler, $p=.000$; Semantically-Unrelated versus Filler, $p=.02$). This effect is consistent with posterior N1 activation, an ERP index that presentation of either type of probe word aroused the central auditory system. Later in time, Semantically-Related and -Unrelated conditions also elicited ERP activity more positive in amplitude than Fillers at the frontal region of the scalp during T204 (see Figure 8) (main effect of condition, $F(2,52)=12.07$, $p=.000$; Semantically-Related versus Filler, $p=.001$; Semantically-Unrelated versus Filler, $p=.01$), and during T306 (see Figure 8) (main effect of condition, $F(2,52)=15.06$, $p=.000$; Semantically-Related versus Filler, $p=.002$; Semantically-Unrelated versus Filler, $p=.000$). The former is consistent with P2 activation, another indicator that word presentations aroused the central auditory system, while the latter is consistent with P300 activation, an ERP index of context-updating. These effects reveal differences in how probe word trials versus Filler trials were processed. Three additional effects, reported next, were sensitive to the semantic relationship between probe word and preceding picture.

T126, frontal component. In addition to a posterior N1 component, reported above, T126 also generated frontal ERP activity (see Figure 8) associated with a main effect of condition ($F(2,52)=70.56$, $p=.000$). As shown in Figure 9, both Semantically-

Figure 9. Mean factor scores and 95% confidence intervals summarizing the ERP variance registered at T126, frontal region.

Unrelated and Semantically-Related probe words elicited ERP activity more negative in amplitude than Fillers, differences confirmed by Bonferroni-corrected pairwise comparisons (Unrelated versus Filler, p=.000; Related versus Filler, p=.000). These effects are consistent with frontal N1 activation, an ERP index of capture of auditory attention. Critically, Related was even more negative in amplitude than Unrelated (p=.02), suggesting that a semantic relationship between preceding picture and probe word captured greater attention than when the two events were unrelated.

T476 components. T476 generated a frontal component (see Figure 8) associated

with a main effect of condition (F(2,52)=4.00, p=.03). As shown in Figure 10, Semantically-Unrelated was more negative in amplitude than Filler, a difference confirmed via pairwise-comparison with Bonferonni correction (p=.003). As discussed below, this effect is consistent with a frontal N400-type ERP component.

Figure 10. Mean factor scores and 95% confidence intervals summarizing the ERP variance registered at T476, frontal region.

T476 also generated a posterior component (see Figure 8) associated with a statistically significant interaction of Group and Condition (F(2,52)=3.59, p=.04). As shown in Figure 11, for the PWS, Semantically-Related was more negative in amplitude than Filler (p=.001), as was Semantically-Unrelated (p=.000). For the PWNS , only

Semantically-Unrelated was more negative in amplitude than Filler (p=.003). The former

is consistent with activation of a standard N400 ERP for the PWS in response to probe

words both Semantically-Related and -Unrelated to preceding pictures; versus standard

N400 activation for the PWNS only in response to probe words Semantically-Unrelated

to the pictures.
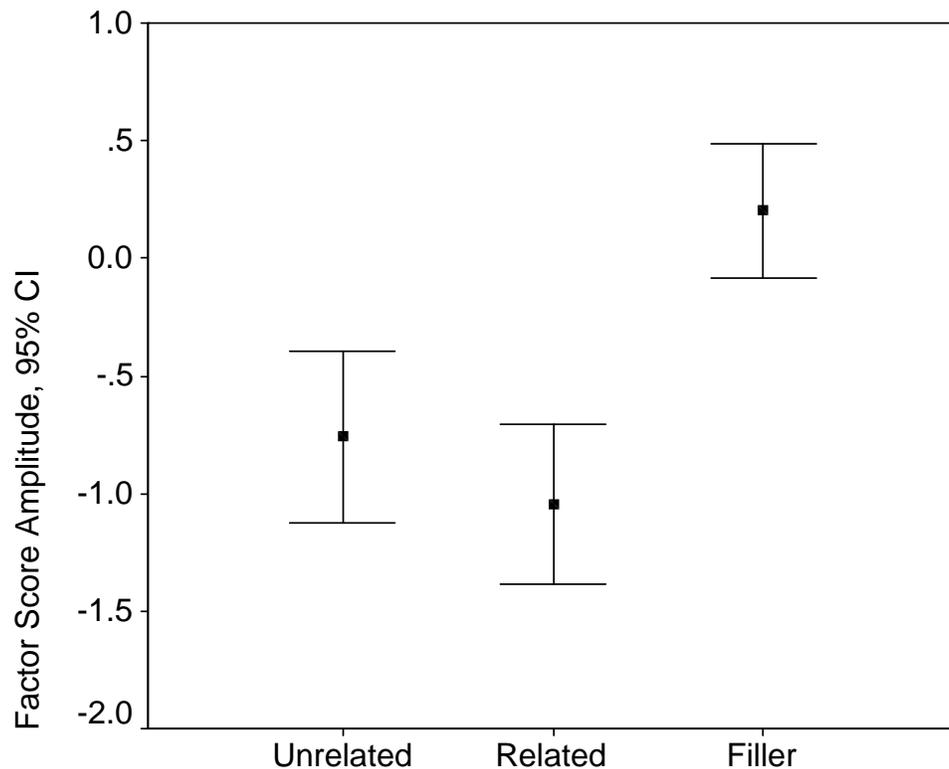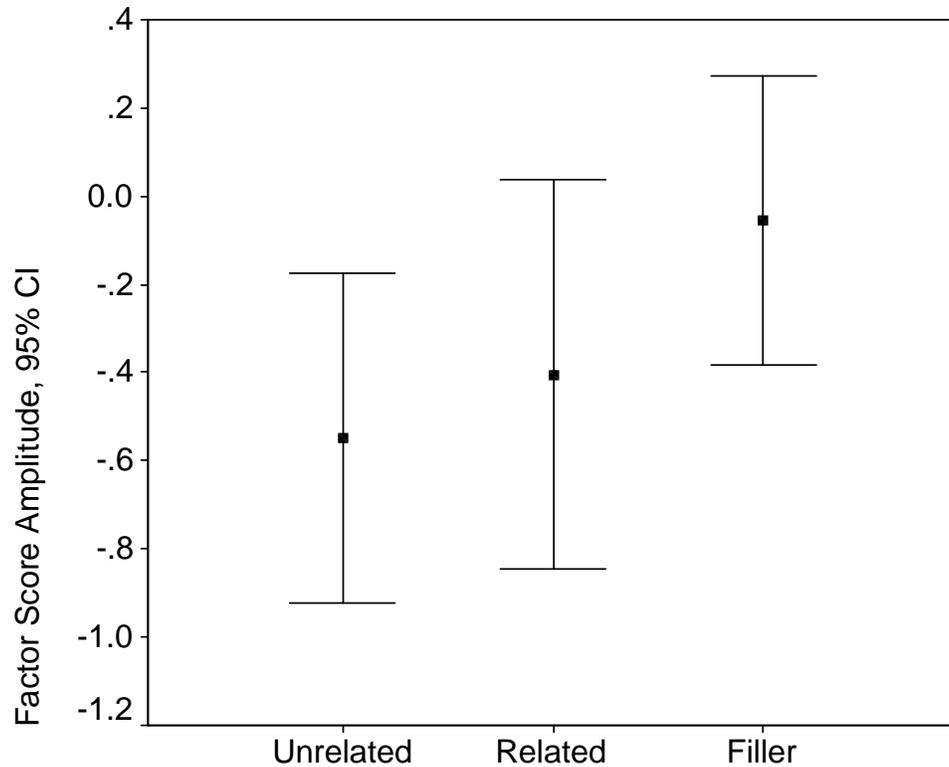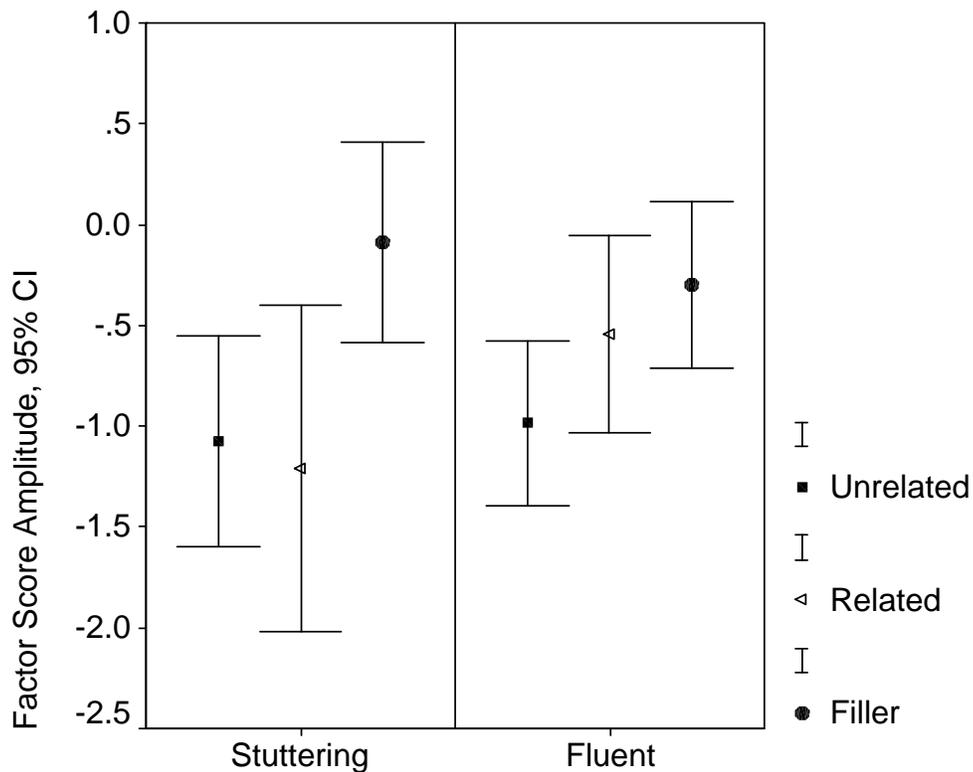

Figure 11. Mean factor scores and 95% confidence intervals summarizing the ERP

variance registered at T476, parietal region, separately for each group.

Summary of ERP Findings Related to Semantic Picture-Word Priming

Presenting an auditory probe word after a picture was shown here to elicit several

ERP components, including a posterior N1, anterior P2 and P300. Probe words also

elicited an anterior N1 that was larger in amplitude than when the probes were related to the labels of preceding pictures. Finally, probes that were Semantically-Unrelated to preceding pictures elicited two N400-like effects: One frontal, and one posterior. For the PWS, probes that were Semantically-Related to preceding pictures also elicited a posterior N400 effect. As discussed below, this latter effect suggests that semantic picture-word priming was not as robust for PWS as for PWNS.

Analysis of Phonological Conditions

Grand average waveforms for both Groups are shown in Figure 12 at midline electrodes (Fz, Cz, Pz) for Phonologically-Unrelated trials, Phonologically-Related trials, and Filler trials. Relative to Filler trials, Phonologically-Related and -Unrelated trials elicited several ERP activations, specifically, early negative-going activity, later positive-going activity, and then a negative-going wave. The data for these conditions were submitted to a Temporal-Spatial PCA. A total of 13 temporal factors were identified, i.e., 13 different time windows contained distinct, large-variance ERP activity, accounting for 80.16% of the variance in the data set. A spatial PCA was then conducted for each of the 13 time windows in order to identify topographically coherent regions of ERP activity (spatial factors) within each time window.[6] Factor scores for each temporal-spatial factor combination were submitted to ANOVA to test for condition effects, group effects, and group-by-condition interactions in the voltage variance within the time window represented by the temporal factor, at the scalp region represented by the spatial factor.

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[6] Thirteen separate spatial PCA's were conducted, one for each of the 13 temporal factors.
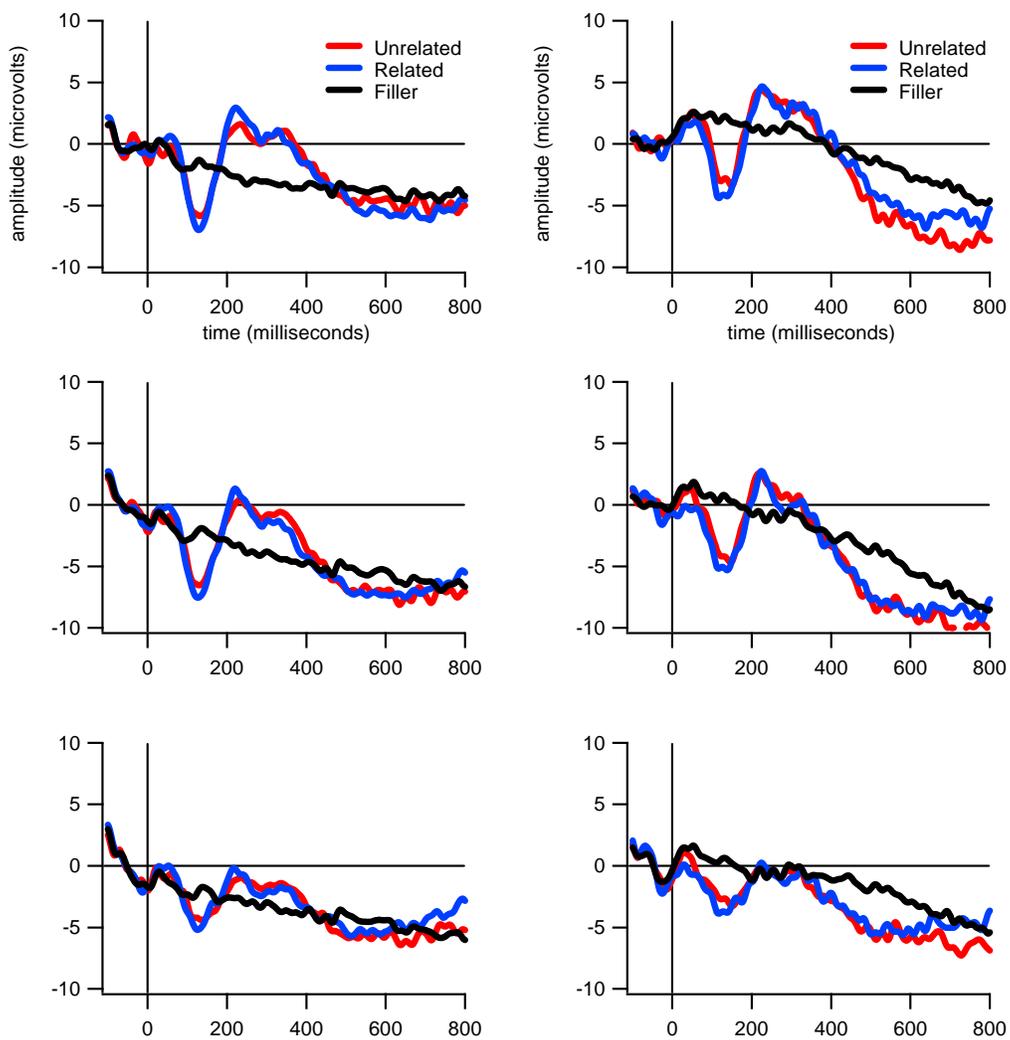
Figure 12. Grand average ERP waveforms for the PWNS (left) and PWS (right) at Fz (top), Cz (middle), Pz (bottom) for Filler Items, Phonologically-Unrelated Probe Words, and Phonologically-Related Probe Words.
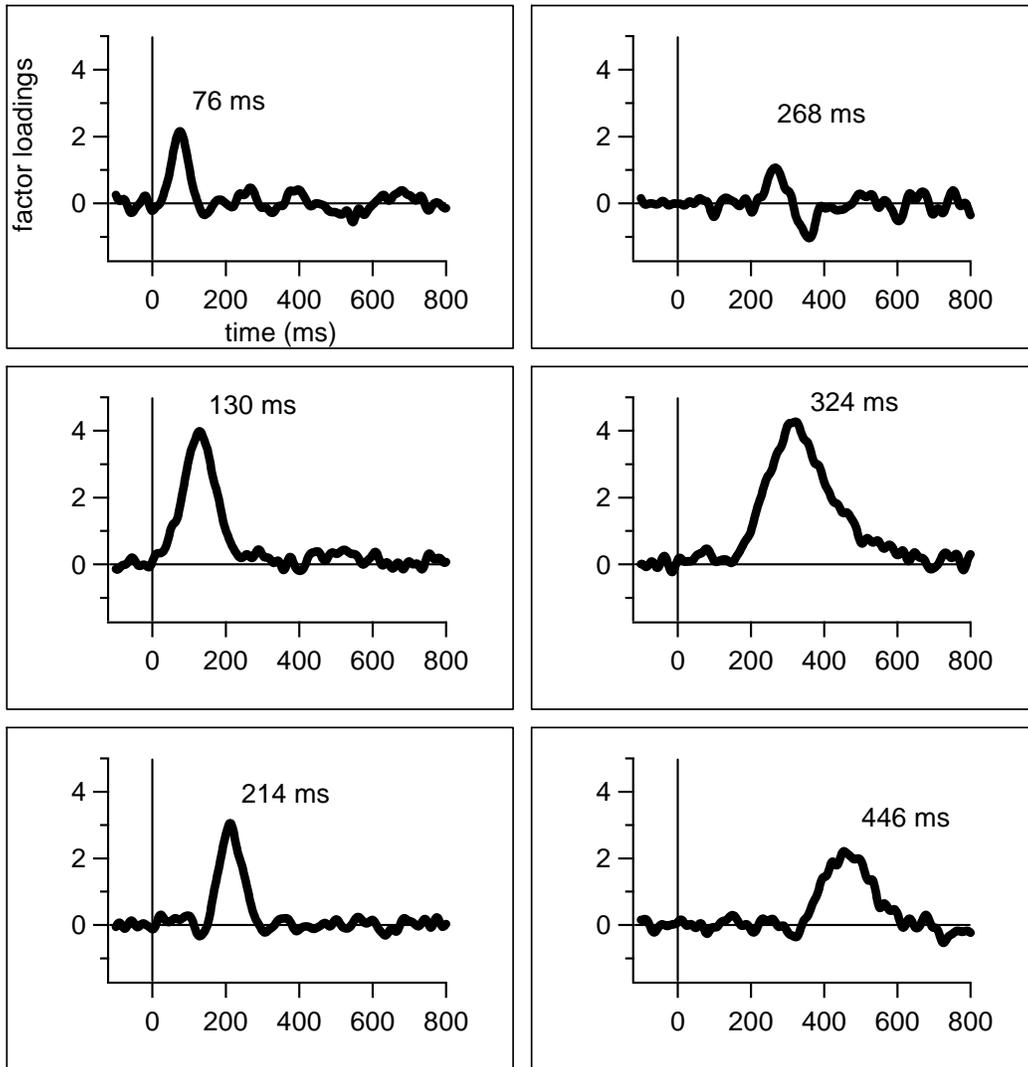
Figure 13. Factor loadings of six relevant temporal factors, each capturing a time window during which distinct ERP activity was detected.

	T76	T130	T214	T268	T324	T446
Frontal	●	●	●		●	
Posterior		●		●		●
Time Window	T76	T130	T214	T268	T324	T446
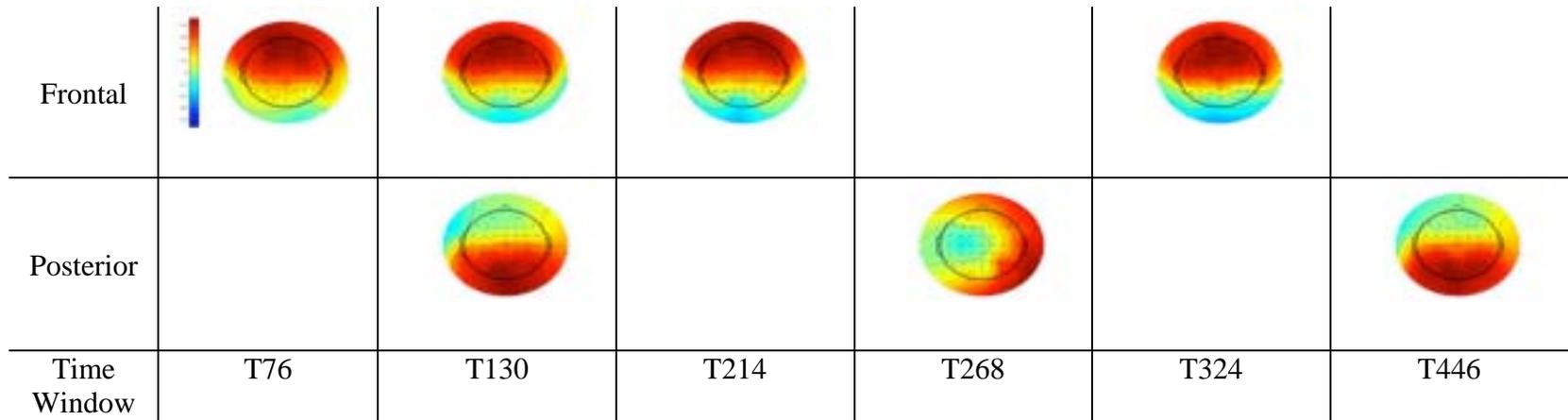
Figure 14. Spatial factors associated with statistically significant experimental effects within each of six critical time windows.

Six of the 13 time windows yielded spatial factors associated with statistically significant effects. Figure 13 shows the factor loadings and peak latencies for each of the six time windows (hereafter, T76, T130, T214, T268, T324, and T446, respectively). Figure 14 shows the spatial factors, within each time window, at which statistically significant ERP effects were detected.

As for the Semantic manipulations, several of the temporal-spatial factor combinations observed here captured ERP activity that differentiated both the Phonologically-Related and Phonologically-Unrelated probe word trials from the Filler trials. For example, both conditions elicited ERP activity more positive in amplitude than Fillers at the frontal region of the scalp during T76 (see Figure 14) (main effect of condition, $F(2,52)=6.73$, $p=.003$; Phonologically-Related versus Filler, $p=.02$; Phonologically-Unrelated versus Filler, $p=.03$). This effect is consistent with P1 activation, an ERP measure of auditory inhibition and sensory gating. It is unclear why this effect was not also observed for the Semantic conditions. Later in time, Phonologically-Related and -Unrelated both generated frontal ERP activity more negative in amplitude than Fillers during T130 (see Figure 14) (main effect of condition, $F(2,52)=43,77$, $p=.000$; Phonologically-Related versus Filler, $p=.000$; Phonologically-Unrelated versus Filler, $p=.000$). A nearly identical effect was observed within the same time window (T130) at posterior electrodes (see Figure 14) (main effect of condition, $F(2,52)=10.28$, $p=.000$; Related versus Filler, $p=.001$; Unrelated versus Filler, $p=.01$). The posterior negativity is consistent with an N1 effect indexing arousal of the central auditory system, while the frontal negativity is consistent with an N1 effect indexing

capture of auditory attention. Even later in time, Related and Unrelated both generated

frontal ERP activity more positive in amplitude than Fillers during T214 (main effect of

condition, $F(2,52)=14.06$, $p=.000$; Related versus Filler, $p=.001$; Unrelated versus Filler,

$p=.003$), and during T324 (main effect of condition, $F(2,52)=10.72$, $p=.000$; Related

versus Filler, $p=.001$; Unrelated versus Filler, $p=.003$). The former is consistent with P2

activation, an additional indicator that word presentations aroused the central auditory

system, while the latter is consistent with P300 activation, an ERP index of context-

updating. Finally, during T446, both Related and Unrelated generated ERP activity more

negative in amplitude than Filler at posterior electrodes (see Figure 14) (main effect of

condition, $F(2,52)=5.42$, $p=.007$; Related versus Filler, $p=.03$; Unrelated versus Filler,

$p=.03$). This activity is consistent with activation of a standard N400 effect for both

Phonologically-Related and unrelated probe words. Therefore, a shared word-initial

phoneme between probe word and preceding picture label did not modulate the amplitude

of the standard N400. However, an additional effect was sensitive to word-initial

phoneme overlap.

T268, right posterior component. T268 generated a right posterior component (see

Figure 14) associated with a main effect of Condition ($F(2,52)=3.74$, $p=.03$). As shown in

Figure 15, Related and Unrelated elicited ERP activity more negative in amplitude than

Filler. However, Bonferroni-corrected pairwise comparisons revealed that only Unrelated

and Filler were statistically different ($p=.04$). This effect is consistent with a Phonological

Mismatch Negativity, observed when the phonological make-up of a probe word is

dissimilar to that of a preceding word, and attenuated when probe and preceding word are

phonologically similar.
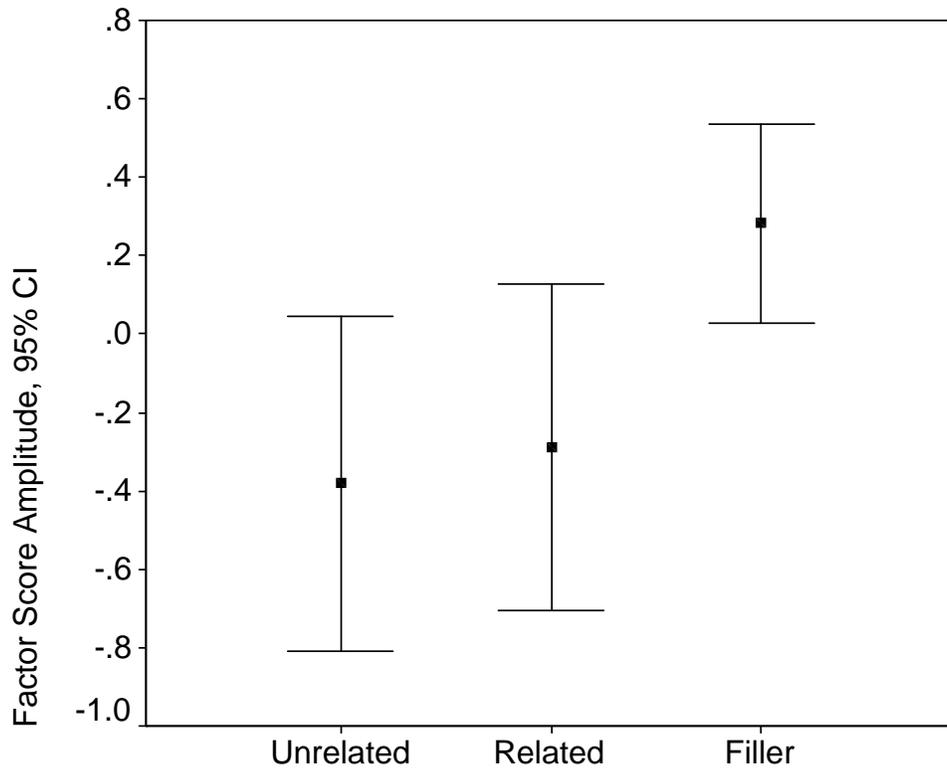
Figure 15. Mean factor scores and 95% confidence intervals summarizing the ERP variance registered at T268, right parietal region.

Summary of ERP Findings Related to Phonological Picture-Word Priming

Presenting an auditory probe word after a picture was shown here to elicit several ERP components, including an anterior P1, anterior and posterior N1 components, anterior P2 and P300. The probe words examined here, which were either Unrelated to the label of the preceding picture or shared a word-initial phoneme, also elicited a posterior standard N400 effect. Unlike the pattern reported above for semantic picture-

word similarity, anterior N1 amplitude was not modulated by initial phoneme similarity between picture label and probe word. Initial phoneme similarity also failed to modulate the amplitude of the standard N400 effect. Interestingly, a frontal N400 effect was not observed here for either Unrelated or Related picture-word combinations. However, an earlier negativity (peaking at ~268 ms) was elicited by Phonologically-Unrelated picture-word pairs but not by Phonologically-Related pairs. None of the effects summarized here differentiated the PWNS from PWS groups.

DISCUSSION

Summary of Experiment and Findings

The aim of this study was to examine the activation of semantic and phonological word networks in PWS and PWNS using a neuroscience approach. ERPs were recorded at the presentation of auditory probe words in a picture-word priming task. Auditory probe words were either Semantically-Related to their corresponding pictures, Phonologically-Related (shared the initial phoneme) to their corresponding pictures, or Semantically- and Phonologically-Unrelated to their corresponding pictures. ERPs were also recorded on trials that required only naming of pictures without presentation of an auditory probe word (Filler trials). The task was designed to answer two questions: 1) Does picture-naming activate a network of semantically-related words in adults who stutter in the same manner as that seen for adults who do not stutter, as evidenced by semantic N400 priming effects in a picture-word priming task? 2) Does picture-naming activate a network of phonologically-related words in adults who stutter in the same manner as that seen for adults who do not stutter, as evidenced by phonological N400 priming effects in a picture-word priming task?

Semantically-Related and Semantically-Unrelated probe words each elicited ERP components not observed on Filler trials. Semantically-Unrelated probe words elicited N1, P2, P3, and two N400-like components. Semantically-Related probe words elicited an even larger N1 activation than that seen for Semantically-Unrelated words. Semantically-Related probe words also elicited P2 and P300 activations. While

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Semantically-Related probe words did not elicit any N400-like activations for the PWNS, a robust bilateral parietal N400 activation was observed in response to Semantically-Related probe words for the PWS.

Similar to the ERP results obtained for the Semantic probe word conditions, both Phonologically-Related and Phonologically-Unrelated probe words elicited ERP activity not observed on Filler trials. Phonologically-Unrelated probe words elicited N1, P2, P3, and N400 ERP components, as well as an ERP component resembling the Phonological Mismatch Negativity, described in further detail below. Phonologically-Related probe words elicited all of these same components except for the Phonological Mismatch Negativity. This pattern of results was seen for the PWNS and PWS groups. Effects that were most central to our research question are discussed in the sections that follow.

<div align="center">**Discussion of Semantically Related Findings**</div>

Semantically Driven Findings at ~126ms

ERPs elicited by auditory probe words in a picture-word priming study included two early sensory-evoked potentials typically seen in response to auditory stimuli (N1 and P2). The most significant of these was the N1 ERP component which, as noted above, had a frontal scalp distribution and a peak latency at ~126 ms after the onset of auditory probe words. The functional significance of auditory N1 has been investigated a number of times in the past. Naatanen and Picton (1987), who reviewed this body of research, concluded that there are at least three different N1-type components generated

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by the brain. All three N1 responses can be elicited by the onset or offset of an auditory stimulus. However, it is possible to differentiate the N1 components by their latency, location on the surface of the scalp, and – most importantly – by their sensitivity to different task and subject factors. One N1 component is a frontocentral negativity that is sensitive to auditory selective attention. For example, if participants are instructed to listen to tones of different frequencies, and respond by pressing a button only when a tone of low frequency is presented to one ear, N1 is larger in amplitude to those target stimuli than to other tones (i.e., high tones presented to the same ear, and any tone presented to the opposite ear). The N1 component seen in response to auditory probe words in our study closely resembles this N1 component, functionally indicating that participants' attention was captured by the auditory stimuli.

As reported above, N1 had a larger amplitude when auditory probe words were Semantically-Related to their corresponding pictures than when the stimuli were Semantically-Unrelated. This suggests that a conceptual-semantic relationship between preceding picture and probe words captured greater attention than when the two events were unrelated. A similar finding has been reported in at least one previous study. Novick, Lovrich, and Vaughan (1984) conducted a study wherein participants were randomly presented with both real words and nonsense words under four different conditions. Depending on the condition, participants were asked to respond to all spoken words; to a specific real word; to a specific nonsense word; or to a spoken word belonging to a specific semantic category. For trials where participants had to monitor for specific semantic categories, Novick et al. (1984) reported a slightly later negative going

waveform, as compared to other conditions, initiated at ~150ms and lasting to ~ 250 ms post stimulus onset. Similarly to the N1 seen in our study, these results suggest that semantic (categorical) processing of lexical stimuli can differentially impact auditory selective attention, as evidenced by modulations in frontocentral N1 activation.

Semantically Driven Findings at ~ 476 Milliseconds

Two N400-like components were observed for the semantic task. One was a negative-going component with a frontal scalp distribution, whose amplitude was larger for Semantically-Unrelated trials than for Filler trials. A frontal N400-like component has been observed by other researchers in response to Semantically-Unrelated word pairs (Franklin, Dien, Neely, Waterson, & Huber, 2007). When the words in each pair were both Semantically-Related *and* highly associated with one another (e.g., dog-cat), the frontal N400-like component was attenuated in amplitude. In contrast, word pairs that were Semantically-Related but not strong semantic associates (e.g., dog-lizard) were not shown to modulate the amplitude of frontal N400. This pattern of results seen by Franklin et al. (2007) suggests that frontal N400 is sensitive to concept formation; a level of psycholinguistic processing that precedes lexical selection.

As noted in the Method, we selected auditory probe words that were strong conceptual associates of their corresponding picture labels (determined via free association norms published by Nelson, McEvoy, & Schreiber, 1998). When the auditory probe words were reassigned to semantically and conceptually unrelated pictures, frontal N400 activation was observed for both the PWNS and PWS. In other words, presenting

auditory probe words that were not strongly conceptually related to their preceding

pictures elicited a robust frontal N400 wave. One interpretation is that this wave

represents the activation of concepts represented by the auditory probe words. This is

based on our finding that, when auditory probe words followed pictures to which they

were strongly conceptually associated, frontal N400 was not detected. Absence of frontal

N400 activation for this condition suggests that preceding pictures conceptually primed

auditory probe words, an effect that was seen for both the PWNS and PWS groups.

The other N400-like component observed in our Semantic task had a posterior

scalp distribution. This component is consistent with the standard (or "classic") N400

effect. As noted in the Introduction, the amplitude of standard N400 is inversely related

to a word's activation level in memory (Van Petten & Kutas, 1991). When a target word

is primed semantically (i.e., preceded by a semantically-related word or words), it elicits

a relatively small posterior N400 component versus when the target word is unprimed.

This effect is known to occur as long as participants attend to the prime word (Deacon &

Shelley-Tremblay, 2000); which, in the case of our experiment, was the picture label on

each trial. While the PWNS exhibited this priming effect for Semantically-Related words,

the PWS did not exhibit this effect.

The posterior N400 priming effect seen for the PWNS group is consistent with

N400 priming effects reported by Jescheniak et al. (2002), who also tested PWNS. This

priming effect indicates that retrieving a picture label activates Semantically-Related

words in the mental lexicon. When one of those words is presented auditorily directly

after the picture-to-be-named, the N400 ERP elicited by the auditory probe word is

relatively smaller in amplitude than when the label of the preceding picture is Unrelated to the probe word. Absence of N400 attenuation (i.e., N400 priming) for Semantically-Related probe words in the PWS group may be interpreted in at least two different ways.

One interpretation is that semantic network activation operates inefficiently for PWS. That is, labeling a picture may not automatically activate a network of Semantically-Related words, as appears to happen for PWNS. This result coincides to some extent with previous research reviewed in the Introduction. Most notably, Wingate (1988) reported that PWS performed more poorly on the WAIS. Qualitative analysis of performance on the WAIS indicated that PWS used fewer synonyms to generate definitions, an indirect indicator of poor semantic network connections. In a different study, Bosshardt and Fransen (1996) reported that PWS had slower reaction times identifying category-specific words than PWNS. This, too, indirectly points to weakness in the activation of semantic networks in PWS. Finally, Prins, Main, and Wampler (1997) found that lower-frequency words had a large effect on lexicalization time despite the vocabulary levels of PWS. Participants in this study heard a word on each trial and were then shown pictures of various items. Instructions were to press the space bar on a keyboard when the picture corresponding to the word was shown. PWS were found to be slower than PWNS when selecting word-picture combinations that were particularly low in frequency (e.g., wench, laggard). Prins et al. (1997) conjectured that slow processing during beginning stages of lexicalization, specifically semantic processing of words, was at-play in PWS, and went further to speculate that slow semantic activation of words might be to blame for disrupted fluency in PWS. All three findings outlined here

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indirectly point to inefficient activation of semantic word networks, in line with our N400 results. Noteworthy is our finding that frontal N400 priming but not parietal N400 priming was observed for the PWS. This implies that PWS encounter difficulty not at the level of concept formation but specifically involving the activation of words in semantic networks.

A different interpretation is that PWS exhibit over-activation of semantically associated words on the path to picture naming, resulting in disproportionately high competition between words comprising semantic word networks. One study conducted by Newman and Ratner (2007) used pictures of highly familiar words to assess naming speed using RT, accuracy, and fluency in PWS and PWNS. They found that while various lexical factors (i.e., word frequency, neighborhood density, and neighborhood frequency) had a similar effect on the naming *speed* of PWS and PWNS, more naming *errors* were made by PWS (AWS 94.3%, AWDNS 97.6%). Word frequency also had a particularly negative effect on fluency for the PWS. In addition, PWS were shown to supply very low-frequency responses to relatively common stimuli (e.g., "patella" for knee). Newman and Ratner suggest that PWS "could have a fundamental difference in a basic level of language processing" (p.208). This fundamental difference could be explained via over-activation of semantic networks, an effect that might possibly be learned. PWS often learn to keep multiple synonyms in-mind in order to readily substitute words as a strategy for avoiding moments of stuttering. That is, they circumlocute or substitute words as a coping mechanism when stuttering is anticipated, which may inadvertently cause an initial over-activation of Semantically-Related words

(Guitar, 2006, p.158). In the context of our task, this may have manifested in maintained

activation of multiple potential word entries at the presentation of the pictures. Having

more than one possible word entry in mind may have induced an interference effect at the

presentation of Semantically-Related auditory probe words, resulting in parietal N400

activation not seen for these items in the PWNS group. The pattern of naming errors in

PWS reported by Newman and Ratner (2007) supports this conclusion.

Both interpretations of the N400 effects entertained here are tentative and require

further study. Although the PWS did not display a typical posterior N400 priming effect

for Semantically-Related probe words, their picture naming ability was grossly similar to

that seen for the PWNS (see Results, Behavioral Data). This finding aligns with those of

Weber-Fox (2001), who found that PWS exhibited atypical N400 activations while

participating in a visual sentence processing task. At the same time, behavioral data did

not differentiate the PWNS and PWS in her study. PWS and PWNS performed similarly

on the Test of Adolescent and Adult Language, a standardized language assessment, and

had similar accuracy for detecting semantic anomalies embedded within sentences

(Weber-Fox, 2001). Weber-Fox and Hampton (2008), too, reported atypical N400

activations for PWS compared with PWNS, while behavioral linguistic performance was

not found to differ between groups. Findings from both studies align with our results that

although behaviorally PWS may perform similarly to PWNS, covert aspects of lexical

processing may differ as evidenced by ERPs. Therefore, it appears to be important to

look beyond behavior, to covert processes, when investigating clinical phenomena such

as stuttering.

Discussion of Phonologically Related Findings

Phonologically Driven Findings at ~268 Milliseconds

Several ERP effects were observed for the Phonology task that differentiated processing of auditory probe words from Filler trials, among them anterior P1, anterior and posterior N1 components, anterior P2 and P3 components, and a posterior standard N400 effect. However, none of these components differentiated processing of Phonologically-Related from Phonologically-Unrelated stimuli, and none differentiated the PWNS versus PWS groups. An additional ERP component was observed that did differentiate processing of Phonologically-Related versus Phonologically-Unrelated words. This was the Phonological Mismatch Negativity, a negative-going wave elicited only by Phonologically-Unrelated words, which peaked in amplitude at ~268 milliseconds post stimulus onset.

The Phonological Mismatch Negativity was first observed by Praamstra and Stegeman (1993) and was later labeled by Praamstra, Meyer and Levelt (1994). Praamstra and Stegeman (1993) had ten participants complete two tasks requiring them to listen to pairs of words and non-words. Some trials contained word pairs or non-word pairs that rhymed, while other trials contained word pairs or non-word pairs that did not rhyme. Participants were instructed to judge whether the two auditorily presented words comprising each trial rhymed. Praamstra and Stegeman (1993) observed a significant modulation in ERPs during the time window spanning 300 to 600 milliseconds after second word onset, with ERPs to non-rhyming stimuli more negative in amplitude than

ERPs to rhyming stimuli. This ERP modulation was largest at central and temporoparietal electrode locations on the scalp.

In a later study (Praamstra et al., 1994), 24 participants completed two experiments both involving a delayed or immediate response task. In one experiment, participants heard pairs of words or non-words that rhymed. In the second experiment, participants heard pairs of words or non-words that alliterated. For each trial, in both experiments, participants were required to judge whether auditorily presented words rhymed or alliterated. Similar to the results reported by Praamstra and Stegeman (1993), here analysis of the ERP data revealed that unrelated word pairs elicited a larger, more negative-going wave between 450-700 milliseconds after second word onset for the rhyming words and between 250-450 milliseconds for alliterating real word pairs. Non-word pairs did not elicit N400 priming effects for either experiment. Praamstra et al. (1994) interpreted this effect as "…similar enough to the 'classical' N400 to be provisionally placed in the same category" (p.215). These above mentioned studies both support the notion that phonological priming of words can modulate a late negative ERP component.

We, too, observed a negative going ERP component for Phonologically-Unrelated items that was not observed for Filler trials or for Phonologically-Related trials. This effect had a peak latency of ~268 milliseconds after probe word onset, and was localized to the right temporal-parietal region of the scalp. Our data in conjunction with the above mentioned studies helps to confirm that at least one ERP component is sensitive to phonological priming between words. To our knowledge, we are the first to report that a

Phonological Mismatch Negativity can be elicited via a picture-word priming task. The studies by Praamstra and colleagues, reviewed above, both utilized auditory match-to-sample tasks to elicit and modulate the Phonological Mismatch Negativity.

It is noteworthy, too, that in the present study we did not observe the same phonological priming effects reported by Jescheniak et al. (2002). In that study, they showed phonological priming for an N400 component that was widespread across the scalp at regions more consistent with a traditional N400 effect than with a Phonological Mismatch Negativity effect. This difference in ERP manipulations may be related to the modifications of two aspects in our phonological priming task from that used by Jescheniak et al. (2002). First, in that study, picture labels and auditory probe words shared multiple overlapping phonemes. In contrast, picture labels and auditory probe words in our Phonologically-Related condition shared only the initial phoneme. As noted in Appendix A, we decided to prime initial phoneme only, because stuttering tends to occur on initial sounds. Second, Jescheniak et al. (2002) required participants to explicitly remember and judge auditory probe words. In contrast, we instructed participants to ignore probe words, due to concern that a dual-task requirement would induce disproportionately high rates of stuttering during testing. Stronger phonological priming coupled with a requirement to hold auditory probe words in phonological working memory seems to induce stronger phonological N400 priming effects, although the contribution of each factor is not specifically known at this time.

In contrast to our results for semantic network activation, we did not observe any difference between PWS and PWNS on phonological processing aspects of our task. A

recently-published review of the literature on psycholinguistic ability in PWS (Broklehurst, 2008) concluded that PWS may have a slower rate of phonological encoding than PWNS, but only under increased cognitive load. As reviewed in the Introduction, Weber-Fox et al. (2004) conducted a study wherein PWS and PWNS had to perform rhyme judgment tasks. Participants were shown words that either rhymed and looked similar (e.g., thrown, own), did not rhyme and did not look similar (e.g., cake, own), looked similar but did not rhyme (e.g., gown, own), or did not look similar but rhymed (e.g., cone, own). They found that although ERPs and response accuracy were similar for both groups, RTs were slower for PWS as cognitive load was increased (i.e., on trials for which phonology and orthography of the target words was incongruent). Since our naming task was not particularly demanding, participants may not have faced enough cognitive load to have affected the efficiency of phonological network activation in our PWS.

Summary, Conclusions and Directions for Future Research

Speech production begins with the formation of a concept, followed by two levels of premotor planning. One level involves generating a linguistic utterance plan while the second involves generating a speech motor plan and program. Activation and processing of words plays a key role in generating a linguistic utterance plan. As a speaker forms a concept-to-be-named, words in mental lexicon begin to activate, and activation spreads to a cohort of Semantically- and Phonologically-Related words. The words compete for activation until a "winner" emerges.

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The activation of semantic and phonological word networks was explored in PWS via a picture-word priming task, during which ERPs were recorded. Results indicate that the activation of semantic word networks operates differently for PWS versus PWNS on the path to picture naming. One interpretation of these results was that semantic network activation is under-active or inefficient in PWS. This may be because PWS have weak associations among Semantically-Related words in mental lexicon; an effect that other, behavioral research involving PWS seems to confirm. If true, an under-activation of words at the earliest stages of linguistic utterance planning may affect efficiency of processing in some other stages of speech planning that follow. One method for treating this level of function might be to focus on vocabulary learning and strengthening of word associations, which in turn may "prime" the linguistic utterance planning system to operate more efficiently.

A different interpretation was that our results reflect over-activation of semantic word networks. We speculate that if PWS have over-activation of semantically related words this may have induced an interference effect at the presentation of Semantically-Related auditory probe words, resulting in parietal N400 activation as opposed to attenuation. If true, then therapy might instead need to be aimed at decreasing circumlocution and word substitution behaviors, i.e., in order to reduce the amount of Semantically-Related words active on the path to speech production. Still another possibility is that over-activation of semantic word networks, if real, is not strategic but reflects a developmental problem. That is, the architecture of the mental lexicon in PWS may be disrupted, due to genetic predisposition to weaker language function (Guitar,

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2006), which may spur disorganization in how lexical knowledge is represented and access in PWS; at least semantically.

Because we saw frontal N400 priming effects for both groups and did not see similar posterior N400 priming effects for PWS, we can speculate that differences between PWS and PWNS do not lie within the concept formation stage of planning; rather, the problem seems to involve the processing of lexical items, at least at a semantic level. Although differences in phonological network activation were not observed, one may still ask whether processing differs purely at a lexical-semantic level in PWS, or whether other linguistic processing deficits can be found in PWS. Cuadrado & Weber-Fox (2003) compared processing of syntactic (specifically, verb agreement) violations in PWS and PWNS by investigating the morphology of the P600 ERP elicited from individuals in each group. The P600 is a late, positive-going ERP component elicited by phrase structure and agreement violations. Cuadrado & Weber-Fox (2003) observed atypical P600 ERPs for PWS, evidence of a linguistic processing deficit beyond lexical-semantics. More research is needed to better understand the breadth and depth of atypical linguistic processing in PWS.

Although we did not observe group differences at the level of phonological network activation, it is still possible such differences exist. For example, further research could be conducted using probe words with a stronger phonological relationship with their corresponding picture labels. Another way to further examine phonological encoding in PWS may be to force participants to actively attend to auditory probe words during testing. A task such as this would be more taxing on the system which, as noted

above, may draw-out differences in phonological processing ability between PWS and PWNS.

The current results are consistent with the hypothesis that PWS do not execute linguistic utterance planning in the same way as PWNS. This was evidenced by the atypical N400 effects displayed by PWS while performing Semantically-Related naming tasks. Further research is needed to explore the significance and extent of psycholinguistic processing differences in PWS and PWNS, and the specific manner in which such differences set the stage for moments of stuttering.

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APPENDICES

Appendix A: Research Design

While our research design was similar in many respects to that used by Jescheniak et al. (2002), some important changes were made. Like Jescheniak et al. (2002), we had two general types of trials: Filler trials, and Experimental trials. Filler trials only involved naming a picture at a delayed latency, with no auditory probe word presentation. Experimental trials consisted of a picture-to-be-named, followed immediately by an auditory probe word, followed by a cue to name the picture. Four different probe word conditions were included: 1) Trials for which the probe word was Semantically-Related (but not phonologically-related) to its corresponding picture; and 2) Trials for which those same probe words were reassigned, each to a different picture to which it was Semantically- (and Phonologically-) Unrelated. Also included were 3) Trials for which the probe word was Phonologically-Related (but not semantically-related) to its corresponding picture; and 4) Trials for which those same probe words were reassigned, each to a different picture to which it was Phonologically- (and Semantically-) Unrelated. In summary, we had five conditions in total: Semantically-Related, Semantically-Unrelated, Phonologically-Related, Phonologically-Unrelated, and Filler.

Research Design Modifications

We modified the task design used by Jescheniak et al. (2002) in two different ways. The first modification concerned the level of attention participants were required to pay to the auditory probe words. In Jescheniak et al. (2002), participants were instructed to explicitly remember the auditory probe words. Their task included

a "word check" at the end of each experimental trial, requiring them to see a printed

word and decide whether this word was the auditory probe word they heard for that trial.

We removed this requirement, and instructed participants to ignore the auditory probe

words. The task was made passive due to concern that the dual-task nature of naming

while remembering a probe word might induce disproportionately high rates of stuttering

in at least some of the participants who stuttered. Of key importance, Jescheniak et al.

(2002) did not analyze ERPs recorded to Fillers. However, we incorporated ERPs

elicited by these trials into our analysis. Specifically, the Filler (naming-only) trials were

used to establish ERP baseline activity, i.e., ERPs elicited on Filler trials were seen as

reflecting processing activities underway while participants waited to name pictures but

did not hear auditory probe words. The critical test of our ERP analysis was to determine

whether each of the four experimental (probe word) conditions elicited ERP activity that

differed from ERPs elicited by Filler trials. ERP differences between Experimental and

Filler trials should reflect activity specifically related to processing the auditory probe

words.

The second change concerned the nature of our Phonologically-Related condition. For

this condition we elected to use only auditory probe words that shared the initial phoneme

with their corresponding pictures. In contrast, Jescheniak et al. (2002) used auditory

probe words that heavily rhymed with their corresponding pictures. We changed the

degree of phonological overlap because word-initial phonemes usually

attract more stuttering than phonemes occupying any other word position (Bloodstein,

1995). Priming word-initial phonemes allowed us to investigate

how the activation of phonologically-related words sharing only the initial phoneme

operates in PWS versus PWNS.

Appendix B: Picture labels and priming words

Picture name	Freq.	# of phon.	Semantic probe words	# of phon.	Unrelated probe words	Phonological probe words	# of phon.	Unrelated probe words
balloon	1.946	5	pop	3	cave	bagpipe	6	frame
bat	2.708	3	cave	3	wood	beach	3	hill
Bed	5.136	3	sleep	4	game	bank	4	frost
bell	3.332	3	ring	3	open	bruise	4	moon
book	6.075	2	read	3	toad	barrel	4	dive
broom	2.197	4	sweep	4	ape	bone	3	dent
camel	3.258	5	desert	5	spoon	concert	6	wheat
cannon	1.946	5	ball	3	water	key	2	drought
cheese	3.466	3	mouse	3	neck	chime	3	flag
comb	1.792	4	brush	4	pop	kite	3	trial
desk	4.522	4	chair	2	movie	drought	4	pole
dog	4.754	3	cat	3	ring	dent	4	melt
door	5.958	3	open	4	time	dive	3	patch
fish	5.1	3	water	4	glass	frost	5	concert
football	3.526	6	game	3	chair	frame	4	shrink
fork	2.773	3	spoon	4	web	flag	4	sand
frog	2.303	4	toad	3	hand	phone	3	bank
giraffe	1.099	4	neck	3	cut	juice	3	cycle
glove	2.996	4	hand	4	desert	ghost	4	beach
hammer	2.485	4	nail	3	ball	hill	3	bone
map	3.714	3	road	3	bird	mold	4	bruise
match	4.06	3	fire	3	brush	moon	3	key
monkey	2.944	5	ape	2	road	melt	4	barrel
nose	4.407	3	face	3	camp	nickle	4	chime
penguin	1.792	7	bird	3	fire	plate	4	mold
pizza	1.099	5	food	3	dirt	patch	3	walrus
popcorn	0.693	6	movie	4	mouse	pole	3	bagpipe

saw		2	wood	3	cat	sand	4	Kite
scissors	1.609	5	cut	3	foot	cycle	4	phone
shoe	4.382	2	foot	3	read	shade	3	twine
shovel	1.609	4	dirt	3	car	shrink	4	stand
snake	3.178	4	bite	3	bathroom	staff	4	web
spider	2.079	5	web	3	nail	stand	5	nickle
tent	3.807	4	camp	4	face	trial	4	juice
toilet	3.367	5	bathroom	6	sweep	twine	4	shade
watch	3.714	3	time	3	food	wheat	3	plate
wheel	3.807	3	car	2	bite	web	3	ghost
window	5.303	5	glass	4	sleep	walrus	6	staff

Appendix C: Behavioral Data

Subject #	Filler Trial	Unrelated Semantic	Semantically Related	Unrelated Phonological	Phonologically Related	Stutterer / Fluent
1	75	37	38	38	37	s
2	76	38	38	38	38	s
3	76	38	38	38	38	s
4	75	38	38	38	38	s
5	76	38	38	38	38	s
6	76	37	38	37	38	s
7	75	38	38	38	38	s
8	72	37	37	36	37	s
9	76	38	37	37	38	s
11	76	38	38	38	38	s
13	76	38	38	38	38	s
14	76	38	38	38	38	s
15	74	37	37	37	37	s
33	76	38	38	38	38	s
16	76	38	38	38	38	f
17	75	38	38	38	38	f
18	76	38	38	38	38	f
19	76	38	38	38	38	f
20	73	38	37	35	37	f
22	75	38	36	37	37	f
23	76	38	38	38	38	f
24	76	38	38	38	38	f
26	76	37	38	38	38	f
27	76	38	38	38	38	f
29	76	38	38	38	38	f
31	73	37	37	37	38	f
34	76	38	38	38	38	f
35	76	38	38	38	38	f