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Wave-ering: An ERP study of syntactic and semantic context effects on ambiguity resolution for noun/verb homographs

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Abstract

Two event-related potential experiments investigated the effects of syntactic and semantic context information on the processing of noun/verb (NV) homographs (e.g., park). Experiment 1 embedded NV-homographs and matched unambiguous words in contexts that provided only syntactic cues or both syntactic and semantic constraints. Replicating prior work, when only syntactic information was available NV-homographs elicited sustained frontal negativity relative to unambiguous words. Semantic constraints eliminated this frontal ambiguity effect. Semantic constraints also reduced N400 amplitudes, but less so for homographs than unambiguous words. Experiment 2 showed that this reduced N400 facilitation was limited to cases in which the semantic context picks out a nondominant meaning, likely reflecting the semantic mismatch between the context and residual, automatic activation of the contextually-inappropriate dominant sense. Overall, the findings suggest that ambiguity resolution in context involves the interplay between multiple neural networks, some involving more automatic semantic processing mechanisms and others involving top-down control mechanisms.

Keywords

lexical ambiguity resolution; NV homographs; syntactic context; ERP; frontal negativity; N400

One central feature of language is that a single spelling or pronunciation is oftentimes associated with multiple senses. The appropriate interpretation of a word therefore needs to be established via a variety of contextual constraints, including lexical associations among co-occurring words, restrictions set by the syntactic structure, message-level semantic information built as context unfolds, pragmatic factors, world knowledge, and so forth. A primary goal of psycholinguistic research is thus to understand how information gleaned from individual lexical items is brought together with that derived from the larger language and communicative

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[2]Van Petten & Kutas (1987) do explicitly comment on the lack of difference between the waveforms elicited by sentence final ambiguous and unambiguous words in their probe study. However, there are a number of procedural differences between their study and the present one, as they used a mixture of NN- and NV-homographs, sentence contexts that consistently biased toward the subordinate meaning of a homograph (whereas bias was unpredictable in the present study), and a slower (900 ms SOA) presentation rate.

context – and, in particular, how different sources of contextual information are processed, both neurally and cognitively, and how they shape the interpretation of individual words.

Most of the large body of research on semantic ambiguity resolution has focused on meaning selection within a particular syntactic category (usually nouns) – for example, on how people determine whether the word *organ* is being used to refer to a musical instrument or a body part. Correspondingly, within this part of the literature, studies of context effects have manipulated the availability of semantic constraints, either from lexically associated words or from sentence message-level meaning. However, there are actually multiple types of ambiguity, some of which have been less well studied. For some words, meaning ambiguity co-occurs with word class ambiguity – the word *tire*, for example, has a different meaning when used as a noun than when used as a verb. When meaning ambiguity is linked with word class ambiguity in this way (we will refer to this type of word as an NV-homograph), syntactic features of context could also theoretically play a role in semantic ambiguity resolution. Critically, the smaller literature looking at syntactic context effects on meaning ambiguity resolution for NV-homographs has yielded substantively different conclusions than that looking at semantic context effects for within class, NN-homographs. In what follows, we first overview each literature and the conclusions about the role of context in ambiguity resolution that have been drawn from it, and we show why integrating them in their current state is difficult. We will then show how findings from a third literature – using hemodynamic imaging methods to examine ambiguity resolution – point to a possible source for the differences that have been observed. Finally, then, we will introduce our pair of studies, which aim to bring these three literatures together to yield a coherent picture of how ambiguous words are processed across different types of contexts.

Effects of semantic contexts on meaning ambiguity resolution for NN-homographs

Decades of work have established that semantic constraints, built up incrementally over the course of a sentence or other higher-order language context, can facilitate word processing (Marslen-Wilson & Tyler, 1980; Kutas, Van Petten, & Besson, 1988; Van Petten & Kutas, 1990; Van Petten & Kutas, 1991). For example, within semantically constraining contexts, monitoring latencies to words have been found to become progressively faster the later the word appears in the sentence (Marslen-Wilson & Tyler, 1980). Similarly, the amplitude of the scalp-recorded N400 – an event-related potential component that has been linked to semantic access (Kutas & Federmeier, 2000, Federmeier & Laszlo, in press) – has also been shown to reduce progressively over the course of sentences with semantic constraints (Kutas, Van Petten, & Besson, 1988; Van Petten & Kutas, 1990; Van Petten & Kutas, 1991). Findings like these suggest that semantic information builds across a context, easing processing by providing increasingly strong constraints on the features of upcoming words and even allowing the pre-activation of those features (Federmeier & Kutas, 1999; Delong, Urbach, & Kutas, 2005; Laszlo & Federmeier, in press).

Within the domain of lexical ambiguity resolution, a core question has been whether such context information can affect lexical access, allowing selective activation of the contextually appropriate meaning of a homograph. The accumulated data suggest that it can, albeit in a manner that interacts with meaning dominance. When semantic constraints in the context pick out the less frequent meaning of a biased homograph, it seems that multiple meanings of the ambiguous word are nevertheless often activated (e.g., Duffy, Morris & Rayner, 1988; Rayner & Frazier, 1989; Rayner, Pacht & Duffy, 1994; Swaab, Brown & Hagoort, 2003; Tabossi & Zardon, 1993). However, evidence for selective access, typically operationally defined as a lack of processing difference between ambiguous and matched unambiguous words, has been obtained in a number of studies, especially when the context provides strong constraints for the more frequent meaning sense of a homograph (e.g., Paul, Kellas, Martin & Clark, 1992;

Rayner & Frazier, 1989; Tabossi, 1988; Tabossi, Colombo & Job, 1987; Tabossi & Zardon, 1993) or contains lexically associated words (Meyer & Federmeier, 2007; Seidenberg et al., 1982). Collectively, then, this body of work suggests that, although it may be difficult to completely suppress activation of dominant meaning features, semantic context information can shape meaning access and thereby reduce the selection demands typically associated with ambiguity.

Effects of syntactic contexts on meaning ambiguity resolution for NV-homographs

Syntactic context information has also been established to affect word processing (Marslen-Wilson & Tyler, 1980; Tyler & Warren, 1987; Wright and Garrett, 1984; West and Stanovich, 1986), but in ways that are different from semantic context effects. Whereas semantic constraints build incrementally, the influence of syntactic context seems to be more localized. For example, although word monitoring latencies are facilitated by syntactic context, it is local phrase structure and not global syntactic structure that drives these effects (Marslen-Wilson and Tyler, 1980; Tyler and Warren, 1987). Correspondingly, sentences with syntactic structure but no coherent semantic message do not lead to incremental N400 reduction (Van Petten & Kutas, 1991).

In addition to coming on line more locally, syntactic constraints are considerably more general (e.g., requiring a noun but providing very little information about its features), whereas semantic constraints can be more specific. However, syntactic constraints are also definitive in a way that semantic constraints cannot be – a factor that would seem important for lexical ambiguity resolution. A sentence beginning *"Jim tried the …"* requires a noun phrase; thus, if an NV-homograph such as *register* were then presented, the syntactic constraints established by the context would seem to rule out its verb use and corresponding meaning. In contrast, a sentence beginning *"Mary went to the fireplace to get the …"* may provide evidence in favor of one meaning of a subsequent ambiguous word, such as *poker*, but cannot then rule out a continuation like *"… chip, which had fallen from the table."*

Perhaps surprisingly, then, the relatively few studies that have examined the influence of syntactic contexts on ambiguity resolution have tended to suggest that, despite its more deterministic nature, syntactic information alone is not sufficient to immediately resolve meaning ambiguity for NV-homographs, even when their more frequent word class usage is being picked out (Lee & Federmeier, 2006; Seidenberg, Tanenhaus, Leiman & Bienkowski, 1982; Tanenhaus, Leiman & Seidenberg, 1979). For example, Tanenhaus et al. (1979) embedded NV-homographs in sentence contexts that contained neutral semantics but well-specified syntactic cues (e.g., *"I bought the/began to watch"*). Auditory sentences were followed by visual probe words (e.g., *look*) to be named. When there was no delay before the presentation of the probes, naming latencies were significantly reduced for words related to both the context-appropriate and context-inappropriate meanings of the NV-homograph. The results thus suggest that, even in well-specified syntactic contexts that logically rule out one reading for an NV-homograph, multiple meanings are initially accessed. Processing costs for NV-homographs in syntactically constraining but (initially) semantically neutral sentences (e.g., "*Mark noticed that the count was wearing an expensive sword from Italy*") have also been observed in the form of increased gaze durations in the post-homograph region (Folk and Morris, 2003).

ERP data further support the conclusion that syntactic context information does not eliminate the meaning ambiguity associated with NV-homographs. In a series of prior studies, we embedded NV-homographs in a variety of syntactically constraining but semantically neutral contexts, including the midsentence positions of congruent sentences (e.g., "*Jeremy wanted* *to/the watch even though …*"; Federmeier, Segal, Lombrozo & Kutas, 2000) and minimal phrases (e.g., *to/the watch*; Lee & Federmeier, 2006). In all cases, ERPs obtained during natural reading (participants' task was to respond to comprehension probes that followed some of the sentences/phrases) showed a sustained frontally-distributed negativity, beginning around 200 ms, to the NV-homographs as compared with responses to matched unambiguous words. Importantly, this effect is not due to the syntactic ambiguity alone, as word class ambiguous items whose meanings are very similar across their noun and verb senses (e.g., *drink*) do not elicit this response (Lee & Federmeier, 2006). Furthermore, syntactic ambiguity does not seem to be required to elicit this effect, as sustained frontal negativity has also been observed in other cases in which there are multiple referents for a single (class unambiguous) word form (Van Berkum, Brown, Hagoort & Zwitserlood, 2003; Van Berkum, Brown & Hagoort, 1999). Therefore, the frontal negativity to NV-homographs seems to specifically reflect processing linked to these words' meaning ambiguity.

The ERP data are thus consistent with behavioral and eye-gaze findings in revealing a processing difference than obtains between unambiguous words and NV-homographs, even when the homographs are in syntactically well-specified contexts. Further, the ERP data suggest that this difference arises fairly early in the processing of the ambiguous lexical item itself.

Conflicting conclusions

In sum, whereas the literature looking at the processing of NN-homographs in the presence of semantic biases suggests that constraining contextual information can (at least sometimes) shape meaning access for ambiguous words, the literature looking at the processing NV-homographs in the face of syntactic restrictions suggests that it cannot. Understanding the basis for these differing conclusions is complicated by the fact that both the type of homograph under investigation and the type of context information that was manipulated has differed across the two literatures.

On the one hand, then, it is possible that the disparity across the literatures arises because multiply ambiguous NV-homographs are less affected by context information of any kind. Indeed, there is some data to support this hypothesis. Using the cross-modal naming task, Seidenberg et al. (1982) found that contexts containing a lexically associated word allowed selective access for NN-homographs (e.g., *The autoworkers picketed the plant*). However, in the same type of contexts – containing both lexico-semantic and syntactic cues for the disambiguation of an NV-homograph (e.g., *The gardener cut the rose*) – probes related to both of the NV-homograph's meanings showed facilitation, suggesting that the contextually-irrelevant meaning had been activated. Additionally, in the eyetracking study of Folk and Morris (2003), the increased gaze durations observed in the post-homograph region for NV-homographs in syntactic contexts remained when the prior context contained semantic constraints as well. Overall, then, the literature to date has provided no evidence to suggest that semantic constraints aid in ambiguity resolution for NV-homographs in the way that they seem to (at least in some circumstances) for NN-homographs.

On the other hand, it may instead be the different nature of the context information that is most critical for driving the observed patterns. This hypothesis receives support from patterns that can be found in a growing literature using brain imaging methods to study the nature of the processing costs associated with ambiguity. Across studies, several brain areas/networks have been associated with ambiguity resolution, in a manner that at first glance seems somewhat inconsistent and a bit puzzling. Yet a closer look suggests that ambiguity resolution may be subserved by multiple processing mechanisms, which are differentially affected by semantic and syntactic constraints. If true, this might not only help to reconcile the two literatures looking at context effects on ambiguity resolution, but also to explain the inconsistencies that have been noted within the functional neuroimaging of ambiguity literature itself.

Multiple mechanisms and context effects

Activity associated with the processing of lexical ambiguity has been localized to a number of different brain areas, roughly falling into two major clusters: one in the frontal cortex (specifically, the left inferior frontal gyrus) and the other in the temporal lobes (with a focus in left middle temporal gyrus) (Gennari et al., 2007; Ihara et al., 2007; Rodd et al., 2005; Zempleni et al., 2007). Interestingly, although none of the individual studies directly contrasts effects of semantic and syntactic contexts, looking across the literature at the characteristics of the stimuli used in these studies and their concomitant effects, we find suggestions that the two activation clusters that have been associated with ambiguity resolution may be differentially sensitive to different context types and may reflect activity in two brain networks that play different, but complementary roles, in lexical ambiguity resolution.

Activation in the left inferior frontal gyrus has been reported across conditions in which ambiguous words occurred without much prior disambiguating semantic information. They either occurred in the sentence initial position (Zempleni et al., 2007), in minimal contexts, such as a one-word syntactic cue (e.g. to/the bowl) (Gennari et al., 2007) or a one-word semantically related prime (Ihara et al., 2007), or, in the case of Rodd et al. (2005), embedded in a sentence together with several other ambiguous words (e.g. "*The shell was fired towards the tank*"), which offered more ambiguous than disambiguating information. Enhanced temporal lobe activity, on the other hand, has been observed under more restricted circumstances and has been shown to be modulated by semantic context and meaning dominance. Zempleni and colleagues (2007), for example, used biased Dutch homographs in sentences that ended with a word favoring either the dominant or the subordinate interpretation of the ambiguous word. Their results showed that the inferior and middle temporal gyri were bilaterally more activated to sentences containing ambiguous words when the subordinate meaning was highlighted. However, no differences between the dominant-biased sentences and unambiguous control sentences were found in these areas.

This pattern thus suggests the possibility of multiple, interacting brain networks involved in word processing and lexical ambiguity resolution in context. Activity in the frontal network may reflect more effortful, controlled selection, which seems to be necessary when syntactic constraints are available to resolve ambiguity but semantic constraints are not. This frontal lobe activity seems to be a promising candidate for the source of the sustained, frontally-distributed effect reported in the ERP ambiguity studies. The availability of semantic constraints, however, may preclude the need to recruit these frontal processing resources, as suggested by Zemplini et al's (2007) data. This is the pattern that has been observed for the sustained frontal ERP effect elicited by (within class) referential ambiguity (Van Berkum, Brown, Hagoort & Zwitserlood, 2003; Van Berkum, Brown & Hagoort, 1999), which was found to be eliminated in the context of semantic information that created a bias toward one of the potential referents (Nieuwland & Van Berkum, 2006) or rendered one less plausible (Nieuwland, Otten & Van Berkum, 2007). Establishing whether the same pattern holds for the similar ERP effect seen to NV-homographs is thus a key question, and one that the present set of studies aims to address.

However, in the presence of semantic constraints, it seems as though there may still be processing differences – of a different nature – between ambiguous and unambiguous words. Behavioral data suggest that selective access may be possible for the dominant meaning of a homograph in the presence of semantic constraints, but is unlikely to be possible for the nondominant meaning (Paul, Kellas, Martin & Clark, 1992; Tabossi, 1988; Tabossi & Zardon, 1993; Rayner, Pacht & Duffy, 1994; Duffy, Kambe & Rayner, 2001). Thus, even if semantic constraints can mitigate the need for controlled selection mechanisms, under conditions in which context picks out a non-dominant interpretation of an ambiguous word, there may continue to be automatic activation of dominant-associated features. Mismatch between these automatically activated features and those of the context might be responsible for the enhanced temporal lobe activity that has been seen in studies looking at ambiguity resolution in the presence of semantic constraints (e.g., Zemplini et al., 2007). In the ERP signal, the amplitude of the N400 would be expected to reflect a mismatch of this type.

The present studies

In order to understand the conflicting conclusions and data patterns that have been seen within and across different kinds of studies looking at ambiguity resolution in the presence of biasing context information, it is thus critical for the influence of syntactic and semantic contextual constraints to be assessed on the processing of the same set of items (namely, NV-homographs) in a within subjects design. The present pair of ERP experiments do this, with the further aim of testing the specific hypothesis, suggested by the neuroimaging literature, that ambiguity resolution unfolds in functionally and neurally different ways when words are encountered in different types of contexts.

In the first experiment, we directly compare the influences of syntactic and semantic context information on ambiguity resolution for NV-homographs (e.g., *watch*, *duck*). In particular, we examine whether the presence of semantic constraints will mitigate the need to recruit selection mechanisms indexed by the frontal negativity. If so, we might still expect to see processing consequences of ambiguity in the form of enhanced N400 potentials, reflecting a mismatch between the features automatically elicited by the incoming word and those (pre)activated by the semantic context. In Experiment 2, then, we test the prediction that N400 ambiguity effects to NV-homographs in the presence of semantic context information are modulated by meaning dominance, similar to patterns that have been seen behaviorally for within-class homographs.

Experiment 1

The aim of the first experiment is to compare the effects of syntactic and semantic context information on the resolution of ambiguity for NV-homographs, and, in particular, to determine whether the processing consequences of ambiguity are qualitatively different in the presence of syntactic and semantic constraints. To do this, we examine ERP responses to NV-homographs at the end of congruent sentences, which provide both a well-specified syntactic structure and constraining semantic information (e.g., *After walking around on her infected foot, she now had a* <u>*boil*</u>), and to the same homographs embedded in syntactic prose, which offers identical syntactic cues but is semantically incoherent (e.g., *After trying around on her important jury, she now had a* <u>*boil*</u>). To avoid the possibility of backward priming, which tends to compromise the interpretation of results obtained from targets following ambiguous words (see Van Petten and Kutas, 1987, for a discussion), we assess the processing at the critical ambiguous words themselves, comparing ERPs time-locked to the onset of NV-homographs with those to matched unambiguous words in each type of context (e.g., Congruent sentence: *In the theater, the actors rehearsed before the performance of the* <u>*drama*</u>. Syntactic prose: *In the food, the laws heated before the predator of the* <u>*drama*</u>.).

Based on our prior work using disambiguating syntactic contexts (Federmeier et al., 2000; Lee & Federmeier, 2006), we expect to see a frontal negativity for NV-homographs relative to unambiguous words in the syntactic prose condition. We also expect to replicate the long-standing finding that the availability of semantic constraints eases word processing, as reflected in reduced N400 amplitudes for critical words in the semantically coherent contexts as compared to the syntactic prose contexts (e.g. Kutas and Hillyard, 1980; Van Petten and Kutas, 1991), and we expect this to be true for both the NV-homographs and the control words. Critically, then, we will examine whether the presence of semantic constraints alters the nature of the mechanisms at work during ambiguity resolution.

Methods

Materials: Two different types of words were each embedded in two different types of contexts. Word types included **NV-homographs**, which are both syntactically and semantically ambiguous (e.g., *the watch/to watch*), and semantically and syntactically **unambiguous words** (e.g., *the logic/to choose*). These two types of words completed sentences that provided different types of contextual constraint. **Congruent sentences** (e.g., *I knew the meat needed more flavor, but found that it wasn't all that easy to season*) provided a noun- or verb-specifying syntactic frame as well as constraining semantic information. In contrast, **syntactic prose sentences** provided the same syntactic frames with no coherent semantics (e.g., *I knew the girl threatened more teammates, but commented that it wasn't all that willing to season*). Syntactic prose sentences were created by replacing the content words of each congruent sentence with randomly selected words of the same grammatical category from other congruent sentences. Across all word type and sentence type conditions, care was taken to ensure that the sentence final words were always syntactically congruent with prior context. Word type and sentence type were fully crossed, resulting in four experimental conditions. In addition to the two experimental context types, fillers were created in which the order of words from syntactic prose sentences was scrambled. Fillers thus served to make the availability of syntactic information, like the availability of semantic information, unpredictable.

Each participant read 172 sentences, including fillers. Six lists were generated to allow target words to be rotated through context types (including scrambled filler sentences), with each participant seeing each critical word only once and each viewing at least 28 sentences of each word type in each context type. Across the lists, each homograph appeared equally often as a noun and a verb (in different sentence contexts, which, in the case of congruent sentences, picked out the meaning sense appropriate to the syntactic frame in which the homograph was embedded). Unambiguous words always appeared in syntactically appropriate frames. Ambiguous and unambiguous words were both used in each type of sentence context equally often. We did not specifically look into the factor of word class in this experiment. However, within each list the number of nouns and verbs was matched across the homograph and unambiguous word sets in order to reduce the possibility of any word class influences on the ambiguity effect.

Target words were matched across conditions, globally and within each individual list, for lexical features including log frequency (Kucera & Francis, 1967), word length, and usage-specific concreteness (Lee & Federmeier, 2008). In addition, the semantic distinctiveness of the homographs – i.e., the similarity of their noun and verb meanings, as determined by a norming study (Lee & Federmeier, 2006) – was also controlled across context types. Table 1 provides the values for these lexico-semantic features.

Sentences containing unambiguous words and NV-homographs were also matched for length, cloze probability and plausibility (Table 2). The norming studies used to obtain plausibility and cloze probability are described next; participants used for the norming procedures were drawn from the same pool as that used for the ERP recordings, but no individual participated in both the norming and the experimental phase. Participants in the norming studies received course credit for their time.

Plausibility: Plausibility ratings were obtained using a paper-and-pencil norming test completed by 28 monolingual English speakers at the University of Illinois at Urbana-Champaign (19 male; mean age 19 years, range 18-21 years). A total of 301 sentences were rated, including 92 ending with NV homographs used as nouns, 92 ending with (the same) NV homographs used as verbs, 46 ending with unambiguous nouns, 46 ending with unambiguous verbs, and 25 implausible fillers. Participants were told to rate each sentence on a scale of 1-7, where 7 indicates that the sentence “makes perfect sense” and 1 indicates that the sentence “makes no sense at all”.

Cloze probability: The 276 plausible sentences rated in the plausibility norming study were also subjected to paper-and-pencil cloze probability norming, completed by 37 monolingual English speakers at UIUC (23 men; mean age 19 years, range 18–22). The sentence frames were evenly divided into two lists, with 19 participants completing one list and 18 completing the other. In the norming booklet, participants were given sentences with the last word replaced by a blank line. Next to the column of sentence frames were three columns for potential endings. Participants were asked to complete the sentence with the word they first thought of when reading each sentence in the first column. If multiple words came to mind, they were told to write down the one they think fits best in the first response column and to then list the additional endings that came to mind in the second and third response columns. Cloze probability for a given word was calculated as the percentage of people who provided that word as their first response.

The results from the plausibility and cloze probability norming were used to select the final set of 258 sentences, 172 ending with NV-homographs (one each for the noun and verb meaning of the homograph) and 86 ending with unambiguous words. Both sets of sentences contain equal number of nouns and verbs in the sentence final position. Average plausibility across the set was 6.5 and average cloze probability across the set was 50%.

Participants: Twenty-four UIUC undergraduate students (12 males; mean age 20 years, range 18–37) participated in the ERP phase of the study for cash or course credit. All participants were right-handed as assessed by the Edinburgh inventory (Oldfield, 1971); 16 reported having left handed family members. All were also monolingual speakers of English with no consistent exposure to other languages before age 5. None of the participants had a history of neurological/ psychiatric disorders or brain damage. Participants were randomly assigned to one of the six experimental lists.

Procedure: Participants were seated 100 cm in front of a 21″ computer monitor in a dim, quiet testing room. They were given written instructions and a 9-trial practice session before the experiment to familiarize them with the experimental environment and the task. At the start of each trial, a series of plus signs appeared in the center of the screen for 500 ms. After an SOA ranging randomly between 1000 and 1500 ms (jittered to lessen the influence of slow, anticipatory potentials on the average ERPs), a sentence was displayed word by word in upper case in the center of the screen. Each word was presented for 200 ms, followed by a 300 ms blank screen. At the end of the sentence, the screen went blank for one and a half second before a probe word appeared in upper case, red letters. Half of the probe words were new words; among the old probe words, half were content words chosen randomly from the sentence context (up to the final word) and the other half were the sentence final target words. Participants were instructed to judge whether or not that probe word had appeared in the immediately preceding sentence and to indicate their response by pressing one of two buttons, held in each hand; hand used to respond “yes” was counterbalanced. The probe disappeared upon the participant's button-press response. The next trial then began two and a half second after the offset of the probe. A small square (3 by 3 pixels) remained on throughout the experiment, positioned just below the center of the screen, in order to help participants keep their gaze centered.

The whole experiment was divided into eight blocks, each lasting about three minutes. A paper-and-pencil sentence recognition task was administered at the end of every two blocks. The sentence-recognition test contained 96 sentences in total, half of which were old sentences (drawn in equal numbers from both of the word types in congruent, syntactic prose, and scrambled sentence frames) and half of which were new (also consisting of equal numbers of each context type). New sentences of each type were selected from among experimental sentences on different lists. Since many of these sentences contained some of the same words as those the participant actually viewed, word level recognition alone would be insufficient to allow participants to score highly on this test. Participants were asked to check off each sentence that they thought they had seen in the previous two blocks. The word and sentence recognition tasks were used in tandem to ensure that participants were carefully attending to each individual word while also attempting to integrate those words into a holistic unit.

EEG recording and data analysis: The electroencephalogram (EEG) was recorded from twenty-six geodesically-arranged silver/silver-chloride electrodes attached to an elastic cap (Figure 1). All scalp electrodes were referenced on-line to the left mastoid and re-referenced off-line to the average of the right and the left mastoids. In addition, one electrode (referenced to the left mastoid) was placed on the left infraorbital ridge to monitor for vertical eye movements and blinks, and another two electrodes (referenced to one another) were placed on the outer canthus of each eye to monitor for horizontal eye movements. Electrode impedances were kept below 3kΩ. The continuous EEG was amplified through a bandpass filter of 0.02-100Hz and recorded to hard disk at a sampling rate of 250Hz.

Epochs of EEG data were taken from 100 ms before stimulus onset to 920 ms after. Those containing artifacts from amplifier blocking, signal drift, eye movements, or muscle activity were rejected off-line before averaging, using thresholds selected for each participant through visual inspection of the data. Trials contaminated by eye blinks were corrected for 15 participants who had enough blinks to obtain a stable filter (Dale, 1994); for all other participants, trials with blink artifacts were excluded from analysis. Trial loss averaged 13%. Artifact-free ERPs were averaged by stimuli type after subtraction of the 100 ms pre-stimulus baseline. Prior to statistical analyses, ERPs were digitally filtered with a bandpass of 0.2–20 Hz. To correct for violations of sphericity associated with repeated measures, the Huynh–Feldt adjustment to the degrees of freedom was applied for each analysis of variance (ANOVA). Consequently, for all F tests with more than 1 degree of freedom in the numerator, the corrected p value is reported. For all analyses, main effects of electrode and interactions with electrode sites are not reported unless they are of theoretical significance. We also report 95% confidence intervals (CI) around the difference of the means, which were calculated based on the mean squared errors of the relevant effects from the particular analysis.

Results

Behavior

Behavior: ***Word recognition task:*** Overall accuracy for the word recognition task was 98%, showing that participants were reading the sentences carefully enough to remember individual words. Participants' performance was assessed using the discriminability index d′. Memory performance was better for words in congruent sentences than for words in syntactic prose: d′ scores for probes from sentences containing ambiguous and unambiguous critical words were 2.90 and 2.90, respectively, in the congruent condition, and 2.82 and 2.75 in the syntactic prose condition. An omnibus analysis of variance (ANOVA) with two levels of Ending Word Type (sentences ending with unambiguous and ambiguous critical words) and two levels of Context Type (congruent and syntactic prose) revealed a significant main effect of Context Type [$F(1,23)=7.24$; $p=.01$; $D_{(congruent-sytactic)}=.116$, 95% CI= (.027, .206)] but no main effect of Ending Word Type or significant interaction between the two factors.

Sentence recognition task: Overall accuracy for the sentence recognition task was 93%, again attesting to participants' engagement with the task and showing their ability to integrate the words and encode the sentences as a unit. D′ scores again revealed better memory performance for congruent sentences (2.53 and 2.57, respectively, for sentences ending with ambiguous and unambiguous critical words) than for syntactic prose (1.70 and 1.96). Similar to the results of the word recognition task, an ANOVA with two levels of Ending Word Type and 2 levels of Context Type revealed a significant main effect of Context Type on d′ scores [$F(1,23)=89.38$; $p<.0001$; $D_{(congruent\text{-}sytactic)}=.726$, 95% CI= (.568, .885)], but no main effect of Ending Word Type or interaction between the two factors.

In summary, the behavioral data show that participants read and integrated the words in the experimental sentences. Additionally, the data revealed that the addition of semantic constraints to syntactic ones aided memory in both a short-term word-level memory test and a long-term sentence-level memory test, and did so similarly for sentences ending with NV-homographs and with unambiguous words.

ERPs: ERP responses to sentence-final NV-homographs and unambiguous words in the syntactic prose (left panel) and congruent (right panel) sentences are shown in Figure 2 at a representative sample of scalp channels. All conditions were characterized by early perceptual components typical for visual stimuli, followed, between 250 and 500 ms, by a broadly-distributed negativity with a centro-posterior focus that peaks around 400 ms (N400), which appears notably reduced in congruent as compared with syntactic prose sentences.

Semantic context vs. syntactic context: Replicating the well-established pattern (e.g., Van Petten and Kutas, 1991), N400 amplitudes to final words in congruent sentences are globally reduced relative to those in syntactic prose sentences, reflecting the buildup of message-level semantic constraints in the congruent condition (shown more clearly in Fig. 3). As expected, this reduction is seen for both ambiguous and unambiguous words. An omnibus ANOVA with 2 levels of Context (congruent sentences and syntactic prose), 2 levels of Ambiguity (ambiguous and unambiguous words), and 11 levels of central/posterior Electrode Site (including MiCe, LMCe, RMCe, LDCe, RDCe, MiPa, LDPa, RDPa, MiOc, LMOc, and RMOc) was conducted on mean amplitudes between 250-500 ms (this is the time window and electrode distribution most typical for characterizing N400 effects). The results revealed a main effect of Context [$F(1,23)=41.25$; $P=<.0001$; $D_{(syntactic–congruent)}= 2.738$, 95% CI= (1.856, 3.62)], with smaller (more positive) N400s in congruent sentences (mean amplitude 3.93μV) than in syntactic prose (mean amplitude 1.20 μV). The effect of Context did not interact with Ambiguity [$F<1$], which had a marginal main effect ($p=.06$) reflecting a tendency for larger N400s to ambiguous than unambiguous words.

NV homographs vs. unambiguous words in syntactic prose sentences: In the syntactic prose sentences, as predicted, an effect of ambiguity can be seen in the form of a frontally-distributed negativity, beginning around 200 ms after stimulus onset and continuing to around 700 ms (when a contingent negative variation (CNV) begins to develop, reflecting participants' expectation for the upcoming probe word). The direction, timecourse, and distribution of this effect replicate that previously reported for semantically and syntactically ambiguous words embedded in neutral sentence contexts (Federmeier et al., 2000) and bare phrases (Lee & Federmeier, 2006). To characterize this effect, mean amplitudes between 200 and 700 ms were subjected to an omnibus ANOVA with 2 levels of Ambiguity (ambiguous and unambiguous words), 2 levels of Anteriority (anterior electrode sites, including MiPf, LLPf, RLPf, LMPf, RMPf, LDFr, RDFr, LMFr, RMFr, LLFr, and RLFr, and central/posterior electrode sites, including MiCe, LMCe, RMCe, LDCe, RDCe, MiPa, LDPa, RDPa, MiOc, LMOc, and RMOc[1]) and 11 levels of Electrode Site. There were no main effects, but there was a significant interaction between Ambiguity and Anteriority [$F(1,23)=5.34$; $P<.05$]. The contrast estimate for this interaction showed greater ambiguity effect over the anterior region than posterior [D=.667, 95% CI= (.07, 1.265)]. This finding was buttressed by follow-up analyses conducted separately over anterior and central/posterior electrode sites, which revealed that the effect of Ambiguity was significant over anterior [F(1,23)=4.65; P<.05; $D_{(amb\ –unamb)}$=-.728, 95% CI= (-1.426, -.03)] but not central/posterior [F < 1; $D_{(amb\ –unamb)}$=.06, 95% CI= (-.688, .808)] electrode sites.

NV homographs vs. unambiguous words in congruent sentences: A different pattern arises when the same words are embedded in congruent sentences, which contain semantic as well as syntactic information. The same analysis as conducted for the syntactic prose sentences revealed no reliable effect of Ambiguity for mean amplitude responses over frontal sites between 200-700 ms [F < 1; $D_{(amb\ –unamb)}$= -.267, 95% CI= (-.714,.181)]. In contrast, differences between the unambiguous and ambiguous conditions were apparent as changes in the amplitude of the N400 component. Analyses were then conducted in the N400 time window (250-500 ms) over central/posterior electrode sites where N400s are most prominent. An ANOVA with two levels of Ambiguity and 11 levels of Electrode Site revealed significantly more negative responses to NV-homographs than to unambiguous words [F(1,23)=4.58; P=<.05; $D_{(amb\ –unamb)}$= -1.24, 95% CI= (-2.438,-.041)].

The results are summarized in the graph in Figure 4, which shows the strikingly different scalp distribution of the effects of the ambiguity manipulation in the two sentence types. As predicted from prior work (Federmeier et al., 2000;Lee & Federmeier, 2006), NV-homographs embedded in syntactically well-specified contexts elicited a sustained frontal negativity between 200 and 700 ms post-stimulus-onset. When additional semantic constraints were available for disambiguation, this effect is greatly reduced and is not statistically reliable. However, the additional semantic context information did lead to a N400 response difference between NV-homographs and unambiguous words, with the former being more negative than the latter in the central/posterior region during the N400 time window. The dissociability of these effects is supported by the outcome of an omnibus ANOVA with two levels of Context (congruent sentences and syntactic prose), two levels of Ambiguity (ambiguous and unambiguous words), two levels of Anteriority (anterior and central/posteriorelectrode sites) and 11 levels of Electrode Site, performed in the 250-500 ms time window during which both effect types were evident. There were main effects of Context [F(1,23)=32.68; P=<.0001; $D_{(congruent\text{-}syntactic)}$=2.116, 95% CI= (1.35, 2.881)] and Ambiguity [F(1,23)=6.54; P=<.05; $D_{(amb\ –unamb)}$= -.699, 95% CI= (-1.264, -.133)]. In addition, there was an interaction of Context and Anteriority [F(1,23)=18.87; P=<.001; Contrast Estimate=-1.244, 95% CI= (-1.837, -.652)], and, most importantly, a three way interaction between Context, Ambiguity, and Anteriority [F(1,23)=8.11; P=<.01; Contrast Estimate=1.536, 95% CI= (.42, 2.652)].

Discussion—As expected, the results in the syntactic prose condition replicated prior work showing that NV-homographs with distinct meanings associated with their noun and verb usages elicit a prolonged (200-700 ms) frontal negativity. This frontal effect has proven to be quite replicable across different types of syntactically constrained but semantically neutral contexts, being seen for NV-homographs embedded in bare syntactic phrases (Lee & Federmeier, 2006), in mid-sentence position of normal but semantically neutral sentence contexts (Federmeier et al., 2000), and, in the current study, at the end of semantically incoherent but structured sentences (syntactic prose).

The precise role of the frontal negativity in ambiguity resolution is still not yet completely understood. However, in addition to being linked to the processing of semantically and/or

[1]The same division into anterior and central/posterior electrode sites and the same sets of electrodes will be used for all subsequent analyses.

referentially ambiguous words, sustained frontal negativity has been related to working memory demands (King & Kutas, 1995) and to control processes related to maintaining and selecting among candidate items during recollection (Rugg, Allan & Birch, 2000). Moreover, although the scalp topography of an ERP effect cannot be used to make direct inferences about its brain source, data from other imaging methods point to a possible functional link between the frontal negativity and selection-related activity observed in frontal brain areas. Several hemodynamic imaging studies have found frontal activation (for example, in the inferior frontal gyrus) associated with the resolution of lexical ambiguity (Gennari, MacDonald, Postle & Seidenberg, 2007; Mason & Just, 2007; Rodd et al., 2005; Zempleni et al., 2007). In particular, Gennari et al. (2007) used NV-homographs embedded in minimal syntactic phrases (e.g., *to/the bowl*) – thus, very similar to the design of Lee and Federmeier (2006) – and found activations in the left inferior frontal gyrus (LIFG) that they linked to selection among competing semantic attributes.

Results like these are buttressed by neuropsychological data linking frontal lobe damage to deficits in semantic tasks related to resolving ambiguity or selecting relevant representations among competitors (Metzler, 2001; Randolph, Braun, Goldberg & Chase, 1993; Robinson, Blair & Cipolotti, 1998; Swaab, Brown & Hagoort, 1998), especially when selection demands are high (Thompson-Schill et al., 1998). In turn, these findings are consonant with the results of imaging studies using more general memory or judgment-related tasks, which have linked frontal areas, especially in the left hemisphere, to the selection of task-relevant semantic (Badre, Poldrack, Pare-Blagoev, Insler & Wagner, 2005; Gennari et al., 2007; Thompson-Schill, D'Esposito, Aguirre & Farah, 1997; Thompson-Schill, D'Esposito & Kan, 1999) or in some cases, syntactic (Mason, Just, Keller & Carpenter, 2003; Stowe, Paans, Wijers & Zwarts, 2004), information from irrelevant competing representations. This body of data thus suggests that the frontal negativity that is elicited by NV-homographs preceded by syntactic cues may index a selection-related mechanism (although possibly not specific to semantics or even to language) recruited in the process of lexical ambiguity resolution.

Of critical interest for the present study was whether, with the addition of disambiguating semantic context information, the same effect patterns would arise as following syntactic information alone. The general effectiveness of our semantic contexts for facilitating word processing was apparent in our replication of the well-established finding that the N400, an ERP component that comprises part of the normal response to words and that has been linked to relatively implicit aspects of meaning apprehension (for a review, see, e.g., Federmeier & Laszlo, in press), was reduced in amplitude for words in the presence of semantic constraints as compared with those in syntactic prose sentences (c.f., Van Petten and Kutas, 1991); as expected, this reduction was seen for both the ambiguous as well as the unambiguous words.

Importantly, in conjunction with this general facilitation for word processing, was a qualitative change in the impact of ambiguity. Strikingly, and confirming our predictions, there was no reliable evidence of frontal negativity for the NV-homographs in the semantically and syntactically congruent sentences. Thus, the accumulated activation/preactivation of semantic information afforded by a constraining, congruent context seems to “resolve” the ambiguity associated with NV-homographs, in the sense of mitigating the need for recruitment of the kind of selection mechanisms indexed by the frontal negativity. The result is a qualitative change in the processing associated with lexical ambiguity.

In the literature on lexical ambiguity resolution, there has often been a tacit assumption that whenever features associated with divergent senses of an ambiguous word become active simultaneously, there will be competition and/or selection demands. The primary comparison, therefore, has been between situations in which ambiguity is associated with processing costs (generally in the form of reaction time slowing), which are typically treated as if they are unitary in nature, and those situations showing a pattern consistent with selective access. However, the data from the present experiment call these assumptions into question. The presence of semantic context information eliminated one effect of ambiguity – the frontal negativity – yet quantitative differences between the word types, in the form of differential N400 amplitudes, remained.

The observed pattern suggests that, even when lexical features, sentence length, and cloze probability are matched, ambiguous homographs do not match their contexts as well as do unambiguous words. It seems likely that this reduced match arises because meaning features of the contextually-irrelevant sense of the homographs continue to become automatically activated. When semantically constraining context information is available, therefore, the processing consequences of lexical ambiguity seem quite similar to those entailed by the processing of any word whose features are less predictable in a given context – for example, if the sentence context *"He licked the last drops of ice cream off of his …"* were ended with the word *fork* as opposed to the word *spoon*. The word *fork* would be expected to elicit a larger N400 response, not because its meaning is unclear or because of competition or selection demands, but simply because some of its features cohere less well with the context than do the features of *spoon*. If contextually irrelevant features of homographs automatically become active to some degree in response to the presentation of an ambiguous wordform, then larger N400 responses would be expected to those words, and this would be true even under circumstances in which a prevailing match between contextually-predicted features and those of the contextually-appropriate sense of the homograph allows for meaning selection without the need for recruitment of additional processing resources.

A remaining question, then, is whether the activation of contextually-irrelevant meaning features of ambiguous words is moderated by meaning dominance, as suggested by the patterns of processing costs seen in the behavioral literature looking at the processing of NN-homographs in semantic contexts (Paul, Kellas, Martin & Clark, 1992; Tabossi, 1988; Tabossi & Zardon, 1993; Rayner, Pacht & Duffy, 1994; Duffy, Kambe & Rayner, 2001). In turn, this behavioral pattern is consistent with predictions of prominent accounts of lexical ambiguity resolution (e.g., Hogaboam & Perfetti, 1975; Duffy, Kambe & Rayner, 2001), which would suggest that processing consequences of ambiguity should be limited to cases in which the context picks out a nondominant meaning sense of the homograph. In contrast, processing of the dominant meaning would be expected to pattern like that for unambiguous words.

In the present study, the congruent contexts were mixed, with some picking out the dominant and some the subordinate senses of the NV-homographs. Individual participants did not see enough congruent items to look at these conditions individually (and they were not matched for lexical or sentential factors), so it is not possible to determine if the effect interacts with meaning dominance. In Experiment 2, therefore, we set out to (1) replicate the N400 difference between NV-homographs and unambiguous words under more naturalistic processing conditions (when all sentences are congruent) and (2) examine whether this difference depends on whether sentence contexts pick out the dominant or nondominant meaning of the ambiguous words.

Experiment 2

To test whether meaning dominance affects the N400 difference between ambiguous and unambiguous words observed in Experiment 1, in Experiment 2 participants read congruent sentences, half of which ended with unambiguous words and half with NV-homographs, which, in turn, were divided into sets biased toward the dominant or a nondominant meaning. Lexical and sentence-level variables were matched across all conditions. We expect to replicate the finding that N400 amplitudes are larger overall to ambiguous than unambiguous words. We also predict that these differences will be larger for sentences that bias toward the nondominant meaning of the ambiguous word.

Methods

Materials: 162 congruent sentences were chosen from the stimulus set used in Experiment 1. Half of the sentences ended with NV-homographs, and the other half ended with unambiguous words. The lexical features of the sentence-final words and the sentential features of the carrier sentences were matched between the ambiguous and unambiguous words (shown in the two right most columns in Table 3).

Sentences ending with ambiguous words were divided into two subsets according to whether the contextually appropriate interpretation of the NV-homograph was or was not its dominant meaning sense. Meaning dominance was determined using the sense frequency listed on the English WordNet 3.0 online database (see Fellbaum, 1998); on average, the dominant interpretations were 6.4 times more frequent than the subordinate interpretations. Lexical and sentential features for these items were also matched (see Table 3). Independent *t*-tests on the means of these features revealed a significant difference ($p = .03$) only for concreteness (all other p values > .1), with dominant senses rated as slightly more concrete than non-dominant senses. The effect of concreteness has been found to be attenuated in congruent sentences (Schwanenflugel & Shoben, 1983). Furthermore, critically, the N400 pattern predicted by the concreteness difference (i.e., larger N400 for more concrete senses of words) would act to reduce rather than enhance our chances of finding the predicted pattern (i.e., larger N400 for non-dominant than dominant meaning senses).

Participants: Twenty-four UIUC undergraduate students (12 males, mean age 19 years, range 18-22 years) participated in this study for cash or course credit. All met the same exclusion criteria as used for Experiment 1; 7 reported having left handed family members.

Procedures: Procedures were identical to Experiment 1.

Results

Behavior: Overall accuracy on the word recognition task (98%) and the sentence recognition task (89%) was comparable to that obtained for congruent sentences in Experiment 1. D′ scores did not differ between NV-homographs and unambiguous words in the word recognition task: 3.90 and 3.88, respectively [F=1]. For the sentence recognition task, sentences ending with NV-homographs were remembered slightly better than those ending with unambiguous words (d′ scores: 2.96 and 2.73, respectively; [$F(1,23)= 7.78$; $P=.01$; $D_{(amb\text{-}unamb)}= .231$, 95% CI= (.06, .402)]. As in Experiment 1, then, the behavioral data indicate that participants read and integrated the words in the experimental sentences.

ERPs: Figure 5 shows the ERP responses to unambiguous and ambiguous words. Analyses were first performed on the overall ambiguity effect (shown in the left-most column of Figure 5) as in Experiment 1. There was no difference in mean amplitude response between 200-700 ms over frontal channels for ambiguous as compared with unambiguous words [$F(1,23)= 1.52$; $P=.2$; $D_{(amb\text{-}unamb)}= -.267$, 95% CI=(-.714, .181)]. However, the response to ambiguous words was more negative between 250-500 ms over central/posterior channels (N400) [$F(1,23) =17.54$; $P<.001$; $D_{(amb\text{-}unamb)}= -.753$, 95% CI= (-1.126, -.381)]. Thus, replicating Experiment 1, there was no evidence for a frontal negativity to NV-homographs embedded in congruent sentences, but these ambiguous items did elicit larger N400s than unambiguous items.

The right side of Figure 5 shows the comparison between the unambiguous and ambiguous word types, split into cases in which the sentence contexts picked out the dominant interpretation of the NV-homograph (middle column) versus the non-dominant interpretation (right-most column). As predicted, the ambiguity effect on the N400 seems to obtain only for cases in which the context points to the non-dominant interpretation of the homograph. The statistics confirm the visual impression: responses to NV-homographs used in their nondominant meaning senses are more negative (250-500 ms, central/posterior channels) than those to unambiguous words [$F(1,23)=17.38$; $P<.001$; $D_{(amb\text{-}unamb)}= -1.057$, 95% CI= (-1.581, -.533)], whereas N400 responses to NV-homographs used in their dominant meaning senses are indistinguishable from those to unambiguous words [$F < 1$; $D_{(amb\text{-}unamb)}= -.082$, 95% CI= (-.743, .579)].

Discussion—Replicating the pattern in Experiment 1, we found that NV-homographs embedded in congruent sentence contexts elicited larger N400s than did unambiguous words. This replication of the effect across the two experiments makes clear that the pattern observed in Experiment 1 was not an artifact of the fact that congruent sentences were mixed with syntactic prose and scrambled sentence types. Even when all sentences read by a participant are both syntactically and semantically congruent, NV-homographs elicit larger N400 responses than do matched unambiguous words.

Moreover, the results of Experiment 2 show that this effect is strongly modulated by meaning dominance, similar to patterns seen in the behavioral literature. When context selects a **non-dominant** meaning sense, N400 responses are larger to ambiguous than to unambiguous words, even when these are embedded in equivalently constraining contexts (as cloze probabilities and plausibility were matched across all conditions). However, the processing of the **dominant** meaning sense of an NV-homograph in the presence of supportive syntactic and semantic context information seems to unfold in a manner indistinguishable from that to unambiguous lexical items. As discussed, this data pattern is consistent with the predictions of prominent theories of lexical ambiguity resolution, such as the reordered access model (Duffy et al., 2001), but, in combination with what is known about the functional nature of the N400, provides additional constraints on those accounts.

The reordered access model (Duffy et al., 1988) assumes that, out of context, multiple meanings of ambiguous words become active, to a degree proportional to their meaning dominance. Context, then, can serve to modulate – i.e., “reorder” – these activation strengths. In a dominant-biased context the combination of a high meaning frequency and contextual support would be expected to lead to strong, rapid access of the dominant meaning, consistent with the observed N400 pattern. A context biased toward a non-dominant meaning, instead, will tend to boost the activation of that non-dominant meaning, making it more similar to the activation level of the dominant meaning.

This increased similarity in the activation levels of the two meanings has sometimes been argued to enhance the “competition” between them (Duffy et al., 2001). On this view, then, N400 amplitude could be taken to index the level of competition between simultaneously active meanings. However, the larger N400 literature suggests that this explanation may be unlikely. Studies comparing N400 amplitudes to plausible but unexpected words in strongly constraining sentences (which tend to strongly activate a single, preferred ending) and weakly constraining sentences (which do not tend to pick out any particular meaning) have found N400 effects of similar size. (Federmeier, Wlotko, De Ochoa-Dewald & Kutas, 2007; Kutas & Hillyard, 1984). Thus, N400 amplitudes do not seem to be sensitive to the presence of semantic “competitors” (such effects emerge, instead, in later parts of the ERP waveform).

Instead, an explanation that we take to be most consistent with the larger literature on the N400 component (see, e.g., Kutas & Federmeier, 2000) is that N400 amplitudes reflect the degree of match between the features set up by the context information and the features automatically elicited by the incoming word – which, in the case of ambiguous words, are biased towards those associated with the dominant meaning sense (Duffy et al., 2001; also see Hogaboam & Perfetti, 1975). Larger N400 responses would thus be expected for ambiguous targets in contexts that point to the nondominant meaning of the homograph, since the activated features associated with the dominant meaning would mismatch the semantic constraints established by the sentence contexts. Importantly, however, this mismatch does not seem to create the kind of selection demands that exist in semantically impoverished contexts, since the frontal negativity is not observed in semantically well-specified contexts, even when it is the subordinate meaning that is being selected. Presumably, constraining semantic context information that activates or preactivates subordinate-associated features, combined with the featural information elicited by the word itself, creates a sufficiently robust and stable activation state to mitigate the need for additional selection-related resources even in the face of residual automatic activation of dominant-associated meaning features. Thus, “selection” of a given sense of an ambiguous word need not entail fully selective access, in the form of activation limited to a single meaning.

General Discussion

In sum, ambiguity effects associated with NV-homographs manifest in two different electrophysiological patterns. A frontal negativity is observed when NV-homographs are embedded in syntactically well-defined but semantically impoverished contexts. Syntactic cues alone thus seem to be insufficient to allow the system to rapidly select one of the two disparate meanings associated with the different word class uses of these words. This is surprising in some ways, as syntactic information is generally thought to be deterministic in nature (and thus quite constraining) and available rapidly (Friederici, 1999, 2002). On the other hand, because word class usage and meaning sense can sometimes be dissociated (e.g., in the gerund form: *the registering student* …), the comprehension system may not be able to use syntactic cues as a reliable cue for selecting the meaning features of these cross-class ambiguous words. The addition of semantic constraints, however, greatly reduces the frontal negativity – even in cases where the contexts picked out the homographs' non-dominant meaning sense. The availability of semantic information, therefore, clearly changes the processing of lexically ambiguous words, arguably reducing selection demands. However, a different effect of ambiguity can be seen when the additional semantic constraints are available. In particular, larger N400 responses are observed when participants access and integrate the nondominant meaning senses of NV-homographs, likely due to the mismatch between context-related semantic features that have been activated throughout the course of the context and the residual activation of meaning features associated with the contextually-inappropriate dominant sense of the word.

The results across this pair of experiments are thus coherent with general findings in the literature on lexical ambiguity resolution and help to resolve some of the disparate conclusions that have been drawn across studies that have looked at different types of ambiguous words in different types of contexts. In the context of what is known about the neural bases and functional sensitivity of the electrophysiological responses under investigation, these data also provide a new perspective for interpreting some long standing effects. Consistent with behavioral literature on the influences of preceding syntactic and/or semantic context on ambiguity resolution (e.g. Seidenberg et al. 1982; Rayner, Pacht & Duffy, 1994), our data show that neither syntactically nor semantically constraining context information can completely prevent the activation of alternative meanings in all circumstances. Extending this literature, our data further suggest, however, that similar behavioral processing costs (lengthened response times) for ambiguity resolution in different context types can arise from qualitatively different underlying neural mechanisms.

In particular, when syntactic constraints demand selection of a particular meaning (i.e., when ambiguity resolution cannot be done on the basis of meaning frequency alone, as might be true out of context), and no biasing semantic constraints are available, determining the appropriate interpretation of the ambiguous word form necessitates the recruitment of additional, selection-related resources (indexed by the sustained frontal negativity). In contrast, when the context provides constraining semantic information, which facilitates the semantic access of words in general (as shown in the massive N400 reduction for unambiguous words, as well as both the dominant and nondominant interpretation of ambiguous words, in congruent contexts; Fig. 3 and Fig. 5), the selection demand is mitigated, such that settling down from multiple activated meanings to a single interpretation can be done more automatically, without recruitment of the selection-related resources manifested in the frontal negativity. During the more automatic ambiguity resolution that is afforded by semantic context information, however, there can nevertheless still be residual levels of activation for contextually inappropriate meaning features, leading to reduced N400 facilitation for ambiguous as compared to unambiguous words. This N400 "mismatch effect" is most apparent when the context favors the nondominant meaning, and is minimal or even nonexistent when the context favors the dominant meaning, presumably because bottom-up activation tends to be stronger for higher frequency meanings. Critically, this N400 mismatch effect is not an ambiguity-specific phenomenon, as similar effects are seen for unambiguous words that contain features that are unpredictable within a given context. This is importantly different from what would have been assumed based on prevailing views of lexical ambiguity resolution.

In particular, aspects of our data are consistent with the reordered access model, which hypothesizes that purely selective access does not occur, but that context can facilitate the access of the intended meaning, without affecting the activation of the unintended meaning. In the context of this model, however, processing costs (such as lengthened gaze durations) for ambiguous words in subordinate-biased contexts have been interpreted as a reflection of selection-related competition – and thus qualitatively similar to costs obtained when semantic context information is not available. Our data suggest instead that these costs reflect general processing mechanisms, at more automatic stages of processing, rather than ambiguity-specific competition, and thus are different from ambiguity-related processing costs seen under other circumstances.

The view of ambiguity resolution suggested by the effects observed in this pair of experiments coheres with data from studies using hemodynamic brain imaging methods to examine lexical ambiguity resolution; indeed, the present data help to clarify what might initially appear to be disparities in the findings across those studies. As reviewed in the introduction of this article, brain imaging studies have uncovered two major clusters of activation during the processing of ambiguous words, one in the left inferior frontal gyrus and one in the temporal lobes (especially left middle temporal gyrus) (Gennari et al., 2007; Ihara et al., 2007; Rodd et al., 2005; Zempleni et al., 2007). Activation in the left inferior frontal gyrus has been reported across studies that have set up conditions in which ambiguous words occurred with very little prior disambiguating semantic information (Zempleni et al., 2007; Gennari et al., 2007; Ihara et al., 2007; Rodd et al., 2005). These contexts are thus similar to those that, in our electrophysiological work, have consistently elicited sustained negativity with a frontal scalp distribution. In light of research suggesting that the LIFG subserves a mechanism for attentionally-mediated selection and/or controlled semantic retrieval (Badre et al., 2005; Novick, Trueswell, & Thompson-Schill, 2005; Thompson-Schill, Bedny & Goldberg, 2005), the role of the LIFG in lexical ambiguity resolution has been interpreted as a top-down mechanism for actively selecting a contextually appropriate meaning of the ambiguous word.

Enhanced temporal lobe activity, on the other hand, has been observed under more restricted circumstances and has been shown be modulated by meaning dominance (Zempleni et al., 2007). For example, Zempleni and colleagues found greater bilateral activation in the inferior and middle temporal gyri in sentences instantiating the subordinate meaning of ambiguous words. However, no differences between the dominant-biased sentences and unambiguous control sentences were found in these areas. This is the same pattern as the one we observed in the present study on the N400 to words in semantically constraining sentence contexts, and, in fact, temporal lobe activity is also believed to be an important source of scalp-recorded N400 activity, as evidenced by data from intracranial recording studies (Elger et al., 1997; Halgren, Baudena, Heit, Clarke & Marinkovic, 1994; McCarthy, Nobre, Bentin & Spencer, 1995; Nobre & McCarthy, 1995). The temporal lobe has been viewed as the storage site for long-term semantic knowledge, accessed during the bottom-up processing of meaningful stimuli like words (Badre et al., 2005; Thompson-Schill et al., 1999). Enhanced temporal lobe activation to lexically ambiguous stimuli has therefore been interpreted as reflecting lexico-semantic processing, semantic integration (Gennari et al., 2007; Rodd et al., 2005) or, more specifically, the consequence of mismatch between the semantic features associated with the dominant meaning of an ambiguous wordform and the meaning features highlighted by a context that is biased toward the nondominant meaning of that word (Zempleni et al., 2007).

The larger literature further suggests that there may be a cooperative interplay between these brain areas and mechanisms. In particular, recruitment of controlled selection mechanisms in frontal brain areas has been found under circumstances in which the information available through more automatic semantic processing mechanisms in temporal lobe areas seems insufficient to meet task demands (Badre & Wagner, 2002) or when the task requirements call for sustained access to content in temporal regions (Noppeney, Phillips, & Price, 2004). This view is consistent with the pattern observed in our electrophysiological studies, and our data further suggest that such recruitment can happen fairly quickly and in parallel with more automatic aspects of meaning processing, given that the temporal onset of the frontal effect coincides with when (as suggested by the timing of the N400) information about a word's meaning features is just beginning to become available (cf., Federmeier et al., 2000; Lee & Federmeier, 2006). That this effect has a more sustained time course than the N400 is consistent with its characterization as an effortful, controlled process. This frontal effect is not seen, however, in congruent contexts because, with the availability of disambiguating semantic information accrued over the course of a sentence, many of the semantic attributes of the contextually-favored interpretation of ambiguous words will have been pre-activated before the orthographic forms are apprehended. This reduces selection demands, presumably by creating a stable state within the more automatic, temporal lobe processing areas – a state that then might be thought of as constituting “meaning selection”. As shown in our data, as well as other brain imaging studies, such mitigation of demands on controlled selection can occur even when there is some degree of residual, automatic activation (as seen in increased temporal lobe activity and larger N400 responses) of the contextually inappropriate sense of the homograph – that is, coactivation of multiple senses does not necessarily entail competition or selection demands.

Note that although in the current experiment ambiguity effects manifested as either a frontal negativity or an N400 difference, but never both, these need not be mutually exclusive. It is conceivable that sentences with weaker semantic constraints than those used in the current experiments might yield a pattern in which both types of effects were visible – that is, where N400 responses were facilitated to some degree, and more so for dominant senses and unambiguous words than for subordinate, but at a level in which controlled selection resources were still called upon, resulting in a frontal negativity despite the presence of semantic context information. What the data from the present study clearly show, however, is that lexical ambiguity can be resolved in functionally and neurally different ways, through the recruitment of top-down executive processes or during more automatic aspects of semantic processing, and

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that which mechanism(s) are used is related to the nature and the strength of the available context information.

The electrophysiological data thus help to link findings from behavioral and eyetracking studies with those from neuroimaging studies, suggesting that multiple neural mechanisms are involved in lexical ambiguity resolution and that the nature of the information provided by different types of context is important for determining when and how these mechanisms are recruited. Successful lexical ambiguity resolution requires that neurocognitive resources be rapidly allocated and coordinated in a manner appropriate to the demands of the task and the varying constraints provided by syntactic, semantic, and lexical context information.

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Appendix

Homographs					
BEAR	DRAFT	JAM	PASS	SEASON	TIRE
BLUFF	DRAW	KEEP	PERMIT	SENTENCE	TOLL
BOIL	DRILL	KID	PICK	SERVE	TOP
BOX	DUCK	LAP	POINT	SHED	TRACK
BREAK	EXCUSE	LITTER	POUND	SHELL	TRAIN
BUG	FAN	LOBBY	PROFILE	SINK	TRIP
CHANNEL	FAST	MATCH	RANGE	SOCK	TRUST
CHARGE	FAULT	MATTER	*RAT*	SPELL	TYPE
COMBINE	FENCE	*MELT*	RATE	STABLE	WATCH
CONDITION	FIGURE	*MIND*	RECALL	STALK	WIND
CONTRACT	FIRE	MOON	RECESS	STAND	WORM
CRUSH	FLOAT	MUG	REST	STICK	
DATE	FLY	NOTICE	*ROCK*	SWALLOW	
DEAL	*INSTITUTE*	PAGE	RULE	SWAMP	
DIE	ISSUE	PARK	SCALE	TERM	

Some homographs (institute, melt, mind, rat, and rock) were not included in Experiment 2 in order to obtain an optimal match for various lexical and sentential features across unambiguous words, homographs with a dominant interpretation and homographs with a subordinate interpretation.

Examples sentences ending with noun/verb homographs (a: congruent sentences; b: corresponding syntactic prose sentence)

Context instantiating the dominant meaning

1. a. He was excited about Sunday's football game, but seeing his team lose was painful to watch.

- **b.** He was proven about something's bottom court, but seeing his class turn was light to watch.

2.
- **a.** One crucial way to prevent a virus attack is to know which websites you can trust.
- **b.** One favorite book to follow a ceiling accident is to catch which people you can trust.

3.
- **a.** None of the berries looked very appetizing, so the man didn't know which to pick.
- **b.** None of the soldiers got very new, so the car didn't get which to pick.

4.
- **a.** We seemed to spend a lot of time idling around, just waiting for time to pass.
- **b.** We drank to get a foot of stadium coming around, just trying for boy to pass.

5.
- **a.** To treat my tooth cavity, the dentist will first have to drill.
- **b.** To make my room job, the coach will first have to drill.

6.
- **a.** She went to the deli to buy turkey and bought one pound.
- **b.** She went to the cat to roast year and discovered one pound.

7.
- **a.** You can usually find the registration desk of a hotel in the lobby.
- **b.** You can usually install the math student of a day in the lobby.

8.
- **a.** He didn't complete his homework again, and the teacher told him she wouldn't accept another excuse.
- **b.** He didn't know his judge again, and the sum told him she wouldn't search another excuse.

9.
- **a.** My grandpa said he hadn't played that game since he was a kid.
- **b.** My board said he hadn't called that volcano since he was a kid.

10.
- **a.** She wanted more privacy in her yard so she built a fence.
- **b.** She got more root in her document so she pulled a fence.

Context instantiating the non-dominant meaning

11.
- **a.** Balancing a tray of wine glasses, the waitress hoped that she would not trip.
- **b.** Balancing a station of family parents, the brain learned that she would not trip.

12.
- **a.** A nurse came running, but it was the doctor that we had been trying to page.
- **b.** A shop began dying, but it was the cd that we had been searching to page.

13.
- **a.** As the ball flew toward the girl's head, her friend told her to duck.
- **b.** As the animal went toward the artifact's body, her resident told her to duck.

14.
- **a.** The criminal searched for someone in the subway station who appeared wealthy whom he could mug.
- **b.** The report lived for someone in the husband stove who got good whom he could mug.

15.
- **a.** The battery of my phone was dying, so I had to quickly plug it in to charge.

b. The employee of my birthday was looking, so I had to quickly put it in to charge.

16. **a.** He really liked the magazine and couldn't wait for the next issue.

b. He really asked the height and couldn't stay for the first issue.

17. **a.** When it was time to light the candles on the birthday cake, she asked me for a match.

b. When it was time to play the students on the lunch document, she wanted me for a match.

18. **a.** When turtles sense a predator, they retreat back into their shell.

b. When bowls sing an employer, they want back into their shell.

19. **a.** He said the long, graceful bird was called a swallow.

b. He realized the young, English life was assigned a swallow.

20. **a.** During the medieval castle tour, the man learned that the strongest part is the keep.

b. During the painful hook time, the flat knew that the best movie is the keep.

Example sentences ending with unambiguous words (a: congruent sentences; b: corresponding syntactic prose sentence)

1. **a.** He got the wrong number, so his calculations must have had an error.

b. He bought the ready day, so his girls must have had an error.

2. **a.** His job at the store was his only source of income.

b. His lot at the submarine was his big pet of income.

3. **a.** According to the school paper, this year the club only had one new member.

b. According to the popcorn tool, this month the tape only had one nervous member.

4. **a.** Tenants in the apartment have to pay rent on the first day of every month.

b. Eggs in the night have to label hammer on the first paw of every month.

5. **a.** After she lost her assignment and failed the test, she was in a bad mood.

b. After she received her turkey and built the graduation, she was in an impossible mood.

6. **a.** The idea hadn't been proven, but it was a good theory.

b. The kitchen hadn't been found, but it was a sore theory.

7. **a.** People said that the older man was a much better athlete in his youth.

b. Clothes thought that the bigger thing was a much older lot in his youth.

8. **a.** The box was so heavy it must have weighed a ton.

b. The game was so easy it must have matched a ton.

9. **a.** When he went to court he swore to tell the truth.

b. When he wanted to ring he decided to wear the truth.

10. **a.** A large ship or submarine is often called a vessel.

b. A nice painting or baby is often considered a vessel.

11. **a.** When the babysitter arrived, my parents told my little brother to behave.

b. When the time went, my muscles warned my boring collection to behave.

12. **a.** She was disappointed that no one attended her graduation because she had really wanted her parents to come.

b. She was disappointed that no one failed her grip because she had really asked her websites to come.

13. **a.** As you get older, your brain continues to develop.

b. As you get better, your child needs to develop.

14. **a.** I hate rewarding him with attention, but my brother's annoying behavior can be impossible to ignore.

b. I hate taking him with ship, but my parents' nervous dentist can be serial to ignore.

15. **a.** I'm trying so hard to win the game because I really hate to lose.

b. I'm going so mad to write the cream because I really need to lose.

16. **a.** The book that she wanted was one that is very difficult to obtain.

b. The ice that she watched was one that is very obvious to obtain.

17. **a.** He was so tense, his coach told him he had to relax.

b. He was so ancient, his tower taught him he had to relax.

18. **a.** The painting by Renoir was the one that I really wanted to see.

b. The vaccine by Illinois was the one that I really managed to see.

19. **a.** There is so much material that the professor must teach.

b. There is so much love that the game must teach.

20. **a.** This question asks for an individual's opinion, so the responses will vary.

b. This room looks for a drivers' homework, so the swordsmen will vary.

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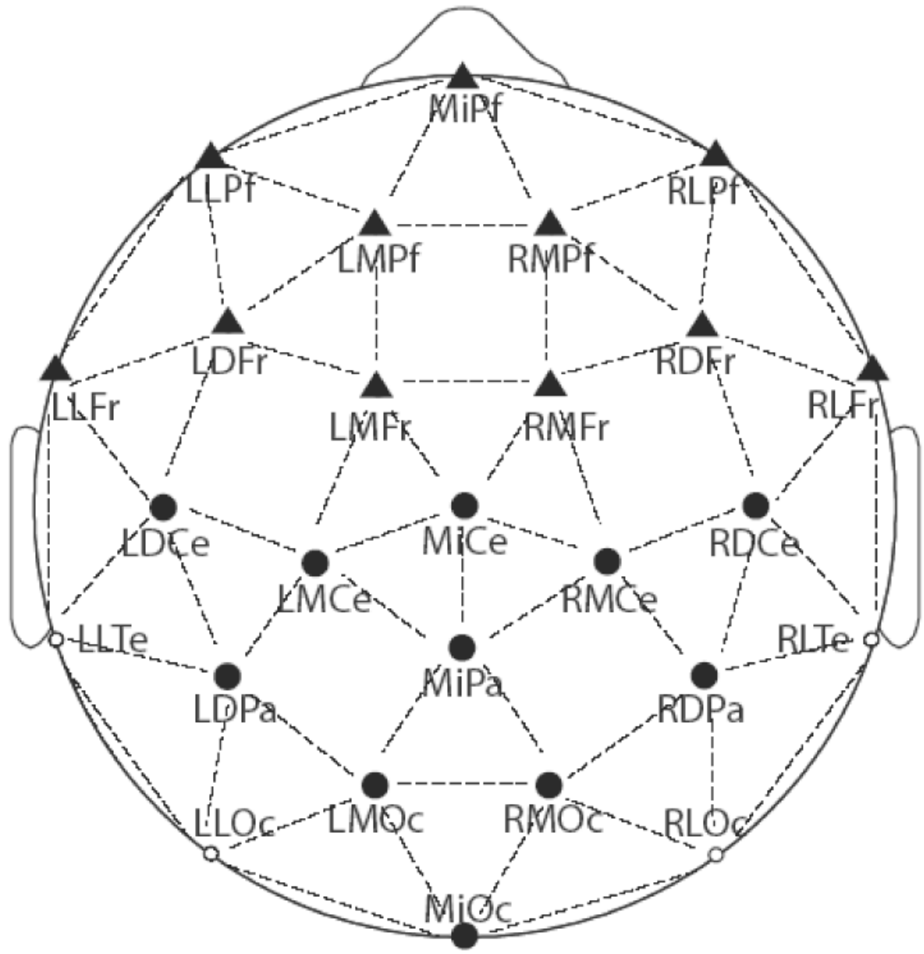

Figure 1.

Shown are the locations of the 26 scalp electrodes, as seen from the top of the head (with the front of the head at the top of the figure). Frontal electrodes are represented as triangles and central/posterior electrodes are represented as circles. The electrodes used for statistical analysis are shown using filled in shapes.

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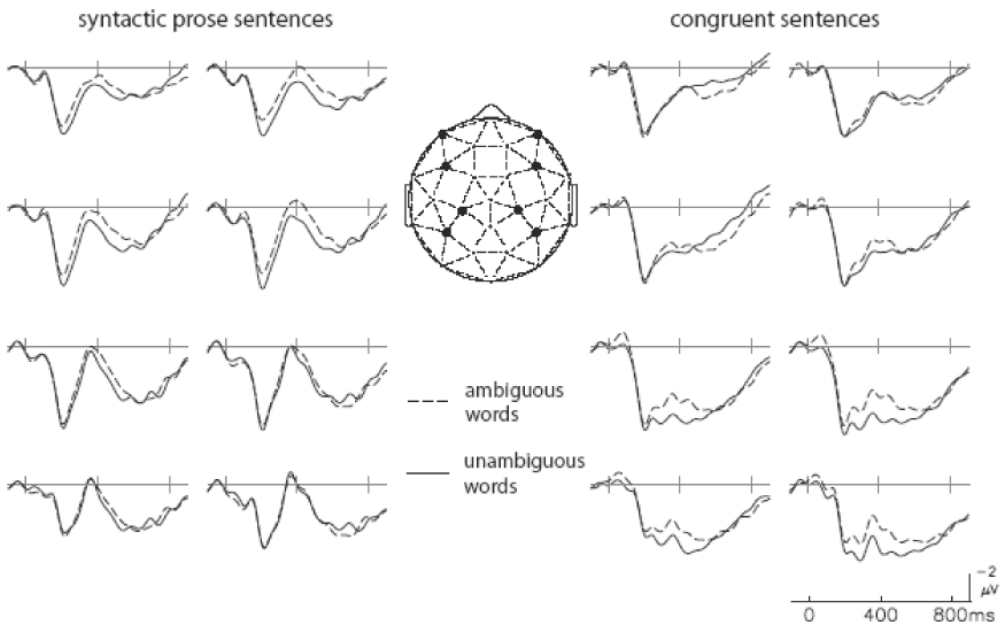

Figure 2.
Grand average ERPs to ambiguous words (dashed line) and unambiguous words (solid line) are plotted separately for syntactic prose sentences (left panel) and congruent sentences (right panel) at 8 representative electrode sites. Positions of the plotted sites are indicated by filled circles on the center head diagram (nose at top). Negative is plotted up for this figure and figure 4. In the syntactic prose sentences, the response to ambiguous words (e.g. 'the season/to season') is more negative than the response to unambiguous words (e.g. 'the logic/to eat') over the frontal channels, between about 200 and 700 ms post-stimulus-onset. In the congruent sentences, there is no enhanced frontal negativity. Instead, the ambiguous words are more negative over central/posterior sites in the N400 time window (250-500ms).

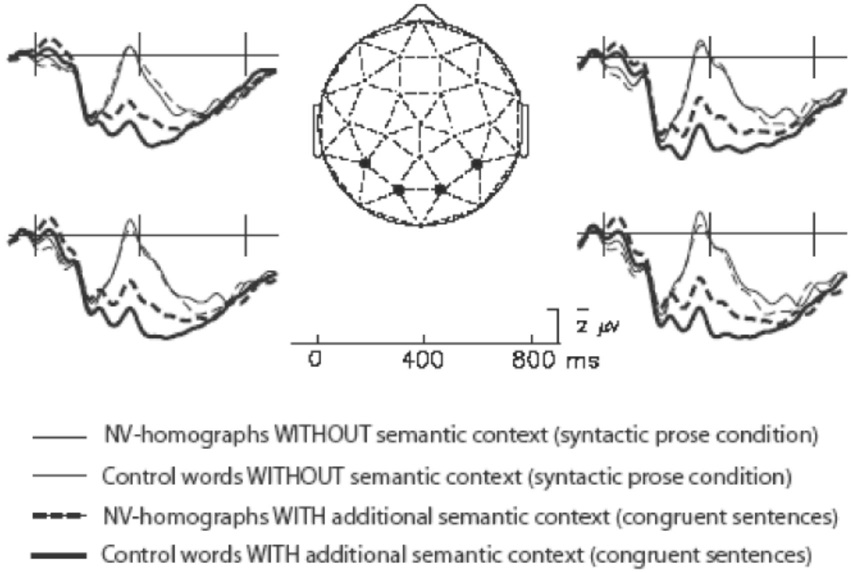

Figure 3.

Grand average ERPs to ambiguous words (dashed lines) and unambiguous words (solid lines) in syntactic prose sentences (thinner lines) and congruent sentences (thicker lines) are overlaid at 4 representative central/posterior electrode sites to highlight the influence of semantic constraints on the N400. N400 amplitudes to both ambiguous and unambiguous words are highly facilitated (made more positive) in the presence of semantic constraints, although this facilitation is greater for unambiguous than ambiguous targets in cloze-probability matched sentence contexts.

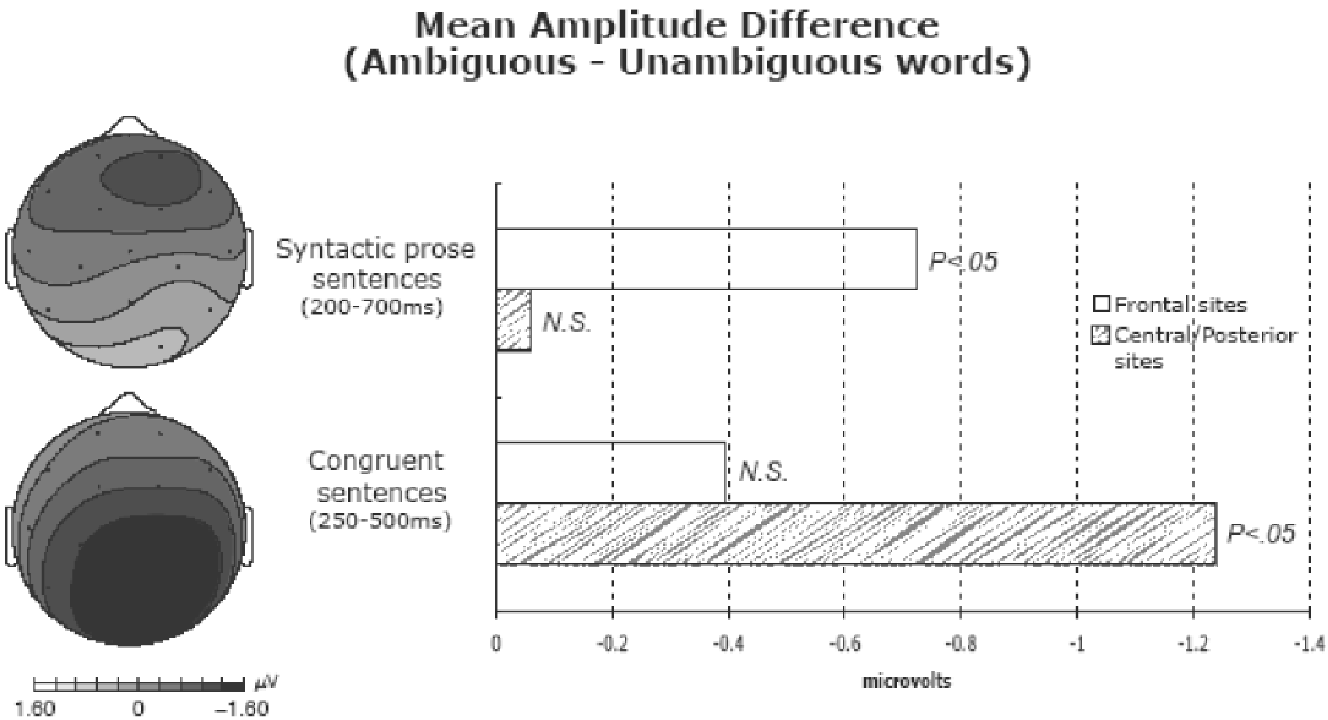

Figure 4.

Mean amplitude differences are summarized as isopotential voltage maps (on the left) and bar graphs (on the right) for the syntactic prose sentences (upper panel) and congruent sentences (lower panel) respectively. The two isopotential voltage maps show distributions viewed from the top of the head for (upper panel) the frontal negativity effect in the syntactic prose sentences in the 200-700 ms time window and (lower panel) the central/posterior N400 effect in the congruent sentences in the 250-500 ms time window. The right side of the figure plots the amplitude differences averaged over the 11 frontal sites and 11 central/posterior sites for the two sentence types. Longer bars indicate more negative brain responses to the ambiguous words than to the unambiguous words. The statistical significance of each difference is noted next to each bar (with N.S. = not significant).

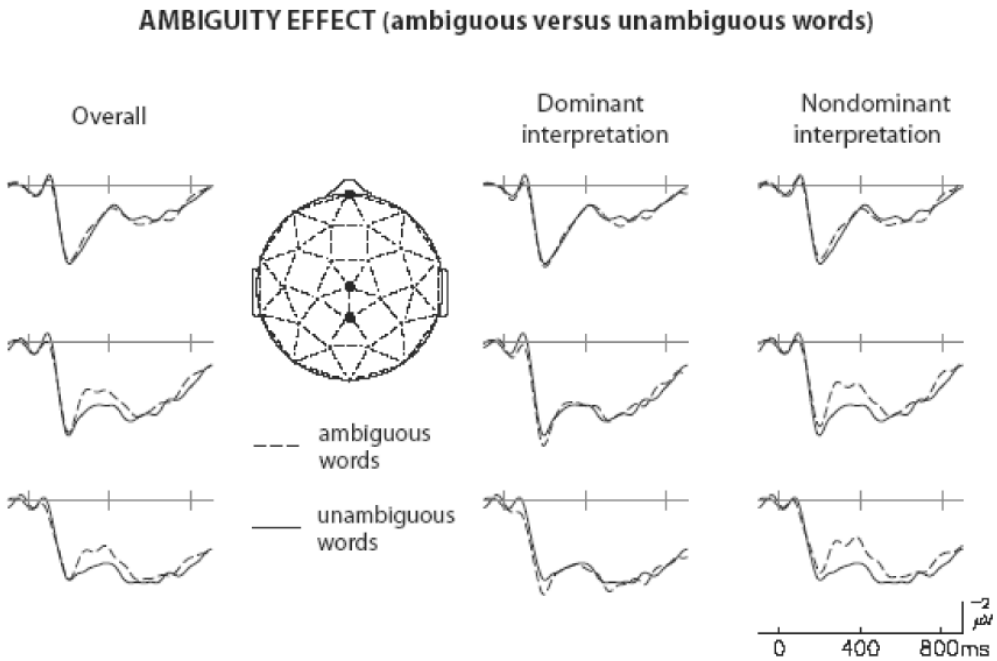

Figure 5.
Grand average ERPs at 3 midline electrode sites for ambiguous words (dashed line) and unambiguous words (solid line) in Experiment 2. The leftmost column overlays the overall brain responses to ambiguous and unambiguous words, irrespective of meaning dominance. Replicating Experiment 1, in syntactically and semantically congruent sentences, N400 responses to ambiguous words are more negative than those to unambiguous words. The two columns on the right side of the figure contrast the brain responses to ambiguous versus unambiguous words when the context favors the dominant interpretation (middle column) or the nondominant interpretation (right column) of the homographs. The data clearly show that when the context picks out the dominant meaning of the homograph, the waveforms from the ambiguous and unambiguous words are indistinguishable. However, when the context picks out a nondominant meaning of the homograph, larger N400s are observed to the ambiguous words.

Table 1

Mean values (with standard deviations in parentheses) of lexical features of the two word types (NV-homographs and unambiguous words) in Experiment 1.

	NV-homographs	**Unambiguous words**
	'the duck'/'to duck'	**'the logic'/'to vary'**
Log frequency	1.56 (0.58)	1.58 (0.51)
Word length	4.8 (1.3)	5.2 (1.1)
Concreteness (1=very abstract; 7=very concrete)	4.7 (1.0)	4.7 (1.0)
Semantic distinctiveness (1=very different; 7=very similar)	2.7 (0.8)	N/A

Table 2

Mean values (with standard deviations in parentheses) of sentential features of congruent sentences ending with the two word types (NV-homographs and unambiguous words) in Experiment 1.

	NV-homographs	**Unambiguous words**
	'the duck'/'to duck'	**'the logic'/'to vary'**
Sentence Length	14.6 (3.6)	13.9 (3.1)
Plausibility (1=least plausible; 7=most plausible)	6.5 (0.5)	6.6 (0.3)
Cloze probability	50% (35%)	50% (32%)

Table 3

Mean values of (1) lexical features of the two subgroups of NV-homographs (when the contextually favored meaning is the dominant meaning sense vs. the non-dominant meaning sense) and (2) sentential features of the sentences ending with the two sub-groups of NV-homographs in Experiment 2.

		Dominant meaning sense	Non-dominant meaning sense	Overall NV-homographs	Unambiguous words
Lexical features of sentence-final words	Log frequency	1.5 (0.4)	1.6 (0.6)	1.6 (0.6)	1.6 (0.5)
	Word length	4.8 (1.4)	4.7 (1.2)	4.8 (1.2)	5.2 (1.1)
	Concreteness (1=very abstract; 7=very concrete)	5.1 (1.0)	4.6 (0.9)	4.7 (1.0)	4.8 (0.9)
	Semantic distinctiveness (1=very different; 7=very similar)	2.8 (0.9)	2.7 (0.8)	2.7 (0.8)	N/A
Sentential features	Sentence length	14.3 (3.3)	14.4 (3.8)	14.4 (3.7)	13.8 (3.2)
	Plausibility (1=least plausible; 7=most plausible)	6.5 (0.4)	6.4 (0.7)	6.4 (0.6)	6.6 (0.3)
	Cloze probability	56% (30%)	47% (34%)	50% (33%)	50% (33%)