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Beyond Orthographic Segmentation: Neurophysiological Evidence That Pseudo-Derived Word Stems Are Processed Semantically

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Masters of Science
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ABSTRACT

Morphological segmentation while reading is essential for new vocabulary learning. The study's aim was to investigate semantic-level morphological segmentation using event-related brain potentials (ERPs) in typical young adult readers. Past research has suggested that, because semantically opaque words prime their stems (e.g., *corner/corn*) similarly to transparent words (e.g., *farmer/farm*), readers recognize complex words from their constituent morphemes without regard to semantic information. However, this priming effect may be due to orthographic and phonological overlap between prime and target words. The research presented here addressed this possibility by creating five conditions in which orthographic, phonological, and semantic relationships between prime and target words were manipulated: Condition 1,wherein prime and target shared no relationship (e.g., *inn/brother*), served as Control. In Condition 2, prime and target were the same (e.g., *brother/brother*). In Condition 3, prime was the stem of target (e.g., *broth/brother*). Condition 4, our critical experimental condition, used primes semantically related to the stem of the target word (e.g., *soup/brother*). Finally, in Condition 5, prime was semantically related to the whole target word (e.g., *sibling/brother*). Semantically priming the stem (Condition 4) did not modulate the amplitude of the standard N400 ERP component (as did Conditions 2, 3, and 5), but did affect an early N400-like ERP component peaking in amplitude at ~262 ms after target. Other ERPs were observed that responded uniquely to shared orthography (Conditions 2, 3). Results set the stage for investigating morphological processing in adult reading impairments to evaluate whether, and to what extent, these readers semantically process morphological stems during text comprehension.

CHAPTER 1: REVIEW OF THE LITERATURE

One of many requisites for attaining academic, social, and professional success in today's society is the ability to extract and synthesize information from written texts (Biancarosa & Snow, 2004). Ironically, while the contribution of proficient reading comprehension skill to achievement is unequivocal, basic mechanisms underlying proficient reading comprehension are not yet fully understood. Models of reading comprehension published over the years offer hypotheses about the cognitive and linguistic processes that drive text comprehension (e.g., Hoover & Gough, 1990; Perfetti, 1992; Seidenberg & McClelland, 1989). In addition to behavioral measures used to test these hypotheses, recent advances in bio-imaging techniques have allowed researchers to explore neural correlates of reading comprehension and make conjectures regarding psycholinguistic processing based on these observations (Turkeltaub, Eden, Jones, & Zeffiro, 2002).

One aspect of reading comprehension not fully understood is how readers process individual written words. As described below, the ability to recognize and process words has traditionally been modeled as involving two potential routes: Whole word recognition and decomposition of a word's *orthography*. Another model of word reading proposes decomposition of a word's *constituent morphemes* as a third route by which readers process written words. After outlining this model, evidence is reviewed suggesting that morphological decomposition does take place during word reading, at least visually. The most significant finding emerging from this body of literature is that a reader will automatically parse a word morphologically if the word contains a plausible stem[1] and affix (e.g., *brother*, where *broth* is the stem and *–er* is the suffix), even if the affix is only apparent and does not function as a true affix (i.e., *brother* is not someone who "broths" the same way a *teacher* is someone who teaches). An open question is whether morphological segmentation stops at the orthographic recognition of stem and affix, particularly in pseudo-derived cases (e.g., *brother*), or automatically advances to a deeper level at which the stem (and the meaning it carries) becomes activated in the mental lexicon. This question was investigated via functional neuroimaging.

Dual Route Cascaded Models

A Focus at the Segmental Level

The Dual-Route Cascaded Model

The Dual-Route Cascaded (DRC) Model of Reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) proposes that written language processing may occur using two simultaneous strategies: 1) a whole word approach (lexical route), and 2) a decompositional approach (non-lexical route). According to this model, depicted in Figure 1, as a word is being read, both routes are activated at once and work in tandem while the reader analyzes different properties of the word. The lexical route provides access to words that are stored as whole units and read without consideration as to their internal structures, while the non-lexical route allows for letter-by-letter decoding. For

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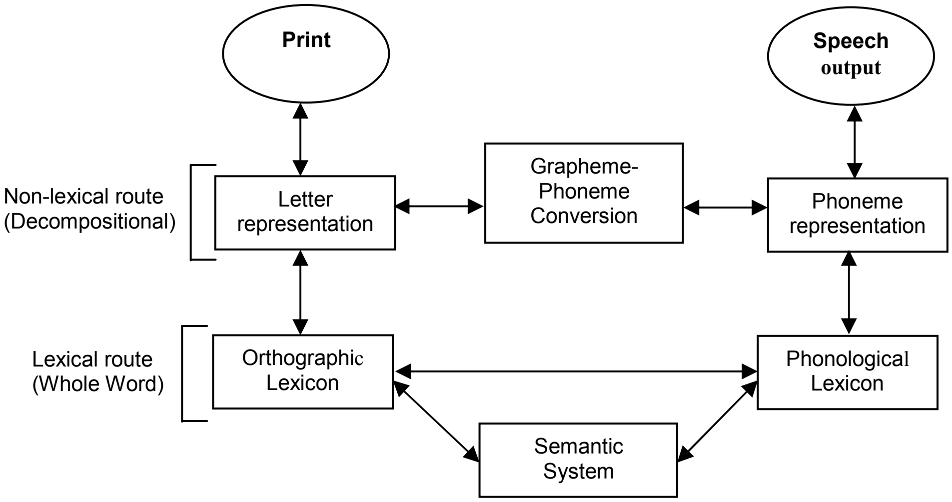
[1] The term *stem* is used in this study to mean a whole word within a derived word that appears to be, but does not function as, a root.

Figure 1. The Dual-Route Cascaded Model of Reading (Colheart et al., 2001 p. 214)



example, when a regularly spelled word, such as *fan*, is encountered, the lexical route analyzes the word in its entirety, accesses its phonological representation either directly or through the semantic system, and, finally, arrives at a pronunciation. At the same time, the non-lexical route analyzes the word serially from left to right and associates the graphemes within the word (f + a + n) with its corresponding phonemic representations (/f/ + /æ/ + /n/) to estimate a pronunciation. Since processing by both routes yields the same pronunciation, the word will be read quickly and accurately.

The distinction between the lexical and non-lexical routes is difficult to make when considering regularly spelled words because they can be correctly identified using either route. Therefore, evidence for the existence of two distinct routes must come from words that can only be processed by one pathway or the other. Coltheart et al. (2001) cite the fact that typically developing readers can read both irregularly spelled words and non-words as support for the dual-route model. The reading of irregularly spelled words, such as *yacht* and *colonel*, relies more on the lexical route since an attempt to decipher the words using grapheme-phoneme correspondences would prove futile. In this case, the non-lexical route produces a pronunciation that conflicts with the pronunciation produced by the lexical route. Word identification may be delayed until this conflict is resolved.

On the other hand, there are circumstances in which readers may rely more on the non-lexical route. Evidence for this can be found when considering the ability to read non-words. Having no orthographic or semantic entry in the mental lexicon, non-words cannot be processed along a lexical route. However, according to Coltheart et al. (2001), since skilled readers can pronounce these words, an exclusive pathway, such as the non-lexical route must exist. As an example, an attempt at reading the non-word *mave* will activate both the lexical and non-lexical pathways. Processing by the lexical route will be stymied in the search for a stored orthographic representation (since such a word does not exist in English) and will not yield a reliable pronunciation. Processing by the non-lexical route will be successful because phonological decoding is not affected by lexical status. As in the reading of irregularly spelled words, a conflict between the two routes is generated in the reading of non-words and word identification may be slowed as a result.

The DRC and Reading Impairments

According to Coltheart et al. (2001), further evidence for having two separate means of word analysis comes from the study of adult acquired dyslexia, the features of which are summarized in Table 1. According to the authors, people with acquired surface dyslexia experience difficulty reading irregular words, but can read regular words and non-words. As suggested by the DRC model, successful identification of irregular words depends on the lexical route while non-words are processed with the non-lexical route and regular words may be read using either pathway. The phenomenon

Table 1. Relationship of Acquired Dyslexia Characteristics to DRC Model

	Non-lexical Route (Surface Dyslexia)	Lexical Route (Phonological Dyslexia)
Irregular words	X	✓
Regular words	✓	✓
Non-words	✓	X

X=impaired; ✓=intact

observed in surface dyslexia suggests that the lexical route has somehow been impaired while the non-lexical route remains intact.

The reverse has been observed among others with reading impairments. Specifically, Coltheart et al. (2001) noted that acquired phonological dyslexia is characterized by poor non-word reading ability, but preserved regular and irregular word identification. This implies that the non-lexical route may be impaired, but the lexical route is operational. It is important to mention here that accuracy in reading regular words represents a redundancy in the DRC model. A reason is that regular words may be analyzed along either route. The failure of one route or the other does not prohibit reading altogether.

A Focus at the Morphological Level

An Interactive-Activation Model

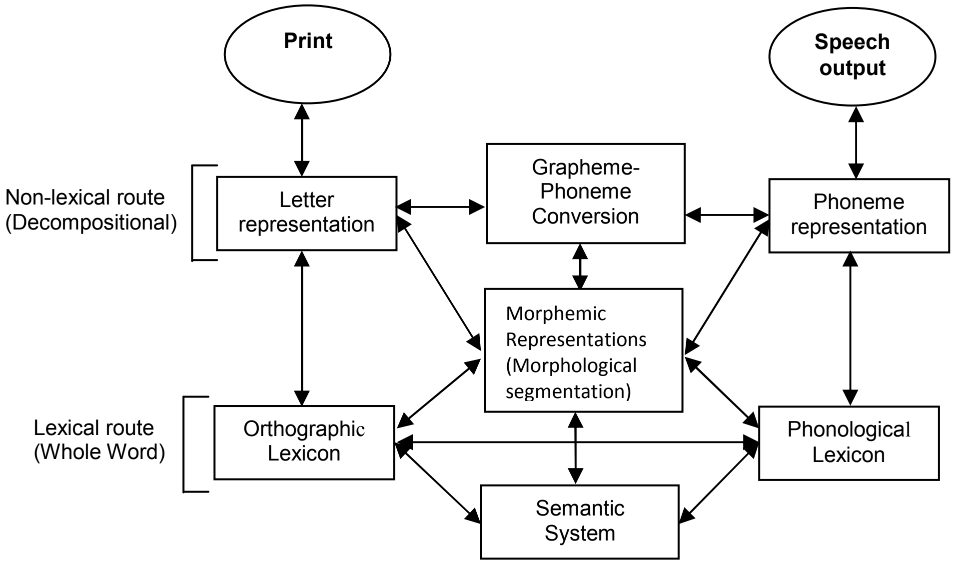
While the DRC model, outlined above, specifically addresses phonemic segmentation, it is possible that decomposition may take place at the morphological level. When encountering an unfamiliar morphologically complex word, one strategy a reader might employ involves activating morphological awareness to segment the word into its morphemic components (e.g., root word + suffix) and associating meaning with each element. Take, for example, the word *joyful*. A reader encountering this word for the first time may recognize *joy* as being synonymous with *happy* and *–ful* as meaning "having a lot of." In this scenario, the non-lexical, or decompositional, route has been engaged to the point that the word has been segmented into smaller meaning-bearing units, but not so far as to divide the word into individual phonemes. However, morphological decomposition does not preclude phonemic segmentation, which may occur if morpheme analysis is unsuccessful.

Taft and Zhu's (1995) interactive-activation model of morphological processing suggests that words are indeed segmented into their constituent morphemes during reading. This model has been superimposed onto the DRC model and the resulting compilation is represented in Figure 2.

The Potential Contributions of Morphological Decomposition

Support for inclusion of a morphological component in the decompositional pathway was found in a child-based study by Carlisle (2000). This study showed that the phonological transparency of derived words affected both the reading and morphological analysis of these complex words in third and fifth graders. Participants completed a measure of word reading, comprised of high-frequency derived words that varied in phonological and/or orthographic transparency. This measure was given to assess word reading ability. Students read words that reflected one of four categories: 1) phonologically and morphologically transparent, which were characterized by no changes in either pronunciation or the orthography (*powerful, harmful*); 2) phonological shifts in

Figure 2. Modified DRC Model to Include Interactive-Activation Model (Taft & Zhu, 1995)



which pronunciation changes occurred in the root but not in the orthography (*moisture, direction*); 3) orthographic shifts where changes were made to spellings but not to pronunciation (*daily, trial*); and 4) derivations that entailed both phonological and orthographic shifts (*explanation, easily*). Carlisle (2000) also administered a second measure to assess word analysis skills. A sentence completion task was employed that required either the production or decomposition of a high frequency derived word. For example, in the production component, students were given the word *warm* and the sentence “He chose the jacket for its____.” For the decomposition condition, participants were provided with the derivation, such as *growth*, and then had to decompose the word into its root, for example, in the sentence “She wanted her plant to ____.”

When performance on both tasks was compared, not only did word reading accuracy decrease when there was a phonological and/or orthographic shift between the root word and its derivation, but a significant relationship was found between the word reading and analysis tasks. Because the students' performance was sensitive to changes in the internal structure of derived words, Carlisle attributed the results to active morphological analysis during reading.

To understand how Carlisle's (2000) results are related to the DRC-interactive-activation model, keep in mind that the lexical and non-lexical routes of reading operate concurrently. Also, consider the case of the phonologically and orthographically transparent word *enjoyment*. As this word is processed, access to the semantic representation of *enjoyment* could occur along four different pathways, two involving the non-lexical route and two involving the lexical route. The non-lexical route is engaged when *enjoyment* is recognized either as a compilation of 9 graphemes or as 2 morphemic units, *enjoy* + *ment*. Alternatively, the lexical route allows access to word meaning either on a whole word level or, as with the non-lexical route, as a 2-morpheme unit. Utilization of the non-lexical pathway likely would be successful since the grapheme-phoneme relationship in *enjoyment* is transparent. Employment of the lexical route would also be successful if semantic entries existed for the whole word. Morphological segmentation could occur along either route if semantic entries existed for both morphemic units.

Advantage of a Combined DRC-Interactive-Activation Model

The decrease in accuracy on reading phonologically and/or orthographically shifted words found in Carlisle's (2000) study may be explained by the joint DRC-Interactive-Activation Model. A reader attempting to decode the word *daily* would be stalled at the morphemic representation stage since an orthographic shift has masked the root word (i.e., the "y" in the root word *day* changes to an "i"). By the same token, the phonological shift in the word *moisture* would cause a delay at the grapheme-phoneme conversion stage (i.e., the /t/ in *moist* changes to a /tʃ/ in *moisture*). In an experienced reader, word identification may be delayed, but not rendered inaccurate because sufficient exposure to these high frequency words would have generated the stored orthographic representation (spelling) necessary for the lexical route to be successfully employed. The inaccuracies in derived word reading observed in Carlisle's (2000) results may have been attributable to developmental factors in her young population. In other words, they may not have had enough reading experience or sufficiently elaborated lexical meanings to form whole word entries for some of the derived words and, therefore, may have relied inordinately more on the non-lexical route.

Morphological Awareness and Reading Comprehension

Regardless of which route is employed during reading, text comprehension must be the end result for learning to occur. The study of morphologically complex word reading is of particular interest because of the apparent relationship between morphological awareness and reading comprehension in both typically developing and at-risk readers (Carlisle, 2000; Deacon & Kirby, 2004; Nagy, Berninger, Abbott, Vaughan, & Vermeulen, 2003; Nagy, Berninger, & Abbott, 2006). Furthermore, as Kuo and Anderson (2006) point out in their cross-linguistic meta-analysis of morphological awareness and reading achievement, the acquisition of derivational morphology may extend into early adulthood, highlighting the long-term vocabulary effect derivational knowledge may have on a reader. Both of these points will be discussed in detail in the next section.

In summary, it is apparent that having two available pathways for reading both mono-morphemic and poly-morphemic words facilitates reading speed and/or accuracy and comprehension. Access to only the lexical route limits a reader to those words that have been stored in long-term memory. Access to only the non-lexical route limits a reader to those words that have regular spelling patterns and/or regular (or more transparent) patterns of derivation. Effective and efficient use of these routes by typically-developing readers, as measured by text comprehension, depends partly on morphological awareness, specifically, knowledge of derivational morphology.

Processing Morphologically Complex Words

As noted above, morphological awareness relates to the ability to associate morphemes with meaning and manipulate morphemes in order to produce words (Carlisle, 2004; Kuo & Anderson, 2006). Interactions among the orthographic, phonological, and semantic systems, combined with interactions between these systems and the root and whole word, affect how easily a reader accesses them in the mental lexicon. In fact, Carlisle (2004) argues that this interplay, characteristic of morphological complexity, reflects the integration of word form and meaning. Each morphemic unit contributes in some way to the understanding of the whole word. In addition to its relation to complex word identification, studies have shown that morphological awareness contributes to components of reading comprehension, such as vocabulary. (Carlisle, 2000; Deacon & Kirby, 2004; Nagy et al., 2003; Nagy et al., 2006).

A more valid test of the morphology-reading comprehension relationship is through analyzing intervention studies, as did Kuo and Anderson (2006). In this review, the authors sought to examine whether: 1) morphological awareness was a cause of better reading, a result of reading experience, or if the two had a reciprocal relationship, and 2) morphological awareness and reading skill were not related, but were co-variates of another factor. Based on results from intervention studies involving different alphabetic languages, including English, Kuo and Anderson found that morphological awareness may be a cause of reading proficiency, with some evidence suggesting a reciprocal relationship, and that morphological training yielded improvements in reading comprehension. Furthermore, they found that the possibility of co-variance, specifically with phonological awareness, depended on the age group in question. The studies they considered suggested that, for emergent readers, “the relationship between morphological awareness and reading development may be mediated by phonological awareness” (Kuo & Anderson, 2000, p. 176), while in more experienced readers (fourth grade onward), the contribution of morphological awareness to reading comprehension went beyond that made by phonological awareness.

Derivational Morphology

Development Trajectory of Morphological Complexity

One possibility explaining why young readers are able to understand written language using mainly phonological awareness skills may be the fact that words at this academic level have high frequency in the oral language (Kuo & Anderson, 2006). As readers mature, a larger portion of the words they encounter in text tends to be less frequent in the oral language and more morphologically complex (Kuo & Anderson, 2006). The expectation, therefore, is that reliance on phonological awareness skills gradually gives way (though is never truly phased out) to morphological awareness for word reading and comprehension.

In fact, some findings in the child reading literature reflect this shift. For example, Carlisle and Nomanbhoy (1993) found that, for first graders, phonological awareness made more of a contribution to word reading ability than did morphological awareness. Mahony, Singson, and Mann (2000) showed similar results for third graders, but found that for fifth and sixth graders, morphological awareness was more strongly correlated with word reading ability than was phonological awareness. Additionally, Nagy et al. (2003, 2006) found that the relationship between morphological awareness and vocabulary knowledge was strongest in fourth grade and that in grades 8-9, morphological awareness reliably contributed to literacy skills. These results, in conjunction with the findings from Kuo & Anderson (2006), indicated that derivational morphology continues to develop in children through later childhood, at least into late adolescence and possibly beyond.

Adult Processing of Morphological Complexity

There is new evidence that at least some aspects of morphological word decomposition become automatized by adulthood. For example, one line of behavioral research has focused on how adults visually process each of three different types of words (McCormick, Rastle, & Davis, 2008; Rastle, Davis, Marslen-Wilson, & Tyler, 2000; Rastle, Davis, & New, 2004) (see below): 1) Words comprised of a true derived stem+suffix combination (e.g., *cleaner*, for which -*e*r is a legal suffix and *clean* contributes to the meaning of the whole word) (Transparent Condition[2]); 2) words comprised of a pseudo-derived stem+suffix combination (e.g., *corner*, for which *-er* is a legal suffix but *corn* does not contribute to the meaning of the whole word) (Opaque Condition[3]); and 3) words comprised of an apparent stem coupled with an unproductive suffix (e.g., *brothel*, for which *-el* is not a legal suffix but *broth* is a real word) (Form Condition[4]).

Morphological Segmentation and the Priming Paradigm

Masked priming. In a recent study (Rastle et al., 2004), words of each type were presented to normal adult readers in a masked priming context. With this research design, two words are presented in each trial as follows: One of the three word types listed above is presented so briefly that the reader does not consciously perceive it (e.g., presentation of *corner* for 42 milliseconds), followed by a visual mask (e.g., ######, one masking character per letter in word one), followed by another word with a potential morphological relationship to the first word (e.g., *corn*). The task is to decide whether the second word is a real word, as quickly and accurately as possible. Reaction times were registered while making these judgments and then compared to reaction times registered on control items. In these control items, word 1 was orthographically, phonologically, and semantically unrelated to word 2. As summarized in Figure 3, Rastle et al. (2004)

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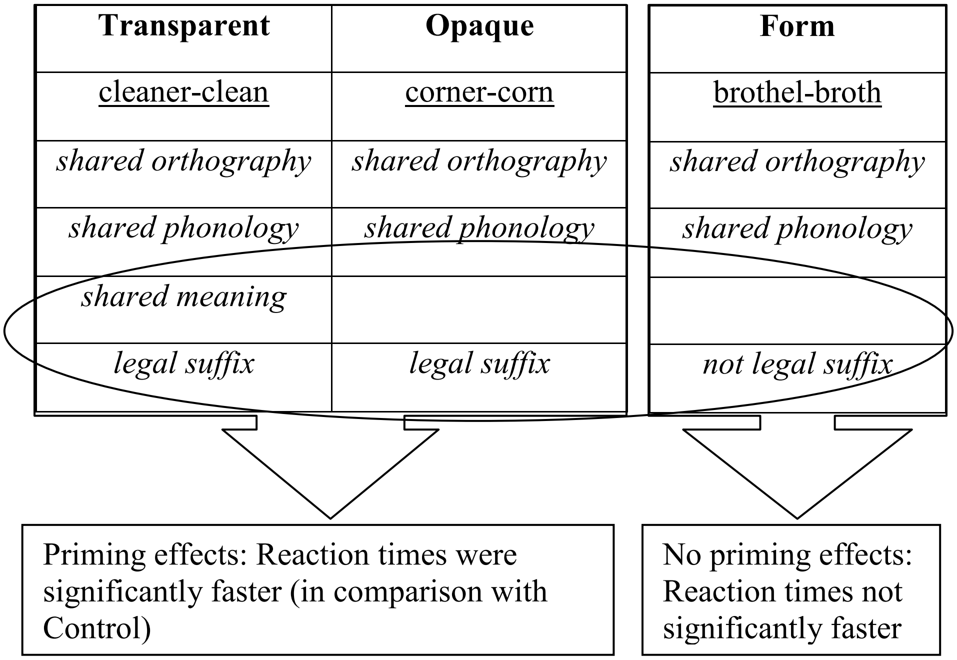
[2] The term *transparent* here refers to words that have a true morphological and semantic relationship.

[3] The term *opaque* here refers to words which have an apparent morphological relationship, but are not readily judged to be semantically related.

[4] Words in the Form Condition contained an apparent stem, but have no morphological relationship.

Figure 3. Summary of Word Priming and Reaction Times



Transparent	Opaque	Form
cleaner-clean	corner-corn	brothel-broth
shared orthography	*shared orthography*	*shared orthography*
shared phonology	*shared phonology*	*shared phonology*
shared meaning		
legal suffix	*legal suffix*	*not legal suffix*

Priming effects: Reaction times were significantly faster (in comparison with Control)

No priming effects: Reaction times not significantly faster

reported that the mean reaction time for each of the two experimental conditions involving words with legal suffixes was shorter (in milliseconds) than the mean reaction time elicited by control items, effects that were both statistically significant. This effect was not observed for the third experimental condition involving words with a non-morphological relationship (e.g., *brothel-broth*).

This pattern of results, which has been replicated in other work (McCormick et al., 2008; Rastle et al., 2000), suggests that words containing a legal suffix are automatically (i.e., within tens of milliseconds) parsed into stem and affix during the early stages of visual word recognition. Interestingly, reaction times to semantically transparent derived words (e.g., *cleaner*) did not differ significantly from those to pseudo-derived words (e.g., *corner*). This provides evidence for rapid, automatic segmentation presumably based on the presence of an apparent suffix (e.g., -*er*), without regard to semantic information. In other words, readers' visual systems appear to decompose any word containing a morphologically complex surface structure automatically, even though morphological decomposition is really only useful for true derived words (e.g., *cleaner*, where the meaning of the stem in relation to the whole word is transparent). These findings also lend support to Carlisle's (2004) assertion that morphology blends form and meaning. To clarify, affixes carry semantic information (e.g., -*er* means "one who;" –*ful* means "full of") that elaborates on words to which they are appended, while preserving the meaning of the original word (e.g., *farmer* is "one who farms"; *joyful* is "full of joy"). Because legal affixes signal the possibility of a derived word (in which is contained semantic information for the root and suffix), reading a word containing an apparent suffix (whether or not it acts as a true suffix) may automatically engage a morphological parsing process in an attempt to gain semantic information from the components. The reader may therefore be seeking meaning within the form of the word.

Cross-modal priming. Another emerging question, then, concerns the depth at which stems dissected visually from morphologically complex words are processed as bona fide lexical entries. If a stem contributes to comprehension of a derived word as a whole, then it would be beneficial to activate the stem in the mental lexicon and consult its meaning. If, on the other hand, a stem does not contribute to the meaning of the whole word, as in the case of pseudo-derived words, processing it fully might interfere with a reader's interpretation of the word as a whole, or at least require a mechanism for disregarding the semantic information carried by the apparent stem.

Three studies, two in English (Feldman & Soltano, 1999; Marslen-Wilson, Tyler, Waksler, & Older, 1994) and the other in French (Longtin, Segui, & Halle, 2003), investigated whether the lexical entries of morphologically complex words were represented by separate stem and affix components. All three studies used a cross-modal priming design, wherein an auditory probe word was presented followed by a written target word. As with the masked priming paradigm outlined above, the task was to decide whether the written target word was real or nonsense. Reaction times registered for experimental conditions were compared with those elicited by controls. Cross-modal priming made it possible to assess whether processing one word (auditory probe) facilitated processing of the second word (written target) while guaranteeing that any priming effects observed were not related to "…overlap in modality-specific access pathways and representations" (Marslen-Wilson et al., 1994, p. 6). In other words, overt orthographic priming can be avoided.

The primary finding emerging from the three noted studies is that a semantically transparent derived word (e.g., *punishment*) first presented as a spoken word primes its subsequent presentation as a written stem (*punish*), an effect not seen for more semantically opaque words (e.g., *casualty-casual*). Marslen-Wilson et al. (1994) further showed that purely phonological overlap between word 1 and 2 (e.g., *bulletin-bullet*) does not induce priming either. This combination of results has twice been replicated (Feldman & Soltano, 1999; Longtin et al., 2003). The main conclusion drawn from this line of studies is that the lexical entry of a semantically transparent derived word is comprised of separate stem and affix components, each of which can be activated independently. Therefore, *punishment* primes *punish*, not due to orthographic overlap (controlled using cross-modal priming), and not due to phonological overlap (pure phonological priming not observed), but because *punishment* can be decomposed morphologically into stem and suffix; the former appearing to prime lexical decisions about the second word, *punish*.

This conclusion is tentative, however, due to concerns about the methodological approach used in generating it. One concern relates to the gross semantic relationship between a semantically transparent derived word and its stem. The fact that priming effects were observed in the transparent condition (e.g., *punishment-punish*) and not in the opaque condition (e.g., *casualty-casual*) could be explained as reflecting the semantic relationship between the prime word, as a whole, and the target word. In other words, a reader might recognize that *punishment* and *punish* are related because they share meaning at both the stem and whole word level. On the other hand, *casualty* and *casual* do not share a readily apparent meaning at either level. In fact, Marslen-Wilson et al. (1994) observed a cross-modal priming effect for word pairs that only overlapped semantically (e.g., *idea-notion*), strengthening the possibility that whole word semantic association may have driven the priming effect observed when word one was a semantically transparent derived word. Specifically, *punishment* may prime *punish* due to the semantic relationship between these two words at a whole-word level; instead of the stem of *punishment* priming itself, as suggested by Marslen-Wilson et al.

A related issue is that the cross-modal priming paradigm allows participants to make judgments strategically. That is, because participants are fully conscious of the auditory prime word and written target word comprising each trial, they may make judgments about the written word based on their perceptions of the relationship between the two words. An easily perceived semantic relationship (e.g., auditory probe word *punishment*- written target word *punish*) may facilitate reaction times while the perception of semantic incongruity (e.g., auditory probe word *corner*- written target word *corn*) may spur caution in participants, slowing their reaction times. This latter effect may help to explain why cross-modal priming was not observed for semantically opaque words (e.g., *corner-corn*). As noted above, Rastle and colleagues (2004) showed that effect occurred even though these words were decomposed into separate stem and suffix components, at least visually. If the brain does attempt to process the stem in *corner* as a separate morphological component in the lexical entry of this word, this effect could be masked by the influence of strategic responding on reaction time. Because of these methodological limitations, it remains unknown whether the stems of morphologically derived words are processed beyond the level of visual decomposition and activated in the mental lexicon. The aim of our study was to investigate this unanswered question.

Combined cross-modal priming. Other recent attempts to answer this question have sought to limit the ability of participants to make strategic comparisons in cross-modal priming experiments, specifically by combining cross-modal priming and masked priming into a single task (see Kiyonaga, Grainger, Midgely, & Holcomb, 2007). With this research design, printed words are presented briefly, followed by a visual mask, followed by an auditory probe word. This paradigm makes it possible to explore the effects of rapid word reading on the processing of a subsequent, auditory word that is similar morphologically, phonologically, and/or semantically – but not orthographically. Theoretically, readers are not able to linger on the initial word long enough to compare it to the following auditory probe word. Therefore, if the stems of morphologically complex words are represented in the mental lexicon as bona fide lexical entries that become activated during word reading, then any priming effects observed (i.e., between a written semantically transparent derived word, such as *punishment*, and its auditory probe word *punish*) should reflect this level of representation and processing.

Unfortunately, the cross-modal masking paradigm only generates reliable priming effects when the initial, printed word on each trial is presented for a minimum of 50 milliseconds. At this duration, readers may still be able to consciously perceive, analyze and compare its features with the second, auditory probe word; making it difficult to know whether reaction time differences observed in specific priming conditions are driven by strategic responding versus the manner in which words are represented in the mental lexicon morphologically, phonologically, and semantically.

Advances in Methods for Assessing Whether Stems of Morphologically-Complex Words Are Activated in the Mental Lexicon

Since it is quite difficult to limit readers' reliance on strategic responding during word priming tasks, a different approach has been to explore dependent measures other than reaction time that are equally sensitive to the rapid time-course of written word processing but less susceptible to the influence of off-line factors such as strategic responding. Event-related potentials (ERPs) are one such measure. ERPs are electrophysiological signals generated by the brain as individuals process stimuli, make decisions, and regulate their behavior. In the psycholinguistic context, ERPs are time-locked to the presentation of linguistic stimuli, such as printed words. The electrophysiological activity observed at the scalp reflects at least some of the brain's activity as it processes those stimuli, with precision on the order of milliseconds. Critically, individual components of the ERP signal reflect the activation of different cognitive and linguistic processes. The current study is focused on whether the stems of morphologically complex printed words are activated in the mental lexicon. As described next, the N400 component of the ERP is an index of this process.

The N400 ERP Component: A Neural Correlate of the Activation of Words in the Mental Lexicon

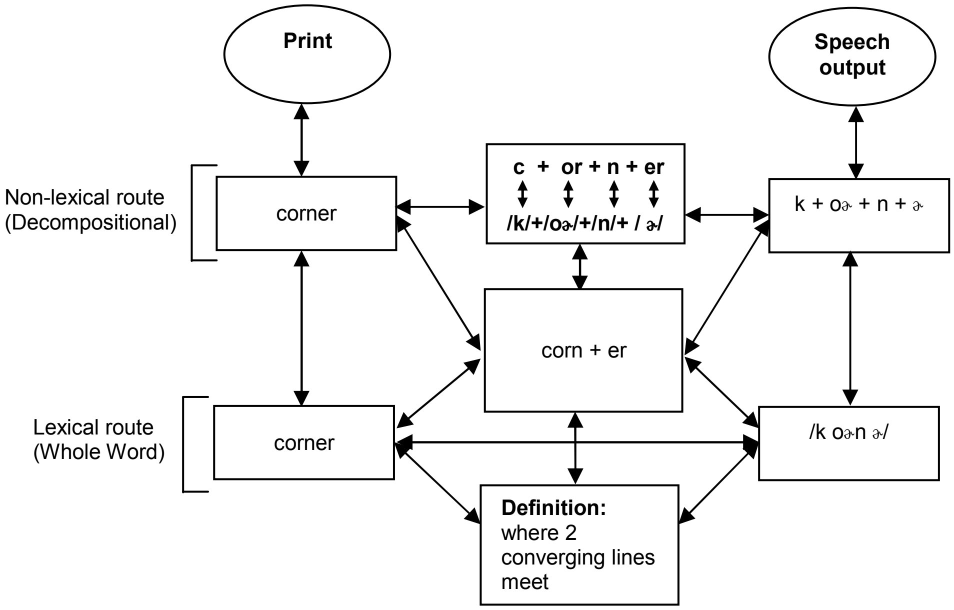
The N400 is typically observed as a negative-going deflection in the ERP signal, largest in amplitude on the posterior parietal region of the scalp, and peaking in amplitude at ~400 milliseconds (ms) after the onset of a word stimulus. The amplitude of the N400 component is a measure of the amount of neural resources recruited as a word is recognized and integrated with its semantic context. For example, some studies have consistently found that conditions in which there is an absence of priming elicit a more robust N400 wave (Bouaffre & Faïta-Ainseba, 2007; Lavric, Clapp, & Rastle, 2007; Zhang, Lawson, Guo, & Jiang, 2006), presumably because different neural networks are activated (i.e., the brain has to work harder to process two different words). In conditions where priming effects are observed, the amplitude of the N400 component was found to be smaller (in microvolts), presumably because similar neural networks are shared between the two words. The inverse relationship between semantic priming and N400 amplitude spurred Van Petten and Kutas (1991) to define the N400 component of the ERP as an index of a word's activation level in the mental lexicon: That is to say, if a word has been semantically primed by a preceding stimulus, N400 amplitude is smaller when the word is presented. Conversely, when a word has not been semantically primed by a preceding stimulus, N400 amplitude is larger.

Word priming effects on ERPs. One method of eliciting and manipulating ERPs in a psycholinguistic context is via word priming, similar to the behavioral methods outlined above. The priming method involves the presentation of word pairs in which a certain relationship between the two words is manipulated. Theoretically, the closer the relationship between the two words, the easier it will be to retrieve the second word following presentation of the first. This is because, at some level, the two words share similar neural networks so that by presenting one word (e.g., *cleaner*), the second word (e.g., *clean*) is more easily accessed, or "primed." By the same reasoning, words that do not share a relationship will not evidence a priming effect.

At least one neurophysiological study has already attempted to tease apart and identify the processes involved in reading morphologically complex words using the priming paradigm. Morris, Grainger, and Holcomb (2008) used ERPs to investigate processing of three sets of derived words in conditions similar to those used by Rastle et al.'s (2004) Transparent word pairs (*cleaner-clean*), Opaque pairs (*corner-corn*), and Form pairs (*scandal-scan*). In this study, word pairs in the Transparent and Opaque conditions were found to prime each other, as evidenced by ERP amplitude modulations in an early time window (200-300 ms after stimulus onset). Specifically, the ERPs elicited by the Transparent and Opaque conditions were smaller in amplitude than the ERPs elicited by the Form and Control conditions, across all regions of the scalp (frontal, central, and parietal). Because the words in the Transparent and Opaque conditions were unique in that they contained apparent suffixes, the authors hypothesized that an early stage of decomposition exists in which all words are segmented, appropriately or not. Any inappropriately segmented words, such as *corn* + *er*, are thought to be filtered out so that processing can advance to whole word analysis.

An application of the modified DRC model. The results from the Morris et al. (2008) study support the modified DRC model to some extent. Upon presentation of the word *cleaner*, a reader recognizes it as a morphologically complex word from the suffix *–er*. The reader may then begin searching for a semantic representation of the word by mapping its graphemes onto their phonological representations, go on to recognize it as being comprised of the morphemes *clean* + *er*, and, finally, recognize the word in its entirety. As shown in Figure 4, the opaque word, *corner*, is initially analyzed in the same way. However, once the reader dissects the word into its constituent morphemes *corn* + *er*, assigns meaning to each morphemic unit and then recombines the morphemes to make sense of the word, the reader will find that no lexical entry exists. The likelihood, therefore, is that the reader will abandon this process in favor of the grapheme-phoneme conversion route or the whole word analysis route. These interpretations assume that stems in both semantically transparent and semantically opaque words are processed as independent morphological components of the lexical entry. However, this effect was not clearly established by Morris et al. due to limitations of their research design.

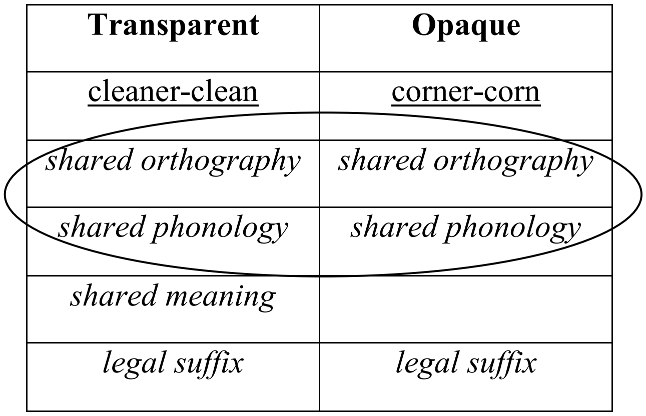
Figure 4. Semantically Opaque Words and the Modified DRC Model.



One problem is that Morris et al. (2008) used word pairs that overlapped in more ways than one. It is important to remember that the relationship between real words and their derivations can vary in three ways: Orthographically, phonologically, and semantically. As seen in Figure 5, for word pairs like *cleaner-clean*, orthographic, phonological, and semantic overlap are all present. For word pairs like *corner-corn*, although the semantic relationship is opaque, the words still overlap orthographically and phonologically. It is difficult to know the contribution of each level of overlap to ERP priming effects observed for each type of word pair.

A second limitation of the research design used by Morris et al. (2008) concerns the order of stimulus presentation. Their results seem to indicate that adult readers automatically visually decompose words that have a suffix, without regard to any semantic information carried by the whole word or by its morphological constituents.

Figure 5. Orthographic, Phonological, and Semantic Relationships in Word Pairs



Transparent	**Opaque**
cleaner-clean	corner-corn
shared orthography	*shared orthography*
shared phonology	*shared phonology*
shared meaning	
legal suffix	*legal suffix*

However, because the derived or pseudo-derived prime word was presented prior to the target stem, the time lapse between word presentations may have been sufficient for readers to move beyond any morphological analysis that took place, and onward to whole word analysis. For example, in the pair *corner-corn*, by the time the reader sees *corn*, *corner* has already been segmented (*corn* + *er*), processed for meaning at both a morphemic unit level and a whole word level, and defined. When *corn* is subsequently presented, the reader has presumably already arrived at the meaning of the whole word *corner*, and then makes a comparison between the two whole words. Measuring neural activity to the non-derived word (*corn*) does not necessarily reveal anything about morphological processing of the preceding pseudo-derived word, *corner*.

Summary, Research Questions, and Predictions

The Dual-Route Cascaded model of Reading (Coltheart, 2001) posits that written word processing occurs along two distinct pathways concurrently: A lexical/whole word route and a non-lexical/decompositional route. Taft & Zhu (1995) proposed in their interactive-activation model that the non-lexical route is responsible for morphological analysis. Both behavioral (Carlisle, 2000) and neurophysiological (Morris et. al., 2008) data support this view. However, the Morris et al. study included word pairs that overlapped in both orthography and phonology (e.g., *corner/corn*; *skewer/skew*) so that it is difficult to say with certainty whether processing the stems as separate components of the lexical entries for the first words in these pairs primed access to the second words, or whether shared orthography and/or phonology accounted for observed priming effects.

The possibility cannot be ruled out that one or both of the shared orthographic and phonological characteristics may have been responsible for the Morris et al. (2008) findings. This possibility prompts asking whether the same phenomenon would be observed in normal adult readers when phonological and orthographic cues were removed. Hence, the purpose of the current study was to assess whether the stems of morphologically complex words were processed as independent morphological components of the lexical entries of morphologically complex words. The primary research question asked whether the stems of morphologically complex, pseudo-derived words, such as *corner,* become activated in the mental lexicon, along with the meaning it carries. This question was addressed in a word priming ERP study that involved the systematic manipulation of semantic, orthographic, and phonological relationships between probe words and pseudo-derived target words.

ERPs were recorded to the pseudo-derived target words. The expectation was that if the stems of pseudo-derived words became activated in the mental lexicon, then their meanings should become available, modulating the amplitude of the N400 ERP when word one was semantically related to the stem of word 1 (e.g., *soup/brother,* where *soup* and *broth* are synonyms). In contrast, N400 priming should not be observed in a condition for which word 1 was semantically unrelated to word 2 (e.g., *inn-brother*).

CHAPTER 2: METHODS

Participants

Participants were recruited from undergraduate and graduate classes at the University of South Florida. A total of 20 adults participated in the study. Data from six participants were excluded: one who was taking medication that affected cognitive function, one due to equipment malfunction, two because they were non-native speakers of English, one because of excessive noise in the ERP readings, and one who did not follow instructions during the experiment. The remaining 14 participants (9 females, 5 males), whose data were included, were between the ages of 19 and 41 years (mean, 25.79 years; standard deviation, ±6.17 years). All included participants met six criteria: Right-handed, monolingual native speakers of American English, normal or corrected-to-normal vision, no history of neurological damage or language impairment, and no medications affecting cognitive function. Each person gave informed consent prior to participating in the study, and received either extra class credit or a modest cash payment of $20 after participating.

The passage comprehension and reading vocabulary subtests of the *Woodcock-Johnson III Test of Achievement* (Woodcock, McGrew, & Mather, 2001) were administered to all participants as a screening measure to ensure that skills in these areas were within at least the average range. These two subtests comprised the Reading Comprehension Composite score. The mean composite standard score was 106.53

(standard deviation, ±9.12), indicating that reading comprehension and general vocabulary knowledge were within the average range of variability.

Materials

Target Words.

The stimulus set consisted of 38 pairs of written English words. The second word in each pair was a pseudo-derived word, which contained an apparent, non-functional suffix. Each of the 38 target words was selected based on two criteria: 1) they contained an apparent suffix (based on Fry's (2004) designation of the most common suffixes) and 2) they were phonologically and semantically opaque but orthographically transparent. This meant that, although the word superficially resembled a derived word (i.e., the whole word had a stem (*brother)* and an apparent suffix (*brother*)), the meaning of the whole word could not be deciphered by assembling its stem and suffix (i.e., *broth* + *er* is not someone who "broths").

Five experimental conditions were then created in which the prime words varied in their orthographic, phonological, and/or semantic relationship with the target word (see examples of conditions in Table 2). In Condition 1 (Unrelated), the prime word and the target word shared no orthographic, phonological, or semantic relationship (*inn/brother*). Conversely, the word pairs in Condition 2 (Identical) overlapped in all three aspects, with the prime and target words being identical (*brother/brother*). Both Conditions 1 and 2 served as standardized conditions. The word pairs in Condition 3 (Identical Stem) overlapped orthographically, but not phonologically or semantically, similar to the experimental "opaque" condition (*broth/brother*) of Rastle et al. (2004). The primes in Condition 4 (Semantically Related Stem) were semantically related to the *stem* of the target word (*soup/brother*), while the primes in Condition 5 (Semantically Related Word) were semantically related to the *whole* target word (*sibling/brother*). Conditions 4 and 5 were inspired by the work of Morris et al. (2008) that examined the semantic processing of semantically opaque complex words (*skew/skewer*). The conditions in this study differed from Morris et al. in that they: 1) utilized semantically *and* phonologically opaque target words and 2) included primes related either to the stem or whole target word (see Table 2 examples).

Prime Words.

The prime words in Condition 1 were randomly selected and carefully paired with the target words to avoid any orthographic, phonological, and/or semantic overlap. Orthographic and phonological overlap was considered to be present if a grapheme and/or phoneme occupied the same word position in both words of a pair. Semantic overlap was considered to be present if a strong semantic association could be made between the prime word and either the stem of the target word or the whole target word. The prime words in Conditions 4 and 5 were selected using three different word association sources: 1) the University of South Florida's Free Association Norms database (Nelson, McEvoy, & Schreiber, 1998), 2) the Edinburgh Associate Thesaurus (Wilson, 2007), and 3) WordAssociation.org (Holliday, 2008). Any target word for which there was no appropriate semantically associated word was paired with a synonym taken from a thesaurus.

Table 2. Examples of Stimulus Items

Condition 1 Unrelated	Condition 2 Identity Priming	Condition 3 Identical Root	Condition 4 Semantic Root Priming	Condition 5 Semantic Whole Priming
inn-brother	brother-brother	broth-brother	soup-brother	sibling-brother
hook-busy	busy-busy	bus-busy	tour-busy	hectic-busy
target-callous	callous-callous	call-callous	phone-callous	mean-callous
goose-capable	capable-capable	cap-capable	shower-capable	adept-capable
sword-cater	cater-cater	cat-cater	meow-cater	serve-cater
muffin-cogent	cogent-cogent	cog-cogent	wheel-cogent	valid-cogent
vase-colony	colony-colony	colon-colony	dash-colony	settlement-colony
lemon-copious	copious-copious	cop-copious	badge-copious	plentiful-copious
pocket-dubious	dubious-dubious	dub-dubious	name-dubious	uncertain-dubious
minimum-earth	earth-earth	ear-earth	listen-earth	planet-earth

Standard Frequency Index.

Once word pairs were created for the five conditions, Standard Frequency Index[5] (SFI) values for each of the words was gathered from Zeno, Ivens, Millard, and Duvvari (1995). The words were then ordered by SFI value. A subset of words in the stimulus set was shown to be particularly low in frequency. Eliminating these words would have reduced the size of the stimulus set to an undesirably low number.

Instead of eliminating those items, each participant received a three-choice, multiple choice quiz in order to assess their familiarity with words which had SFI values in the bottom 25th percentile of the distribution of the frequency values [25th percentile =

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[5] The SFI is an approximation of the frequency of a word in written text per million occurrences.

SFI of 44.3]. The 44-item quiz was given to each participant prior to the main experiment. Any item that a participant missed was excluded from the analyzed data set of that individual. There were 19 items on the vocabulary test that were missed at least once. The mean percent correct score from this informal measure was 92.68% (standard deviation, ±7.08%). The SFI values for these words ranged from 29.3 to 44.20, with an average value of 36.86. A regression analysis revealed no significant correlation between the number of times an item was missed and its SFI value (R^2=.069). A summary of the word characteristics may be found in Table 3. A sample of the quiz may be found in Appendix A.

Procedure

Administration.

The main experiment was comprised of a total of 190 word pairs presented in two blocks of 95 pairs. Within each block, 19 of each pair type were presented randomly. Oral instructions, given prior to testing, informed participants that their task was to read words silently as they appeared on the screen, to repeat the words aloud once the reading cue was displayed, then to judge the degree of semantic relatedness between the two words on a scale of 1-5 by using a response box. Each trial consisted of the following events: 1) a visual fixation point (+) shown in the middle of the computer monitor for 750 milliseconds (ms); followed by 2) word 1 shown in the middle of the monitor for 400 ms; followed by 3) a visual fixation point (+) shown in the middle of the monitor for 200 ms; followed by 4) word 2 shown in the middle of the monitor for 400 ms; followed by 5) a blank screen for 600 ms; followed by 6) a cue to

Table 3**.** Prime Word Characteristics

	Average SFI Value	Average Word Length	Average Neighborhood Density Value
Condition 1	51.18	5.32	2.97
Condition 2	46.6	5.74	2.03
Condition 3	49.73	3.47	11.26
Condition 4	53.65	5.13	5.42
Condition 5	49.82	5.92	3.00

read the two words aloud (“!!!”) shown in the middle of the monitor for 1000 ms; and, finally, 7) a Likert scale (see Figure 6). Participants were required to read and remember each word tacitly upon presentation, and to repeat the words aloud as a pair when the reading cue was presented. Their word production on each trial was electronically recorded using E-Prime software, version 1.1 (Psychology Software Tools, Pittsburg, PA).

Likert Scale Ratings.

Participants were also asked to judge, on a Likert scale from 1-5, the degree to which they felt the words in each pair were related in meaning. A response of “1” meant that the words were identical, while a response of “5” meant that the words were not related at all. For each trial, the Likert scale screen remained on the screen until the participant made a response. Once a response was given, the next trial began. Likert scale responses were electronically recorded from the response box. The inter-trial interval was 1000 ms. The total participation time for the main experiment was

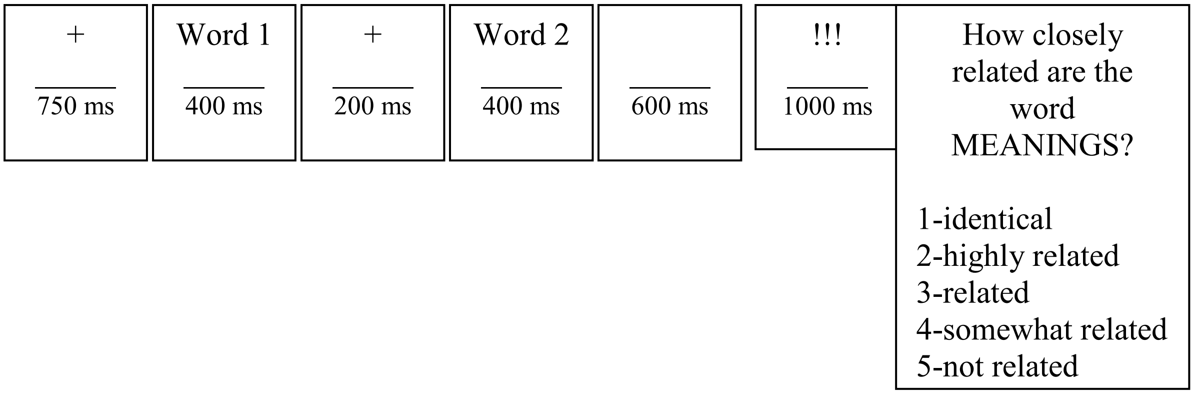
Figure 6. Stimulus Presentation Timeline

approximately 30 minutes, or 15 minutes per block, including a short break that was given in between blocks.

Summary.

Participants received a total of 190 word pairs comprised of 38 pairs in 5 conditions. The relationship between the words in each condition varied orthographically, semantically, and phonologically. In Condition 1, the two words were unrelated in all three aspects (e.g., *inn-brother*). In Condition 2, the words were identical and therefore shared all three aspects (e.g., *brother-brother*). In Condition 3, the first word was only related orthographically to the second word (e.g., *broth-brother*). In Condition 4, the first word was only related semantically to the stem of the second word (e.g., *soup-brother*). In Condition 5, the first word was related semantically to the whole second word (e.g., *sibling-brother*).

Apparatus and Recording

Participants were seated in a dimly-lit, sound-attenuating booth at a distance of 36 inches from the computer monitor. Word pairs were then presented in lowercase, white, 22-point, Garamond font against a black background. A total of 190 word pairs were presented in random order and responses were recorded with E-Prime software.

A continuous electroencephalogram (EEG) was recorded at a sampling rate of 500 Hz (one recording every 2 milliseconds) from each of 62 electrodes positioned in a geodesic arrangement around the top, sides, and back of the head, and from four additional electrodes placed on the face, designed to monitor for ocular artifact.

EEG-to-Average-ERP Data Reduction

Initial Processing.

The continuous EEG record of each participant was segmented into individual epochs. Each epoch was comprised of EEG data recorded from each of the 66 active recording electrodes during presentation of the target (second) printed word in each trial, beginning 300 milliseconds before the onset of the word, and terminating at 1200 milliseconds following the onset of the word. The epoch length was eventually truncated to a critical interval of ERP activity (-100 to 1000 ms 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 the critical time interval.

EEG Ocular Artifact Correction.

Inspection of the EEG data revealed that most participants' recordings were contaminated by eye blink artifact. In order to salvage as many trials as possible, an ocular artifact correction procedure was used as modified from Dien (2005a). The segmented EEG data for each participant were submitted to an Independent Component Analysis (ICA) (Bell & Sejnowski, 1995). 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, but no more than two, blink components were identified for each participant. On average 132 trials (SD = 20.65) out of 190 trials per participant 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 10% of their trials for any condition.[6]

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

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[6] The mean number of trials comprising subject ERP averages was 32.26(3.2) for Condition 1, 32.93(2.87) for Condition 2, 30.21(3.85) for Condition 3, 29.21(4.51) for Condition 4, and 30.5(4.5) for Condition 5.

were averaged together, separately for each condition. As a result, each participant had five sets of ERP averages, one for each condition. The averaged ERP data were truncated to include only the critical time window (-100 to 1000 ms), re-referenced to an average reference, and baseline-corrected (-100 to 0 ms).

Data Analysis

Behavioral Data

Prior to data analysis, the participants' quiz answers, verbal responses, and Likert scale responses during the main experiment were reviewed for accuracy. Trials which included words missed on the quiz or during the experiment (including mispronunciations, incorrect words, or no responses) were excluded from data analysis.

In addition, trials in which Likert scale ratings were inconsistent with expected responses were excluded. For example, responses to word pairs in Condition 1 (*inn*/*brother*) were expected to be "5" (not related) and for Condition 2 (*brother*/*brother*) were expected to be "1" (identical) (see Table 4). Responses of "2," "3," and "4" to word pairs in Condition 5 were considered to be acceptable, since the semantic relationship in this condition was more subjective. So, responses other than "5" (not related) in Conditions 1 (*inn/brother*), 3 (*broth/brother*), and 4 (*soup/brother*) were excluded; responses other than "1" (identical) in Condition 2 (*brother/brother*) were excluded; and responses of "1" (identical) or "5" (not related) in Condition 5 (*sibling/brother*) were excluded. Therefore, the remaining trials included words for which participants were considered to have full semantic and phonological representations. A total of 414 trials

Table 4**.** Expected Likert Scale Responses.

Condition 1 (*inn*/*brother*)	5 – not related
Condition 2 (*brother*/*brother*)	1 – identical
Condition 3 (*broth*/*brother*)	5 – not related
Condition 4 (*soup*/*brother*)	5 – not related
Condition 5 (*sibling*/*brother*)	2 – highly related 3 – related 4 – somewhat related

were removed, leaving 2,446 trials for analysis. Average number of included trials per participant by condition is summarized in Table 5.

ERP Data

Principal Component Analysis (PCA) was used to summarize and manage the analysis of the ERP data set. The averaged ERP data for all participants were combined into a single data matrix comprised of 551 columns (one column for each of the sampling points in the critical time window) and 4,340 rows (the averaged ERP voltages for 14 participants, recorded for each of the five conditions, at each of 62 electrodes; 14 * 5 * 62 = 4,340). This matrix was used as input to a temporal PCA, for which the covariance was computed among sampling points and components derived from the covariance matrix (using eigenvalue decomposition). Conceptually, the aim of the temporal PCA was to identify distinct windows of time in the ERP averages (hereafter, temporal factors) during which similar ERP variance was registered across consecutive sampling points.

As reported below, 10 dominant-variance temporal factors were identified, each representing a distinct pattern of ERP variance within a specific window of time. In order to test for experimental effects, factor scores summarizing the ERP variance within each

Table 5. Mean Number of Items Correct per Condition of 38 Possible Trials.

Condition	Number included
1	33
2	34
3	31
4	31
5	31
Total	160

time window, at five midline electrodes, were submitted to a repeated-measures ANOVA with Word Type as a within-subjects factor with five levels (Unrelated, Identical, Identical Stem, Semantically-Related Stem, Semantically-Related Word), and Electrode as a second within-subjects factor with five levels (FPz, Fz, Cz, Pz, Oz). When the sphericity assumption was violated, the degrees of freedom were corrected (Greenhouse & Geiser, 1959). This correction is reflected in the reported p-values.

The following specific procedures were used to conduct the temporal PCA. First, in order to determine how many dominant-variance components were extracted by each PCA, we used Rule N (Preisendorfer & Mobley, 1988). Rule N 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, 2005b).

CHAPTER 3: RESULTS

Behavioral Data

Participants' responses on the informal vocabulary test and during the experiment were analyzed for accuracy. Items incorrect on the vocabulary quiz were excluded from all trials in which they appeared. Likewise, items that were mispronounced during the experiment were removed from all trials in which they appeared. Trials in which participants did not verbalize one or both words were also excluded. Finally, trials in which Likert scale responses which were out of line with expected responses were removed.

There was considerable overlap in each participant's inaccuracies. For example, a participant that incorrectly defined *cogent* may also have mispronounced the word during the experiment and/or judged the word pair *valid*/*cogent* incorrectly. Therefore, removing incorrect *cogent* trials for one criterion effectively removed them for all criteria. In all, 175 incorrect vocabulary test trials were removed; an additional 76 trials were removed for mispronunciations; an additional 19 trials were removed because the participant reported having not seen the stimuli; and an additional 144 trials were removed because of inconsistent Likert scale responses.

To ensure the validity of the prime-target word pairs chosen for each condition, Likert scale responses for all participants were averaged and analyzed. A summary of these averages is provided in Table 6.

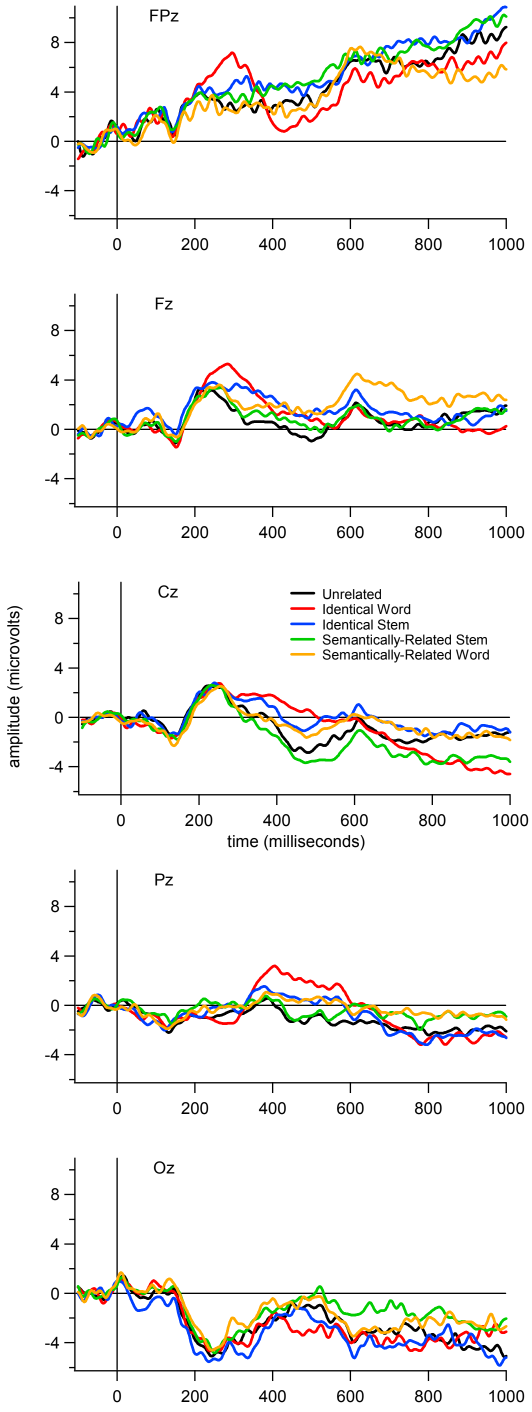
Table 6. Mean Likert Scale Response for Each of the Five Conditions

Condition 1	4.95
Condition 2	1.01
Condition 3	4.68
Condition 4	4.79
Condition 5	2.71

ERP Data

Figure 7 displays grand average waveforms at five midline electrodes. Visual inspection of the waveforms at several of these electrodes reveals possible differences in amplitude between Condition 1 (Unrelated), which served as control, and each of the other five conditions. The ERP activity at these channels was analyzed within specific time windows of interest generated by the temporal PCA, reported next.

Figure 7. Grand Average Waveforms For Each Of The Five Conditions At Five Midline Electrodes.



The principal component analysis generated 10 temporal factors accounting for 95.59% of the variance. As noted previously, each temporal factor represents a time window of distinct ERP variance. Figure 8 shows the factor loadings for each temporal factor. The largest loadings indicate the time points during which a specific pattern of ERP variance was most active. For some of the temporal factors shown in Figure 8, the time-course is difficult to interpret. Those factors likely represent noise. Of the temporal factors having a well-defined time-course, just three were found to summarize statistically significant experimental effects in the ERP variance (see Figure 8, shaded factors shown with their peak latencies). These will hereafter be referred to using their peak-latencies, i.e., T262, T384, and T530, respectively.

T262 Effects.

Repeated measures ANOVA of the factor scores associated with the T262 time window revealed an interaction of Word and Electrode, *F*[16,208]=3.99, *p*=.005. Bonferroni-corrected pairwise comparisons testing the amplitude of Condition 1 (Unrelated) against the amplitude of each other condition revealed statistically significant effects at two different electrodes. At electrode FPz, the difference in amplitude between Condition 2 (Identical Word) and Condition 1 (Unrelated) was statistically significant (*p*=.000). As shown in Figure 9, the Identical Word condition had a larger positive-going amplitude than the Unrelated condition. This effect, with its early time-course and anterior scalp distribution, is consistent with the activation of a P200-type ERP and suggestive of orthographic processing.

Figure 8. Variance-Scaled Factor Loadings For Each Of The 10 Temporal Factors (I.E., 10 Time Regions Of Interest) Identified Using Temporal PCA. Factors With Green Shading Indicate Time Windows Associated With Statistically Significant Experimental Effects (peak latency of each window shown in milliseconds).

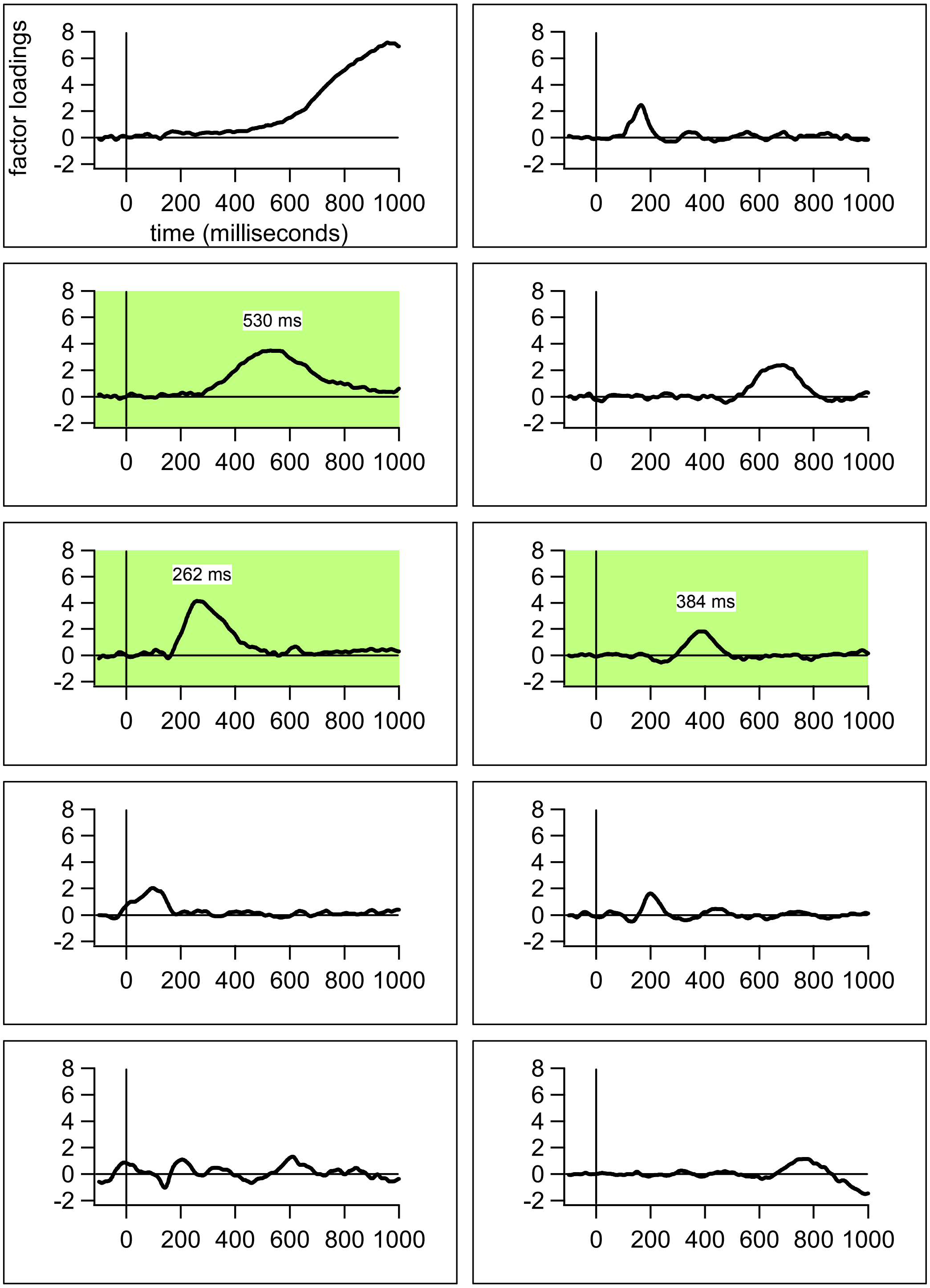
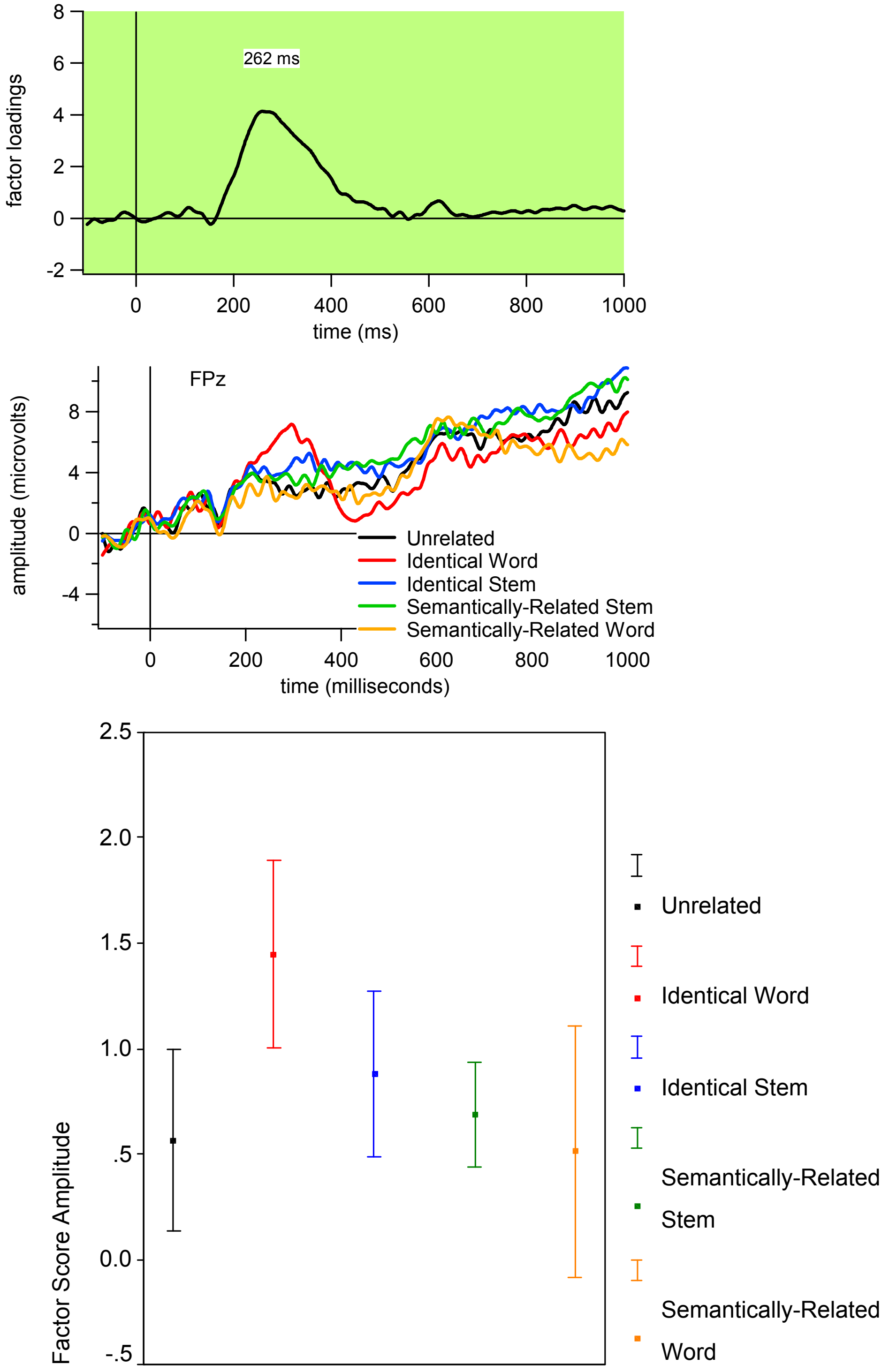


Figure 9. T262 Factor Loadings (Top) And Scores (Bottom) At Electrode Fpz (Middle).



In addition, at electrode Pz, the difference in amplitude between Condition 4 (Semantically-Related Stem) and Condition 1 (Unrelated) was statistically significant (*p*=.016). As shown in Figure 10, the Unrelated condition was associated with negative-going activity that was attenuated in amplitude for the Semantically Related Stem condition. This effect, with its early (T262) time-course and posterior scalp distribution, is consistent with the activation of an N400-type ERP and suggestive of early semantic processing at electrode Pz around 262 milliseconds after stimulus presentation.

T384 Effects.

Repeated-measures ANOVA of the factor scores associated with the T384 time window revealed a main effect of Word, *F*(4,52)=6.13, *p*=.002. Bonferroni-corrected pairwise comparisons, testing the amplitude of Condition 1 (Unrelated) against the amplitude of each other condition, revealed a statistically significant difference between Condition 2 (Identical Word) and Condition 1 (*p*=.023); as well as a statistically significant difference between Condition 3 (Identical Stem) and Condition 1 (Unrelated) (*p*=.032). As shown in Figure 11, the Identical Word and Identical Stem conditions were both associated with positive-going ERP activity relative to the Unrelated condition. This effect is consistent with a P300-type activation, which has been associated with updating of working memory.

Figure 10. T262 Factor Loadings (Top) And Scores (Bottom) At Electrode Pz (Middle).

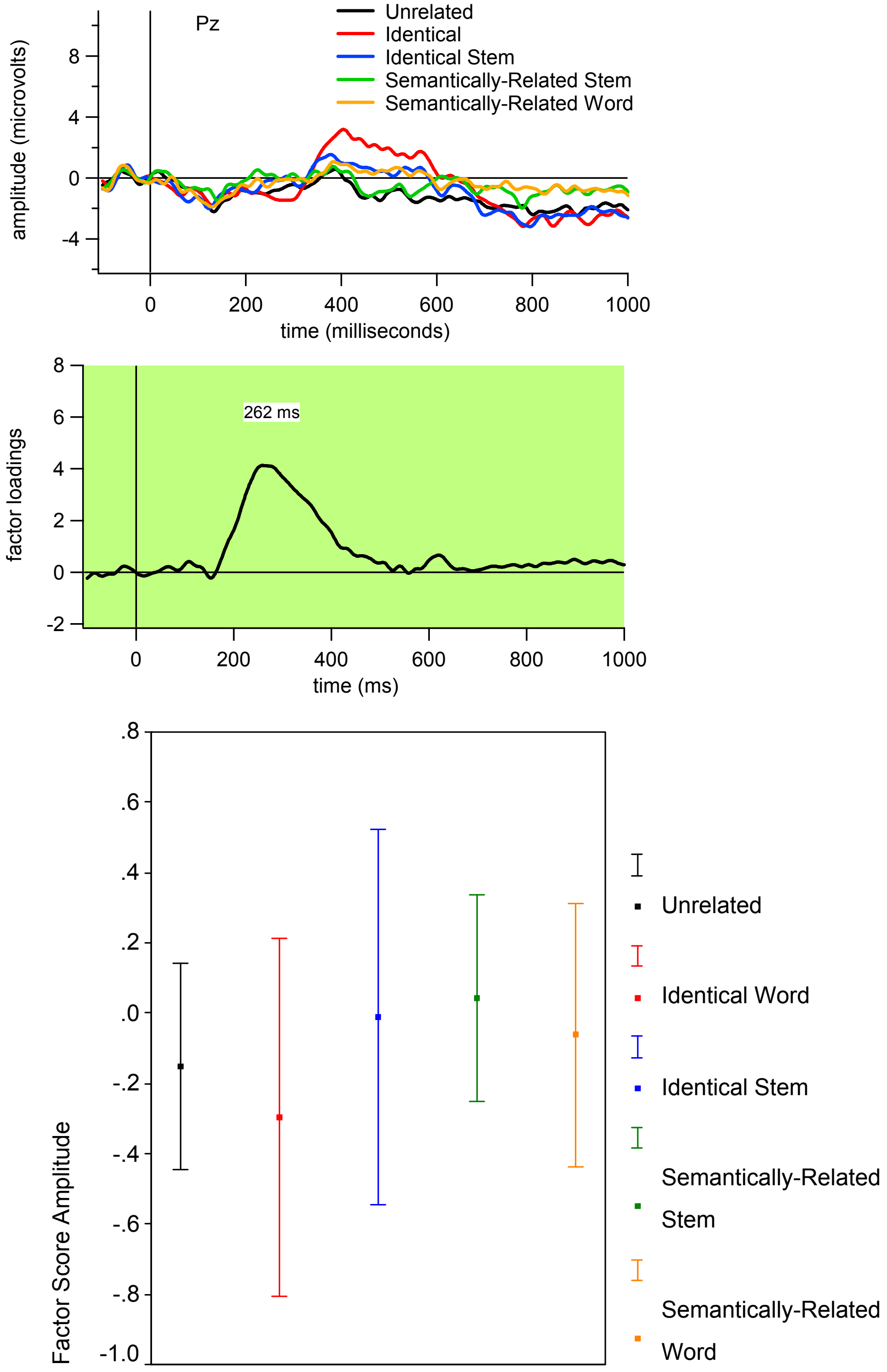
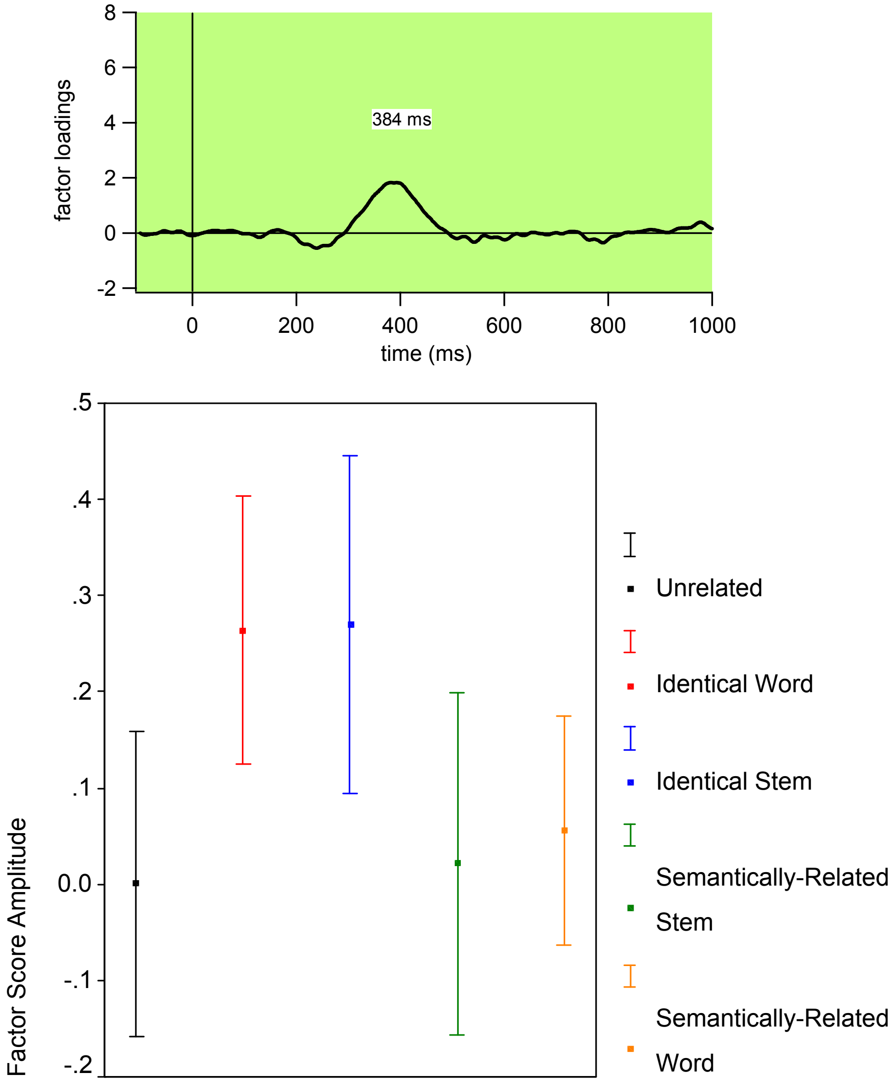


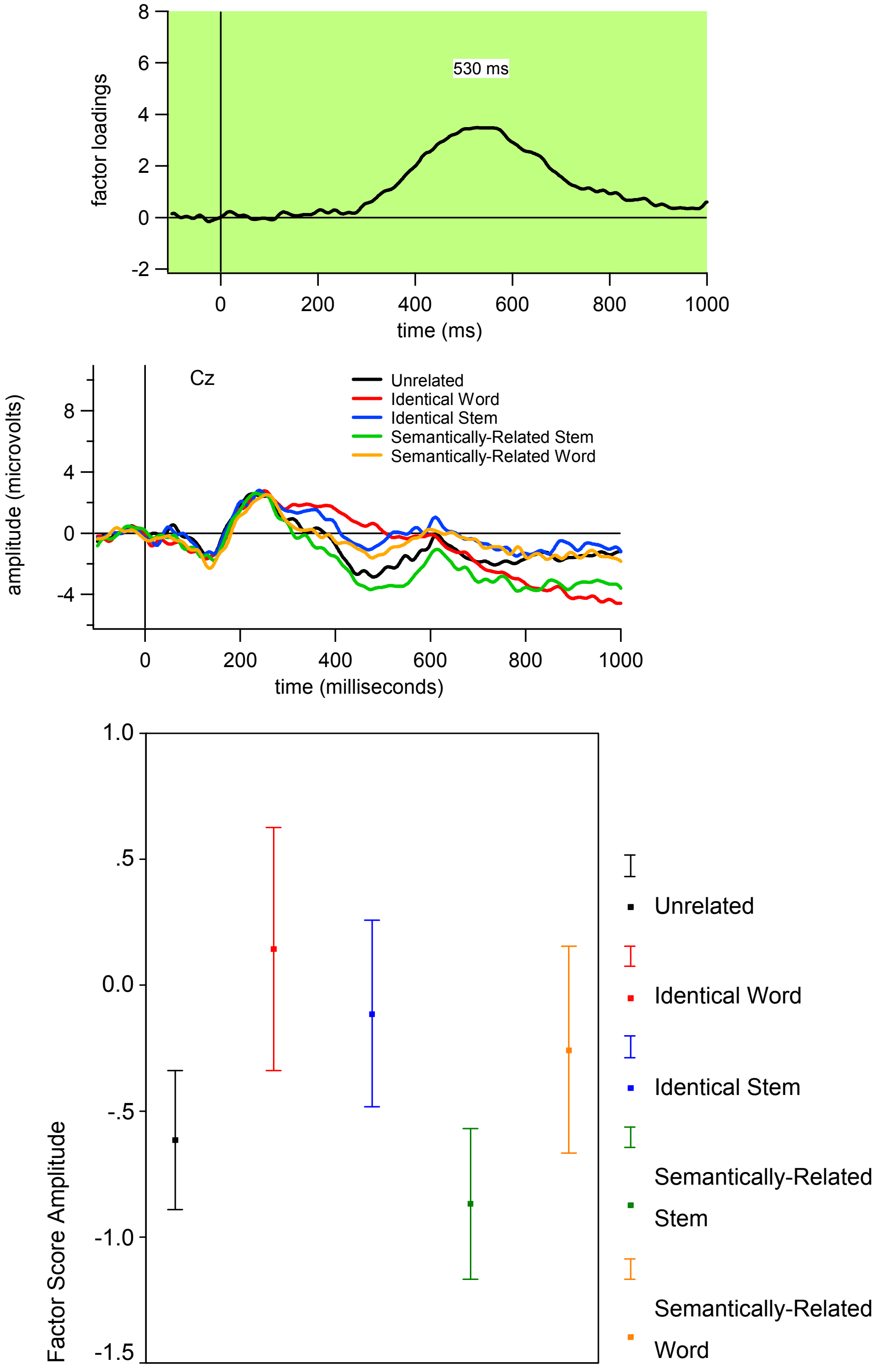
Figure 11. T384 Factor Loadings (Top) And Scores (Bottom) Averaged Across The Five Midline Electrodes.



T530 Effects.

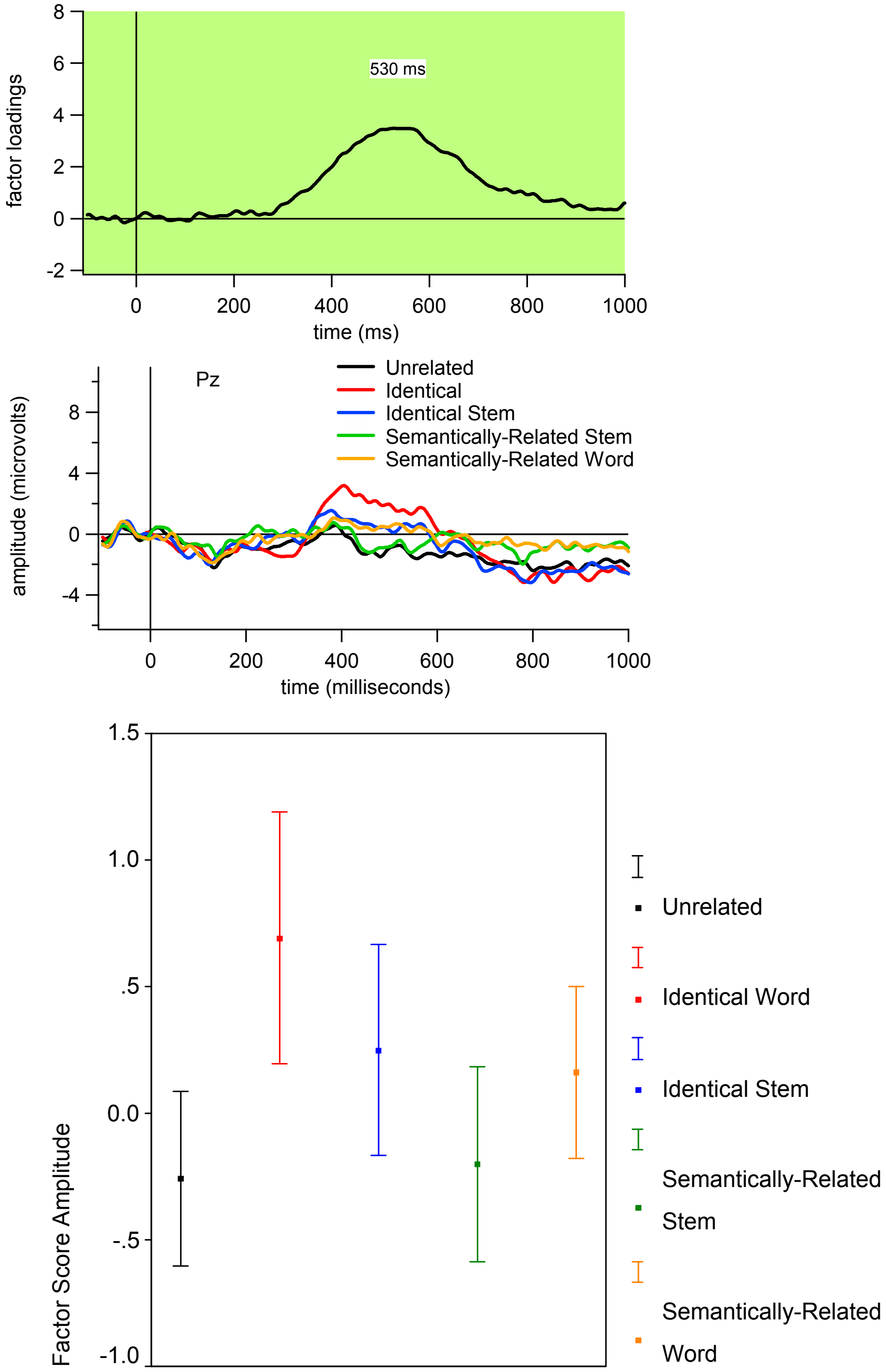
Finally, repeated-measures ANOVA of the factor scores associated with the T530 window revealed an interaction of Word and Electrode, *F*(16,208)=4.07, *p*=.012. Bonferroni comparisons, testing Condition 1 (Unrelated) against the amplitude of each other condition, revealed statistically significant effects at two different electrodes. At electrode Cz, the difference in amplitude between Condition 2 (Identical Word) and Condition 1 (Unrelated) was statistically significant (*p*=.001); as was the difference in amplitude between Condition 3 (Identical Stem) and Condition 1 (Unrelated) (*p*=.015). As shown in Figure 12, the Unrelated condition was associated with negative-going activity, consistent with N400 activation (responsive to semantic information), which was attenuated in amplitude for the Identical Word and Identical Stem conditions.

Figure 12. T530 Factor Loadings (Top) And Scores (Bottom) At Electrode Cz (Middle).



At electrode Pz, the difference in amplitude between Condition 2 (Identical Word) and Condition 1 (Unrelated) was statistically significant (*p*=.001); as was the difference in amplitude between Condition 5 (Semantically-Related Word) and Condition 1 (Unrelated) (*p*=.007). As shown in Figure 13, the Unrelated condition was once again associated with negative-going (i.e., N400-like) activity that was attenuated in amplitude for the Identical Word and Semantically-Related Word conditions, indicative of semantic processing at electrode Pz around 530 ms after stimulus presentation.

Figure 13. T530 Factor Loadings (Top) And Scores (Bottom) At Electrode Pz (Middle).



CHAPTER FOUR: DISCUSSION

The aim of this study was to determine whether typical adult readers analyze pseudo-derived words for morphological components and process the stems semantically. Fourteen participants engaged in a task that required them to read prime-target word pairs. Five conditions were created in which the prime-target relationship varied orthographically, phonologically, and/or semantically, as follows: Condition 1 (Unrelated - *inn*/*brother*); Condition 2 (Identical - *brother*/*brother*); Condition 3 (Identical Stem - *broth*/*brother*); Condition 4 (Semantically-Related Stem - *soup*/*brother*); Condition 5 (Semantically-Related Whole - *sibling*/*brother*). ERPs recorded to the second word in each pair were analyzed at midline electrodes in the duration spanning from word onset to 1000 milliseconds following word onset.

Temporal principal component analysis revealed ERP priming effects (i.e., differences in amplitude) between Condition 1 (Unrelated) and Experimental conditions: 1) in the amplitude of the P200 component for Condition 2 (Identical Word); 2) in the amplitude of an early N400-like component for Condition 4 (Semantically Related Stem); 3) in the amplitude of the P300 component for Conditions 2 (Identical Word) and 3 (Identical Stem); and, finally, 4) in the amplitude of a standard, later N400 component for Conditions 2 (Identical Word), 3 (Identical Stem), and 5 (Semantically-Related Whole). A summary of these results is provided in Table 7. Of primary interest were the two, relatively early ERP effects active during a time window peaking in amplitude at 262 milliseconds after target word onset – one related to orthographic processing (P200) and

Table 7. Summary of ERP Effects Differentiating Experimental Conditions from Control at Latencies Determined using Principal Component Analysis.

Condition	**Early time window (262ms)**	**Later time window (384ms)**	**Late time window (530ms)**
2 (brother-brother)	orthographic priming	memory updating	semantic priming
3 (broth-brother)		orthographic priming?	orthographic & semantic processing overlap
4 (soup-brother)	semantic priming		
5 (sibling-brother)			semantic priming

the other related to semantic processing (N400). As discussed below, the early N400-like effect supports the hypothesis that readers access word stems at a semantic level.

Temporal Patterns of ERP Effects

Early ERP Effects

Two ERP components responded dissimilarly to different experimental conditions within the same, early time window peaking at ~262 milliseconds after the presentation of target words. One was a frontal P2 effect, which was larger in amplitude for Condition 2 (Identical Word) than for Condition 1 (Unrelated). One interpretation is that enhanced P2 amplitude is a neural marker of orthographic processing during word reading (Barnea & Breznitz, 1998). Specifically, Rugg, Doyle, and Wells (1995) and Rugg and Nieto-Vegas (1999) found that immediate visual-visual word repetition elicited an early (200-400ms) positive wave. Because this response was specific to the written domain (as opposed to auditory or cross-modal), and was observed for real words but not for non-words, the authors concluded that this early P2-like effect represented readers' processing of real-word orthography. The ERP response to Condition 2 may reflect this orthographic word repetition effect, as the prime-target words were identical. Since Condition 3 (Identical Stem) did not elicit the same result, it may point to an orthographic process that relates strictly to whole words. Alternatively, it may be that the orthographic process marked by early P2 can only be activated when phonology does not change.

More crucially, within this same time window a posterior, negative-going ERP component was elicited by Condition 1 (Unrelated) but was attenuated by Condition 4. Traditional interpretations of the N400 component associate it with lexical-semantic processing. Van Petten and Kutas (1991) discovered that N400 amplitude was inversely associated with a word's activation level in memory: When a word is semantically primed prior to its presentation, it elicits a smaller-amplitude N400 component than when it is unprimed semantically. N400 is typically largest at parietal and temporal regions, peaking at approximately 400ms post-stimulus onset (Key, Dove, & Maguire, 2005). However, several other studies suggest that semantic processing takes place on the order of 250-270ms post-stimulus onset (Sereno, Rayner, & Posner, 1998; Martín-Loeches, Hinojosa, Casado, Munoz, & Fernandez-Frias, 2004; Penolazzi, Hauk, & Pulvermüller, 2007). Particularly relevant to our results, Penolazzi et al. (2007) found early ERP responses to semantic tasks occurring in a 280-320ms time window, a phenomenon they speculate might be an early N400-like component.

Results corroborate those of other studies in regard to the activation of early negative-going ERP components that respond in various ways to word meaning (reviewed in Dien, 2009). Further, and crucial to the research question, the results reveal that apparent stems embedded within words are not only recognized orthographically, as discussed in the first chapter (Morris et al., 2008), but are also accessed semantically. In

Condition 4, the words in each pair shared a semantic relationship via the stem of the second word (*soup/brother*). As readers read *soup*, past research tells us that a network of semantically related words becomes activated, included among them *broth.* When next presented with *brother*, readers automatically segment this word into two morphemic units (*broth* + *er*). Crucially, readers may go beyond visual stem segmentation to access stem meaning, as suggested by the decrease in amplitude of the response from Condition 1 (Unrelated) to Condition 4 (Word 1 overlapped semantically with the stem of Word 2; e.g., *soup-brother*).

Later ERP Effects

Conditions 2 (Identical) and 3 (Identical Stem) elicited a robust P300-like response relative to the control condition in the T384 time window. This finding correlates with interpretations of the P300 component that it is a measure of working memory updating (Donchin & Coles, 1998). As successive stimuli are presented, working memory is updated with the new information, thereby creating a trace of each stimulus. Segalowitz, Van Roon, and Dywan (1997) found a positive correlation between the amplitude of the P300 wave and the number of times a stimulus item was repeated. The authors argued that the strength of a trace is increased by each successive presentation of a stimulus. The significantly more positive responses to Condition 2, in which the full word was repeated, and Condition 3, in which most of the word was repeated, seem to be in line with this interpretation of the P300.

An alternate interpretation is that the later positivity seen for both Conditions 2 and 3 in this study functionally resembles the early P2 response observed only for

Condition 2. Rugg et al. (1995) showed that the positive wave elicited when the same two real written words were presented in succession had an early onset and continued as a sustained positivity that changed in scalp topography. One possibility is that the early P2 elicited by Condition 2 was sustained, and spread across the scalp later in time. This same positivity may have also been engaged only later in time for Condition 3, which suggested that real word orthographic processing can be engaged at different times depending on the degree of overlap between the words. Both interpretations posed here are tentative and require further study.

Late ERP Effects

Finally, Condition 1 (Unrelated) elicited a robust N400 response that was attenuated in amplitude for three of the other four conditions. As noted above, N400 is an ERP component elicited by lexical stimuli (Fischler, 1990), peaking in amplitude at ~ 400-600 milliseconds after word onset. Crucially, N400 amplitude is inversely related to a word's activation level in memory (Van Petten & Kutas, 1991). 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.

Conditions 2 (Identical), 3 (Identical Stem), and 5 (Semantically-Related Word) evidenced an attenuated N400. While this effect was expected for Conditions 2 and 5, it was arguably less expected for Condition 3. Traditional interpretations of the N400 component associate it with semantic processing tasks. Since the prime-target pairs in Conditions 2 and 5 overlap semantically, an attenuated N400 response was expected. In contrast, the prime-target words in Condition 3 did not overlap semantically. Still, an attenuated N400 component was observed. Two other studies, Holcomb and Grainger (2006) and Morris et al. (2008) found similar results. Holcomb and Grainger speculated that allowing for longer stimulus presentation time (as done in this study) gave readers sufficient opportunity to process words, resulting in more overlap between orthographic and semantic processing. In other words, increased conscious awareness of the stimuli gave rise to simultaneous orthographic and semantic analysis of the words.

The fact that N400-like responses observed in our study differed temporally (one early and one late) raises questions regarding the nature and timing of lexical and semantic processing. In the earlier time window, the N400-like wave responded to word stem semantic priming and the later one responded to orthographic and whole word semantic priming. Franklin, Dien, Neely, Huber, and Waterson (2007) hypothesized that N400 level activity represented post-lexical processing. Penolazzi et al. (2007) found early and late semantically sensitive ERP responses, but discounted the possibility that they corresponded with pre- and post-lexical processing. Whatever the case may be, the temporal differences observed may reveal at least two levels of semantic processing: one at an early stage that deals with morphemic units and one at a later stage involving whole word analysis.

Results in Light of the Modified DRC Model

A return to the modified DRC model may provide some clarification of these results. The model postulates that, when a word containing an apparent stem, such as *brother,* is read, it is processed simultaneously as a whole word and an assemblage of parts (*broth* + *er*). Early P2 suggests that readers do indeed analyze orthography at a whole word level. At about the same latency, readers analyze the morphemic elements for a semantic entry; that is, there is preliminary evidence that readers access at least semantic representations of the stem. In this priming experiment, presenting *soup* to the reader activated soup-related words, which were still active when *brother* was presented 200ms later. Priming was observed in the T262 window, we argue, because the stem of *brother* (i.e., *broth)* was pre-activated at a semantic level when *soup* was presented, although there is no direct evidence of what the brain does with this semantic knowledge. For derived words that are semantically transparent, perhaps the brain starts using stem meaning immediately to arrive at a whole word meaning. In contrast, the stems of pseudo-derived words do not contribute to whole word meaning. Although speculative, the brain may need to ignore or suppress stem semantic processing and access the lexical entry for *brother* via the whole word route.

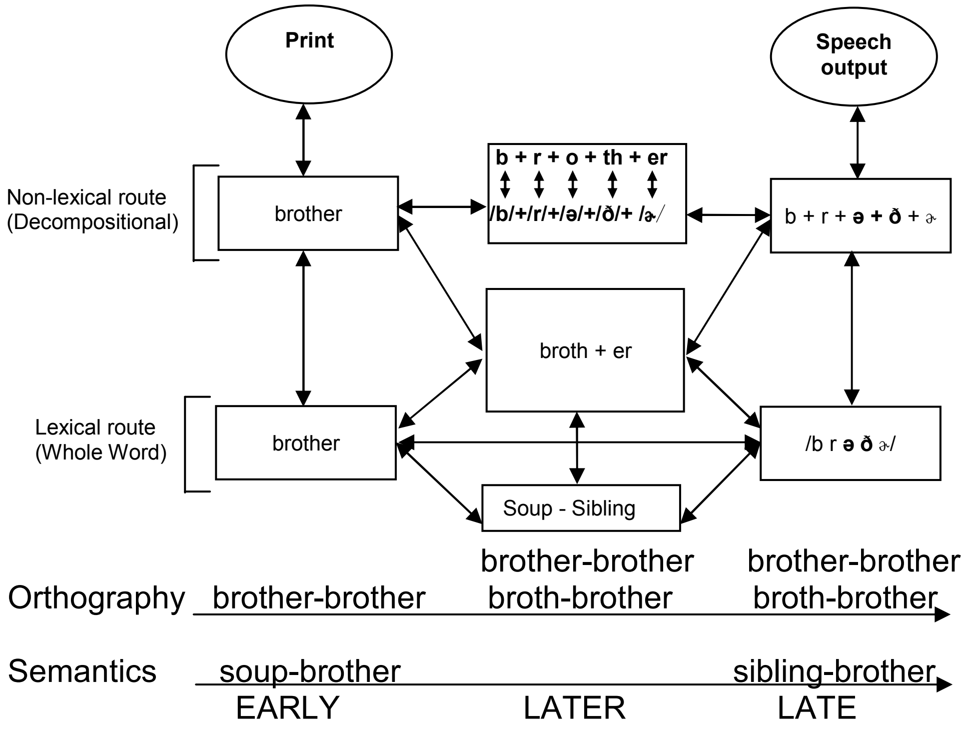
During the T384 time window, readers continue to process orthography at both a whole word and stem level. Processing continues at T530 on whole word orthography, stem orthography, and whole word meaning levels, evidenced in a modulated N400 amplitude by Conditions 2, 3, and 5, respectively. One question for future research is whether stem meaning activation might interfere with semantic processing of words at a whole word level and, if so, what mechanism is in place that allows readers to manage such interference. In other words, the whole word semantic priming effects observed in T530 might otherwise have occurred in an earlier time window had activation of an extraneous set of words (resulting from stem activation) not come about. It would also be theoretically and clinically important to understand how a reader handles the irrelevant information generated by the stem. It might be the case that this mechanism for managing additional layers of semantic representations functions differently for poor readers.

Again, interpreting these questions via the modified DRC model may provide some guidance. As shown in Figure 14, our results suggest that typical adult readers read perceived derived words both as a whole and as morphemic units and accessed meanings of both in parallel processes. Therefore, when a pseudo-derived word is encountered (e.g., *brother*), there must be some mechanism to deal with the disparity between the meaning gained from individual components (*broth – er*) and from the whole word. What, then, is the nature of this mechanism – what role does it play in the modified DRC model and what becomes of the superfluous information? Could it be that a dysfunction of either the morphological segmentation route or the mechanism for managing irrelevant information, or both, manifests in reading comprehension difficulties? Answers to these questions could further our understanding of reading impairments and possibly lead to more informed intervention strategies.

Comparisons with Other Studies

Three previous research studies have examined the architecture and depth of automatic morphological segmentation using both behavioral and neurophysiological methods. Here, each study is compared with the present study and possible explanations are offered for any variance.

Figure 14. Proposed Segmentation of Semantically Opaque Words (Condition 4) to Modified DRC Model and Summary of Timeline of Priming Effects Observed



Variations in Priming and Prime Target Pairs.

Marslen-Wilson et al. (1994) found that reaction times to transparent (e.g., *punishment/punish*) and opaque word pairs (e.g., *casualty/casual*) were not significantly different using a masked priming paradigm, concluding that readers treat these two types of words similarly. The priming effects observed in Condition 4 of this study, evidenced by modulation of the N400 component, support the argument made by Marslen-Wilson et al. that typical readers automatically dissect both complex and seemingly complex words. This pattern occurs in spite of two notable differences between the two studies.

The first difference is related to the priming paradigm: Marslen-Wilson et al. (1994) employed masked priming, whereas, in the current study, a longer-term priming method was used. The second is related to choice of prime-target pairs. Marslen-Wilson et al. included semantically opaque words in which the orthography and phonology of the stem was preserved, which may have yielded stronger priming effects. Pseudo-derived words were selected for this study that also involved a phonological shift in an attempt to isolate orthographic influence from semantic and phonological influence (Condition 3). Importantly, the variations between the studies did not seem to affect the outcomes, indicating that semantic priming is insensitive to stimulus duration and orthographic and phonological overlap.

Variations in Word-Pair Features.

Morris et al. (2008) also found results similar to Marslen-Wilson et al. (1994) in their ERP investigation of long-term priming. Specifically, priming effects were observed in the N400 component for both transparent and opaque conditions, given a longer stimulus presentation time. Our findings also replicate those of Morris et al. in that priming effects were observed in the N400 component for pseudo-derived words. While their priming paradigm was consistent with the one in this study (i.e., long-term priming), their stimuli characteristics were different. As with the Marslen-Wilson experiment, this study differed from that of Morris et al., which included orthographically and phonologically overlapping word pairs. Again, the fact that our study resulted in similar priming effects suggests that orthography and phonology may not have played a crucial role in morphological processing in the N400 component.

Variations in Response Measures.

In contrast to the behavioral and neurophysiological priming effects found in the Marslen-Wilson et al. (1994) and the Morris et al. (2008) studies, as well as the present study, Rueckl and Aicher (2008) found no long-term priming effects for semantically opaque words as measured by reaction times. Hence, the results conflict between this study and the Rueckl and Aicher investigation, despite similarity in the stimulus presentation (i.e., both used long-term priming). One reason may be due to the fact that Rueckl and Aicher used reaction times to measure priming effects. This behavioral measure may not have been a fine enough assessment of the early and precise neurological responses described in the previous section (Results in Light of the Modified DRC Model). Put differently, reaction time measures are limited by the speed with which participants respond and may not accurately reflect neurophysiological processes that occur at a much faster rate.

In summary, our results replicated those of Marslen-Wilson et al. (1994) and Morris et al., (2008), even though all three studies varied in terms of stimulus presentation time, word pair choice, and response measurement. All three studies support the idea that readers automatically parse and process stem meaning, even if stem meaning does not contribute to the meaning of the whole word in which it is contained. These results differ from those of Rueckl and Aicher (2008), who found no long-term priming effects for semantically opaque derived words. One major difference between our study and theirs is in response measurement. Rueckl and Aicher used changes in reaction times to approximate priming effects, while ERPs were used in this study. As mentioned above, reaction times are restrained by how quickly participants can respond. On the other hand, event-related brain potentials have the advantage of gauging neural processing on the order of milliseconds.

One possible limitation of this study relates to the strict inclusionary criterion that the target words be both semantically and phonologically opaque. This severely limited the number of items that could be used in the experiment. The relatively small number of items also posed a problem in stimulus characteristic matching (e.g., frequency, neighborhood density, length, etc.). Therefore, the decision was made to present the opaque word as the target word, rather than as the prime word in the way that the studies of Morris et al. (2008) did. This would ensure that responses were measured to the same word type across all five conditions. It should also be noted that both the Morris et al. study as well as this study utilized statistical estimates of word frequency.

The design of this study has the potential for examining on-line morphological segmentation in clinical populations, such as adult readers with dyslexia. Of particular interest is the subset of dyslexia in which word reading skills are impaired, but reading comprehension skills remain relatively intact. It seems that in this population, readers are able to access semantic information independently from phonological information. The few studies investigating possible compensatory strategies that might explain this phenomenon, including morphological segmentation skills, have yielded inconclusive evidence. Since ERP methodology has the advantage of observing neural responses in fine temporal detail, future studies using this technique may elucidate the relationship between morphological segmentation of derived words and reading comprehension in those with reading impairments, including those whose reading impairments co-occur with an oral language impairment.

Conclusion

In conclusion, this study set out to investigate processing of pseudo-derived words in typical young adult readers. Prior behavioral and neurophysiological studies suggested that because both transparent and opaque derived words were treated similarly by readers, morphological segmentation occurred even for words for which it is inappropriate to do so. A recent behavioral study (Rueckl & Aicher, 2008) found evidence to the contrary. Our results indicate that morphological segmentation for semantically opaque words may in fact occur, but in an earlier time window (262ms). Future studies may look to examining similar processes in reading and language impairments in children, adolescents, and young adults.

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APPENDICES

Appendix A: Sample Quiz Items

1. Muffin:
    a. a small, cup-shaped quick bread, often sweetened
    b. a scarf worn around one's neck for warmth.
    c. anything that veils, screens, or shuts from sight
2. Hoist:
    a. to make damp; to wet in a small degree
    b. to tear down; demolish; level to the ground
    c. to raise or lift, esp. by some mechanical appliance
3. Coupon:
    a. a written statement, usually of complaint, presented to a court
    b. a statement of money owed for goods or services supplied
    c. one of a set of detachable certificates that may be torn off and redeemed as needed
4. Ledger:
    a. a cliff with a vertical, nearly vertical, or overhanging face
    b. an account book of final entry, in which business transactions are recorded
    c. a bar of chocolate candy
5. Callous:
    a. able to receive and respond to external stimuli
    b. of or pertaining to classified information or matters affecting national security
    c. hardened; insensitive
6. Cater:
    a. to provide or supply what amuses, is desired, or gives pleasure, comfort, etc.
    b. having extremely unfortunate or dire consequences
    c. collective and individual human suffering caused by life conditions
7. Cogent:
    a. not reasonable or rational; acting at variance with or contrary to reason
    b. a physical or an abstract system which may change its value while it is under observation
    c. convincing; to the point; relevant
8. Copious:
    a. an inadequate supply; scarcity; lack
    b. large in quantity or number; abundant
    c. inability to fulfill a given purpose
9. Dubious:
    a. doubtful
    b. established as true or sure; unquestionable; indisputable
    c. characteristic of an unbiased estimator of the mean-squared error of a given estimator