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Research Report

An ERP study of syntactic processing in English and nonsense sentences

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ABSTRACT

The timecourse of the interaction between syntactic and semantic information during sentence processing in monolingual native English speakers was investigated using event-related potentials (ERPs). To examine the effects of semantic information on syntactic processing, the results for normal English sentences were compared to those for semantically impoverished nonsense (Jabberwocky) sentences. Within each sentence type condition, half of the sentences contained a syntactic violation. Violations elicited a larger amplitude N1 and more negative ERPs around 200 ms after the onset of the critical word relative to the grammatical condition. Although these effects were observed in both sentence types, they were anteriorly distributed for English sentences only. Moreover, the P600 elicited by the syntactic violation was attenuated in processing Jabberwocky as compared to English sentences. These results suggest that semantic and syntactic information are integrated during the earlier stages of syntactic processing indexed by the anterior negativities, and that these interactions continue in the later stages of processing indexed by the P600.

1. Introduction

A central issue in the study of on-line processing of language is the timecourse of the interaction between syntactic and semantic information. Existing models differ in the specification of when syntactic and semantic processing interact with each other. The serial, syntax-first models propose that syntactic information is processed independently of semantic information and that semantic information could confirm or alter the initial structural analysis at later stages of sentence comprehension (Frazier, 1987; Friederici, 2002). In contrast, interactive models propose that various types of linguistic information, including syntax and semantics, are activated simultaneously and processed in a parallel and interactive fashion throughout comprehension processes (MacDonald et al., 1994; McClelland et al., 1989; Trueswell and Tanenhaus, 1994). The event-related potential (ERP) technique has provided the field of psycholinguistic research a powerful tool to investigate this question. Unlike reaction time and accuracy measures, ERPs enable researchers to examine the timing of neural activity relevant to specific aspects of language processing, with a temporal resolution on the order of milliseconds, without or prior to overt behavioral responses. Moreover, ERP indices of syntactic and semantic processing have been identified that enable researchers to determine when and how these two types of processing interact.

One of the first reported ERP indices of linguistic processing was the N400. In their seminal work, Kutas and Hillyard (1980) reported that anomalies involving violations of semantic expectation built up by prior sentential context

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elicited a negativity peaking around 400 ms after the onset of the anomalous word that was largest over the medial posterior electrode sites. Subsequent research revealed that violation of (morpho-)syntactic rules elicited ERP responses that were distinct from the N400.

ERP effects associated with syntactic processing include earlier negativities and a later positivity (for summaries of studies on the syntax-related ERP effects, see, e.g., Canseco-Gonzalez, 2000; Hagoort et al., 1999; Hahne and Friederici, 1999b). Earlier negativities are typically elicited by violation of syntactic rules. Unlike the N400, these negativities are largest over anterior electrode sites and are often larger over left hemisphere sites (e.g., Friederici et al., 1996, 1993; Hahne and Friederici, 1999a; Neville et al., 1991). Across studies, anterior negativities have been observed in two latency ranges. The first and earlier latency range is approximately 100–200 ms after the onset of the critical word. In studies in which sentences were presented visually, anterior negativities in this latency range manifested as an enhancement of the N1 component (Neville et al., 1991). Some studies conducted in the auditory modality, presenting naturally spoken sentences, have also reported negativities in this early latency range (e.g., Friederici et al., 1996; Hahne and Friederici, 1999a, 2002). Because of the timing and distribution, this effect has sometimes been referred to as the early left anterior negativity (ELAN). The second latency range in which elicitation of anterior negativities has been frequently reported is approximately 300–500 ms post-stimulus-onset (e.g., Gunter et al., 2000; Hagoort and Brown, 2000; Neville et al., 1991; Osterhout and Mobley, 1995). This slightly later effect has sometimes been called the left anterior negativity (LAN). Within a serial, syntax-first model, it has been proposed that anterior negativities elicited with different latencies reflect functionally distinct stages of sentence processing (Friederici, 2002). The earlier anterior negativity has been proposed to index a syntactic structure building process while the later anterior negativity has been considered to index processing of morpho-syntactic information (but see Lau et al., 2006 for an alternative interpretation of this effect).

The later positivity, commonly referred to as the P600, is elicited by both (morpho-)syntactic violations (e.g., Coulson et al., 1998; Hagoort and Brown, 2000; Hahne and Friederici, 1999a; Osterhout, 1997; Osterhout and Mobley, 1995) and disambiguating words in syntactically well-formed but ambiguous (i.e., garden-path) sentences (e.g., Osterhout and Holcomb, 1992, 1993). This effect has an onset latency of about 500 ms and has a posterior medial distribution (Hagoort et al., 1999).

To investigate when syntactic and semantic information interact during on-line sentence comprehension, two types of approaches have been adopted in ERP studies. In the first type, sentences in one condition contain words that are doubly anomalous, violating both a (morpho-)syntactic rule and semantic expectations. The effects elicited by doubly anomalous words are compared with the effects elicited by words that violate only a (morpho-)syntactic rule. In this type of approach, the critical difference in semantic processing (i.e., processing anomalous vs. coherent words) occurs simultaneously with, but not prior to, a (morpho-)syntactic violation. Studies using this approach found no effect of a semantic anomaly on the ELAN or LAN (Friederici et al., 1999; Gunter et al., 2000, 1997; Hahne and Friederici, 2002). Some studies reported that the P600 was reduced or absent in the doubly anomalous condition as compared to the P600 elicited in a syntactic-violation-only condition (Gunter et al., 2000, 1997, Experiment 2; Hahne and Friederici, 2002, Experiment 2), but others have not observed such reduction (Ainsworth-Darnell et al., 1998; Friederici et al., 1999; Gunter et al., 1997, Experiment 1; Hagoort, 2003; Hahne and Friederici, 2002, Experiment 1; Osterhout and Nicol, 1999). The results have been interpreted as evidence that the early stages of syntactic processing indexed by the ELAN and LAN proceed independently of semantic processing while the two types of processes interact at later stages indexed by the P600 under certain conditions, supporting the serial, syntax-first models of sentence comprehension.

The other type of approach adopted to investigate the interaction between syntax and semantics is to examine the effects of a lack of semantic context on syntactic processing. This is accomplished by presenting sentences in which semantic content has been reduced or removed by replacing the primary meaning-bearing, open-class[1] words (e.g., nouns, verbs, and adjectives) with pseudo-words. These sentences have been called “Jabberwocky” sentences (Carroll, 1883). It has been assumed that, in Jabberwocky sentences, syntactic information is maintained by keeping all closed-class items (e.g., articles, prepositions, and conjunctions), including inflectional morphemes (e.g., English past-tense morpheme-*ed*) intact. During Jabberwocky sentence processing, the structural representation of the sentence is constructed based on the syntactic information encoded by closed-class items. However, unlike normal sentence processing, integration of lexical semantics (encoded by open-class words) and syntactic information does not take place, and the resulting representation of the sentence lacks semantic content. To examine the effects of reduced semantic content, the effects elicited by syntactic violations in Jabberwocky sentences are compared to the effects elicited by syntactic violations in normal sentences. Unlike sentences with doubly anomalous words, semantic processing is altered in Jabberwocky sentences (i.e., absence of previous semantic context) well before syntactic violations occur.

To date, only a few studies have used this second approach, and the findings have been mixed. With respect to anterior negativities, ELANs and LANs were elicited for

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[1] In languages such as English, lexical items can be divided into two classes: open and closed. Nouns, verbs, and adjectives, for example, are considered to be “open-class”, in that new lexical items can be readily added to these word categories, while word categories such as articles, prepositions, and conjunctions and inflectional morphemes are considered to be “closed-class”, in that these categories generally do not allow addition of new items (Burling, 1992). Open- and closed-class words also differ in terms of the types of information they encode within a sentence: whereas open-class words have rich semantic content and encode semantic information, closed-class words primarily provide syntactic information and carry little semantic content (Givon, 1984). Because of this distinction, open- and closed-class words have been viewed as the equivalents of semantic and syntactic components of a sentence, respectively.

both normal and Jabberwocky sentences (Canseco-Gonzalez, 2000; Canseco-Gonzalez et al., 1997; Hahne and Jescheniak, 2001).[2] These results suggest that early syntactic processing is performed even when semantic information is absent. However, differences in the distribution of the LAN between normal and Jabberwocky sentences observed in the Canseco-Gonzalez (2000) and Canseco-Gonzalez et al. (1997) study suggest that the processes underlying the effects elicited in the two sentence types are not identical (although Hahne and Jescheniak, 2001, did not observe differences in the distribution of the ELAN between normal and Jabberwocky sentences).

The effects of reduced semantic context on the late positivity have also varied across studies. Canseco-Gonzalez (2000), Canseco-Gonzalez et al. (1997), and Münte et al. (1997) found a greatly reduced or absent P600 for Jabberwocky. These researchers had predicted that the P600 would be reduced when sentences lack semantic content as in Jabberwocky sentences. Because the P600 occurs later than the anterior negativities and is elicited by the disambiguation of syntactic structures as well as by violations, it has been hypothesized within the serial, syntax-first model that the P600 is an index of a second-pass reanalysis process which takes place after the initial recognition of syntactic errors indexed by the anterior negativities (Friederici, 1995; Hahne and Friederici, 1999a). That is, when a listener/reader encounters a word that cannot be readily incorporated into the existing structure, reanalysis is attempted by searching for an alternative structure into which the word can be incorporated without violating any syntactic rules. Some researchers hypothesized that this reanalysis process is based on the semantics of the sentence (Münte et al., 1997). More specifically, the reanalysis process was argued to be an attempt to rescue the meaning of the sentence (Canseco-Gonzalez, 2000; Canseco-Gonzalez et al., 1997). Therefore, when sentences lack semantic content, at least a part of the processes underlying the P600 would not be executed since there is no semantic content to be rescued. The attenuation and absence of the P600 observed for Jabberwocky sentences in these studies were in line with this hypothesis.

In contrast to these findings, the P600 elicited in Jabberwocky sentences was not attenuated relative to the P600 elicited in normal sentences in a study by Hahne and Jescheniak (2001). The authors argued that execution of the processes indexed by the P600 does not rely on the presence of semantic content but depends on the timing with which morpho-syntactic and semantic errors (including semantic emptiness of pseudo-words) were detected. According to their hypothesis (Timing Hypothesis), the processes indexed by the P600 would be blocked when the processing system recognizes both morpho-syntactic and semantic errors. The lack of P600 attenuation for Jabberwocky in their study was attributed to the early detection of syntactic violations between 100 and 250 ms, which in turn prevented subsequent lexical–semantic processing (thus no error detection in the semantic domain); since the processing system recognized an error only in the one domain (namely, syntax), the system proceeded to the stages of processing indexed by the P600. Conflicting findings in the studies conducted thus far may be due to difference in languages (English or German), violation types (phrase structure, morphological agreement, or word category violations), violation positions (sentence-medial vs. sentence-final) as well as to the procedures used (inter mixed vs. blocked presentation of normal and Jabberwocky sentences).

The goal of the present study was to further investigate the effects of semantic context on syntactic processing using English and Jabberwocky sentences (see Table 1 for example sentences). In the previous two Jabberwocky studies (Hahne and Jescheniak, 2001; Münte et al., 1997) discussed above, it was concluded that the anterior negativity reflects specifically syntactic processes, providing evidence against the interactive model of language processing. This conclusion was made based on the findings that the negativity was elicited in Jabberwocky sentences. However, differences in topographical distribution of the anterior negativity were not always examined in previous studies. Therefore, in the present study, in addition to examining whether syntactic violations in English and Jabberwocky sentences would elicit anterior negativities, the distributions of the anterior negativities elicited in the two sentence types were carefully compared. Based on previous findings, we predicted that violations would elicit an anterior negativity in both sentence types, indicating that the presence of semantic information is not necessary at early stages of syntactic processing. Moreover, if initial syntactic processing was completely independent of semantic information, the topographical distribution of this effect would not differ between English and Jabberwocky sentences. However, if semantics affects initial syntactic

Table 1 – Examples of stimulus sentences

Experimental sentences:
  1) Grammatical English sentence:
    Mommy can cut the meat with that knife.
  2) Ungrammatical English sentence:
    Mommy can cut the meat with her *that knife.
  3) Grammatical Jabberwocky sentence:
    Minno can kogg the mibe with that nove.
  4) Ungrammatical Jabberwocky sentence:
    Minno can kogg the mibe with her *that nove.
Distracter sentences:
  1) Grammatical English sentence
    Carrie will give these cards to her friends.
  2) Ungrammatical English sentence:
    Carrie will *these give cards to her friends.
  3) Grammatical Jabberwocky sentence:
    Kallo will goff these kilps to her flomps.
  4) Ungrammatical Jabberwocky sentence:
    Kallo will *these goff kilps to her flomps.

Note. The critical words to which ERPs were averaged are underlined.

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[2] Münte et al. (1997) reported an enhanced negativity around 500 ms after the onset of violations in Jabberwocky, but not in normal, sentences. However, the negativity elicited for Jabberwocky had a central maximum; therefore, it was uncertain whether the negativity in their study indexed the same type of processing as the (E)LAN elicited in the other two Jabberwocky studies.

processing, the anterior negativity would be elicited with different topographical distribution for the two sentence types. Differences in the distribution of anterior negativities for English and Jabberwocky sentences would indicate differential involvement of neural systems during early stages of syntactic processing.

The other objective was to examine whether the P600 elicited by the particular syntactic violation type adopted in the present study was attenuated in Jabberwocky sentences as compared to English sentences. If this effect indexes processes based on semantics, as suggested in previous studies (Canseco-Gonzalez, 2000; Canseco-Gonzalez et al., 1997; Münte et al., 1997), the amplitude of the effect should be reduced when sentences lack semantic content. Since the syntactic violations employed in this study elicit an anterior negativity in an early latency range (<300 ms) according to the pilot results, and since the critical words were all closed-class words, which would not elicit an N400 (Münte et al., 2001; Neville et al., 1992; Nobre and McCarthy, 1994); such attenuation would provide evidence against the Timing Hypothesis proposed by Hahne and Jescheniak (2001).

An additional interest in the present study was to explore how closed-class words were processed in English and Jabberwocky sentences. Closed-class words presented in the visual modality have been observed to elicit a negative peak following the N1–P2 complex over the anterior scalp region (an early negativity which is often referred to as the N280) (Brown et al., 1999; Neville et al., 1992). This negative component has been reported to be greater over the left hemisphere as compared to the right hemisphere (Brown et al., 1999; Neville et al., 1992; Nobre and McCarthy, 1994; Osterhout et al., 2002a, 1997). Following this component, a ramp-like negativity (late negativity which is sometimes referred to as the N400–700) is elicited over the anterior sites lasting until the onset of the subsequent word (Brown et al., 1999; Neville et al., 1992; Osterhout et al., 2002a; Van Petten and Kutas, 1991). In the present study, these two effects were examined by comparing ERPs to the critical words in grammatical English and Jabberwocky sentences to investigate whether closed-class words are processed similarly in sentences with and without semantic content. If the early negative peak indexes search and/or recognition processes of closed-class words as some researchers have speculated (Brown et al., 1999; Neville et al., 1992), this component would be elicited similarly by closed-class words in English and Jabberwocky since such processes are unlikely to differ depending on whether closed-class words appear in normal or Jabberwocky sentences. The later, more sustained negative component has been hypothesized to reflect expectancy for either the upcoming head of a phrase (Van Petten and Kutas, 1991) or the meaningful (i.e., open-class) word (Brown et al., 1999). If this component reflects expectancy for the upcoming head of a phrase, it would be elicited similarly in normal and Jabberwocky sentences since both sentence types should contain enough information about syntactic structure to generate expectancy for the head of a phrase. However, if this negative component reflects expectancy for the upcoming meaningful word, it should be elicited differently in the two sentence types since such expectancy would be generated only in normal English sentences.

2. Results

2.1. *Behavioral results*

The accuracy of grammaticality judgments was evaluated using *A'*. The mean *A'*s for English and Jabberwocky were 0.98 (SD = 0.02) and 0.97 (SD = 0.02), respectively, for the experimental sentences, and 0.95 (SD = 0.05) and 0.92 (SD = 0.07), respectively, for the distracter sentences (possible values ranging from 0.5 = chance performance to 1.0 = perfect performance). Although the *A'* for English was significantly higher than the *A'* for Jabberwocky (experimental sentence: $t(33) = 2.96$, $p < 0.01$; distracter sentence: ($t(33) = 3.32$, $p < 0.005$)), the accuracy was very high for both sentence types. On average, the number of sentences judged incorrectly differed by one sentence between English and Jabberwocky in each grammaticality condition. Mean accuracy of probe word recognition was 92.7% (SD = 6.4) for English and 86.3% (SD = 11.0) for Jabberwocky. The accuracy was significantly higher for English ($t(33) = 2.94$, $p < 0.01$).

2.2. *ERP results—grammaticality effects*

The ERPs elicited by the critical words in the grammatical and ungrammatical conditions during the following time windows were compared: local negative peak amplitudes between 75 and 175 ms (anterior negativity) and mean amplitudes between 180 and 250 ms (anterior negativity) and between 500 and 900 ms (P600). For comparisons of the topographical distribution of grammaticality effects between sentence types, difference measurements (ungrammatical–grammatical) were normalized according to the procedure described under ERP recording and analysis.

2.2.1. *Local negative peak amplitude between 75 and 175 ms (anterior negativity)*

Over the anterior scalp region, critical words in both grammatical and ungrammatical conditions elicited a negative peak around 100 ms (N1) after the onset of the words. As seen in Figs. 1 and 2, the N1 peak elicited in the ungrammatical condition was larger in amplitude than the N1 peak elicited in the grammatical condition in both sentence types. As depicted in Fig. 3a, the increase in negativity with violations in English was largest over the frontal sites (Grammaticality × Anterior/Posterior: $F(3,99) = 10.29$, $p < 0.005$).[3] An analysis including the 12 frontal, fronto-temporal, and temporal electrodes revealed a significant main effect of Grammaticality ($F(1,33) = 5.81$, $p < 0.05$). For Jabberwocky sentences, the increase in negativity with violations was robust and evenly distributed from the frontal to central sites as depicted in Fig. 3b (Grammaticality: $F(1,33) = 6.83$, $p < 0.05$; Grammaticality × Anterior/Posterior: $p > 0.9$). No other significant interaction was revealed in the analysis for either sentence type.

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[3] Parietal and occipital electrodes were excluded from the analyses of this time window. See the ERP recording and analysis section for more details.

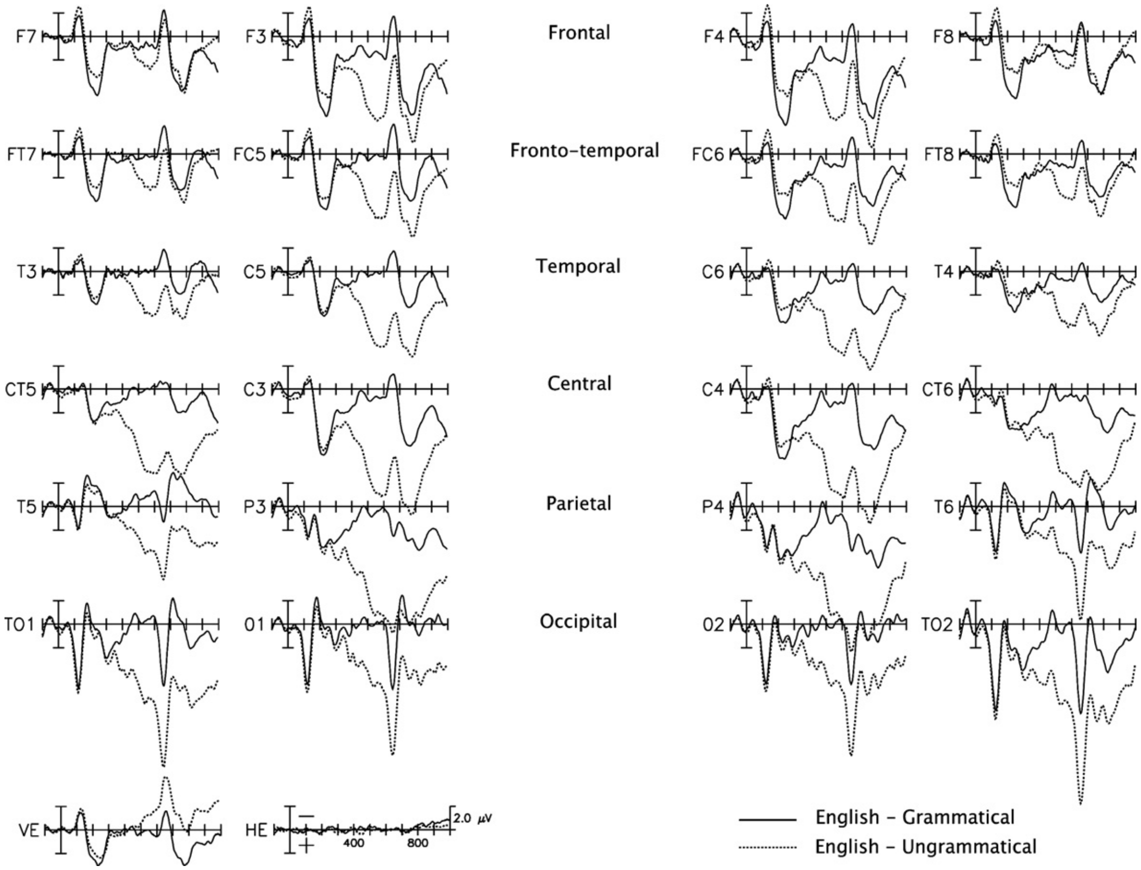

Fig. 1 – Grand-average ERP waveforms for grammatical and ungrammatical English sentences.

The direct comparison of the two sentence types revealed a marginally significant Sentence Type by Anterior/Posterior interaction (*normalized data* — $F(3,99)=3.08$, $p=0.075$), suggesting that the distribution of the grammaticality effect tended to differ between English and Jabberwocky, although the N1 elicited in the grammatical condition did not have significantly different distributions for the two sentence types (Sentence Type × Anterior/Posterior: $p>0.4$).

In summary, in both English and Jabberwocky sentences, the syntactic violation elicited an enhanced early negativity observed over the anterior scalp region. The distributions of the effects tended to be more anterior for English than for Jabberwocky.

2.2.2. *Mean amplitude between 180 and 250 ms (anterior negativity)*

Following the N1, ERPs in both grammaticality conditions showed a positive deflection over the anterior scalp region with a peak around 200 ms post-word onset (P2). Near the peak of the P2 component, ERPs to critical words in the ungrammatical condition were more negative relative to ERPs to critical words in the grammatical condition over anterior electrode sites for both sentence types (Grammaticality × Anterior/Posterior: *English* — $F(5,165)=32.20$, $p<0.001$; *Jabberwocky* — $F(5,165)=13.88$, $p<0.001$). The ANOVAs including the 12 anterior (frontal, fronto-temporal, and temporal) electrode sites revealed a significant main effect of Grammaticality for both English ($F(1,33)=22.52$, $p<0.001$) and Jabberwocky ($F(1,33)=16.93$, $p<0.001$). As seen in Fig. 4a, the negativity effect in English was largest over the frontal sites (Grammaticality × Anterior/Posterior: $F(5,165)=36.24$, $p<0.001$) and over the right hemisphere sites (Grammaticality × Hemisphere: $F(1,33)=8.69$, $p<0.01$) while the effect in Jabberwocky was evenly distributed from the frontal to temporal sites (Fig. 4b) and over the left and right hemisphere sites (Grammaticality × Anterior/Posterior: $p>0.2$; Grammaticality × Hemisphere: $p>0.7$). The direct comparison of the two sentence types yielded significant interactions between Sentence Type and Anterior/Posterior (*normalized data* — $F(2,66)=15.78$, $p<0.001$) and Sentence Type and Hemisphere (*normalized data* — $F(1,33)=6.87$, $p<0.05$).

Thus, during the 180 to 250 ms time window, syntactic violations in both sentence types again elicited significant grammaticality effects of negative polarity. However, these effects were distributed significantly differently for the two sentence types. While the effect was larger over the frontal and right hemisphere sites for English, it was distributed evenly from frontal to temporal sites and exhibited no overall hemispheric differences for Jabberwocky. The patterns of distribution along the anterior/posterior dimension were similar to what was observed for the negative grammaticality effects at the N1.

2.2.3. *Mean amplitude between 500 and 900 ms (P600)*

The late positive effect, the P600, started very early for the current violation type. The grand-average waveforms (Figs. 1 and 2) showed that the effect at some electrode sites started as

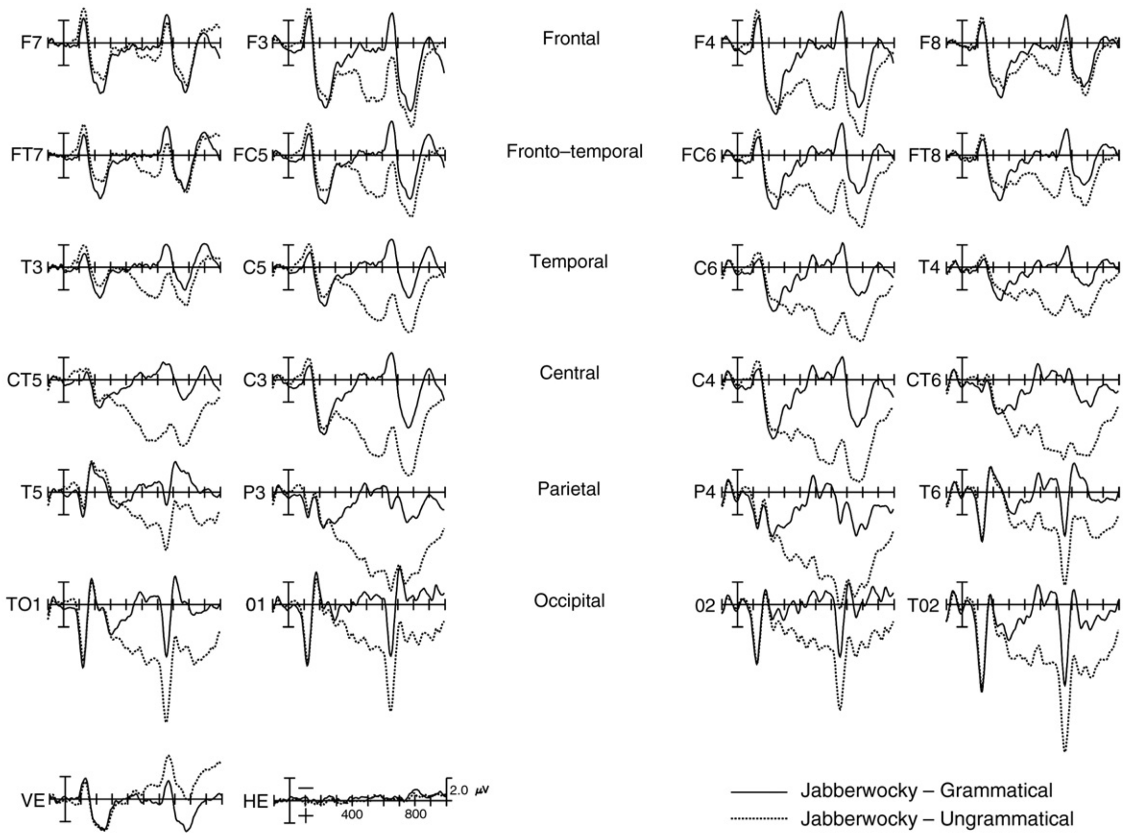

Fig. 2 – Grand-average ERP waveforms for grammatical and ungrammatical Jabberwocky sentences.

early as about 300 ms and reached its maximum amplitude around 600 ms after the onset of critical words. The P600s measured during the 500-900 ms time window were robust in both sentence types (Grammaticality: *English* — $F(1,33)=136.76$, $p<0.001$; *Jabberwocky* — $F(1,33)=95.63$, $p<0.001$) and larger over the posterior medial sites (Grammaticality × Anterior/Posterior: *English* — $F(5,165)=105.20$, $p<0.001$; *Jabberwocky* — $F(5,165)=43.97$, $p<0.001$; Grammaticality × Lateral/Medial: *English* — $F(1,33)=77.62$, $p<0.001$; *Jabberwocky*—$F(1,33)=49.50$, $p<0.001$; Grammaticality × Anterior/Posterior × Lateral/Medial: *English* — $F(5,165)=55.97$, $p<0.001$; *Jabberwocky* — $F(5,165)=36.86$, $p<0.001$). The positivity elicited in Jabberwocky was larger over the right hemisphere sites anteriorly but similar in amplitude posteriorly (Grammaticality × Hemisphere: $F(1,33)=15.57$, $p<0.001$; Grammaticality × Anterior/Posterior × Hemisphere: $F(5,165)=9.61$, $p<0.001$).

As seen in the difference waveforms (Fig. 5), the P600 was attenuated for Jabberwocky relative to English over left hemisphere electrode sites (Sentence Type × Grammaticality × Hemisphere: $F(1,33)=14.72$, $p<0.005$; *12 left hemisphere electrodes*-Sentence Type × Grammaticality: $F(1,33)=6.14$, $p<0.05$). No significant attenuation of the P600 was found over right hemisphere sites ($p>0.1$).

In summary, during the 500-900 ms time window, robust P600s were elicited by syntactic violations in both sentence types. The P600 was attenuated in amplitude for Jabberwocky relative to English over the left hemisphere sites.

2.3. *ERP results—closed-class word effects*

Since the critical words (determiners and pronouns) belonged to the closed-class, the ERPs elicited by these words in the grammatical condition were examined separately for the closed-class word effects. Amplitude of the first local negative peak between 250 and 375 ms following the anterior N1–P2 complex (early negative component) and mean amplitude between 400 and 550 ms (late negative component) were measured over the 12 anterior electrode sites and analyzed.

2.3.1. *Local negative peak amplitude between 250 and 375 ms (early negative component)*

Following the N1 and P2 components, the critical words in grammatical sentences elicited a negative peak over the anterior sites which was more prominent over the left hemisphere sites (Fig. 6). This post-N1–P2 negative peak occurred around 320 ms after the word onset averaged across all 12 anterior electrodes in the present experiment (English: $M=318$ ms; Jabberwocky: $M=321$ ms). Thus, this peak will be referred to as the N320.

As depicted in Fig. 7a, the N320 peak was larger over the left hemisphere relative to the right hemisphere in both sentence types (Hemisphere: *English* — $F(1,33)=45.98$, $p<0.001$; *Jabberwocky* — $F(1,33)=9.11$, $p<0.01$). The degree of left lateralization was greater for English as compared to

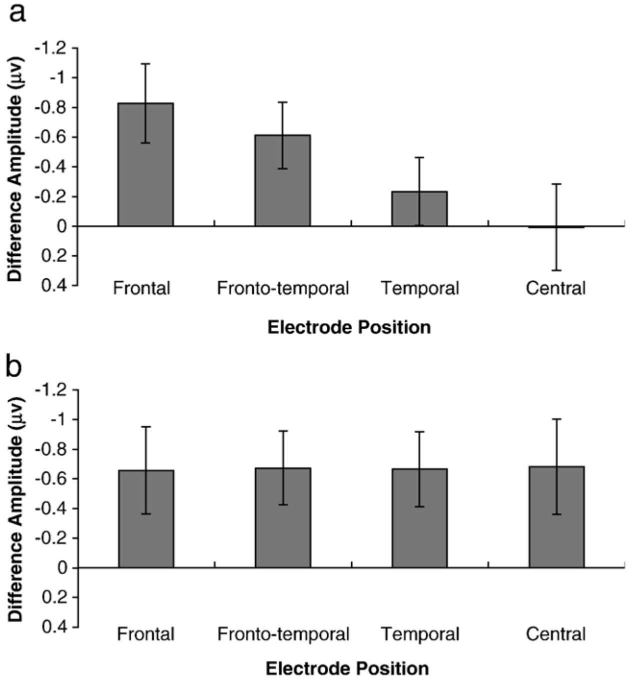

Fig. 3 – Amplitude of the N1 negative grammaticality effect for (a) English and (b) Jabberwocky. The measurement for each electrode position in the figure is the mean of amplitude differences between the ungrammatical and grammatical conditions measured at four electrodes (lateral and medial sites over left and right hemispheres).

Jabberwocky (Sentence Type × Hemisphere: $F(1,33) = 8.58$, $p < 0.001$).[4]

2.3.2. *Mean amplitude between 400 and 550 ms (late negative component)*

Following the N320 peak, the critical words in grammatical sentences elicited negative-going ERPs. As shown in Fig. 7b, during the 400-550 ms time window over anterior sites, ERPs elicited by determiners and possessive pronouns in grammatical English sentences were more negative over the left hemisphere sites relative to the ERPs elicited over the right hemisphere sites, whereas no hemispheric difference was found for the same words presented in Jabberwocky sentences (Hemisphere: *English* — $F(1,33) = 9.38$, $p < 0.005$; *Jabberwocky* — $p > 0.1$; Sentence Type × Hemisphere: $F(1,33) = 4.89$, $p < 0.05$).

3. Discussion

This study investigated the effects of impoverished semantic context on syntactic processing by comparing ERP indices of syntactic processing in normal English and semantically impoverished Jabberwocky sentences. Despite the absence of real open-class words, participants judged grammaticality of Jabberwocky sentences with high accuracy, indicating that the remaining closed-class words provided sufficient syntactic information. Although the difference was very small, the judgment accuracy was higher for English than for Jabberwocky, suggesting that having real open-class words facilitates grammaticality judgments.

In the following sections, findings on the ERP grammaticality effects and closed-class word effects are discussed separately.

3.1. *Grammaticality effects*

3.1.1. *Anterior negativities*

Consistent with previous findings by Canseco-Gonzalez (2000), Canseco-Gonzalez et al. (1997), and Hahne and Jescheniak (2001), more negative ERPs were elicited over the anterior scalp region by syntactic violations in both English and Jabberwocky sentences. The negativity effects to violations were observed around 100 ms and 200 ms after the onset of the critical words. The latency of the negativity effect around 200 ms was earlier than what has been typically reported for the left anterior negativity (LAN).

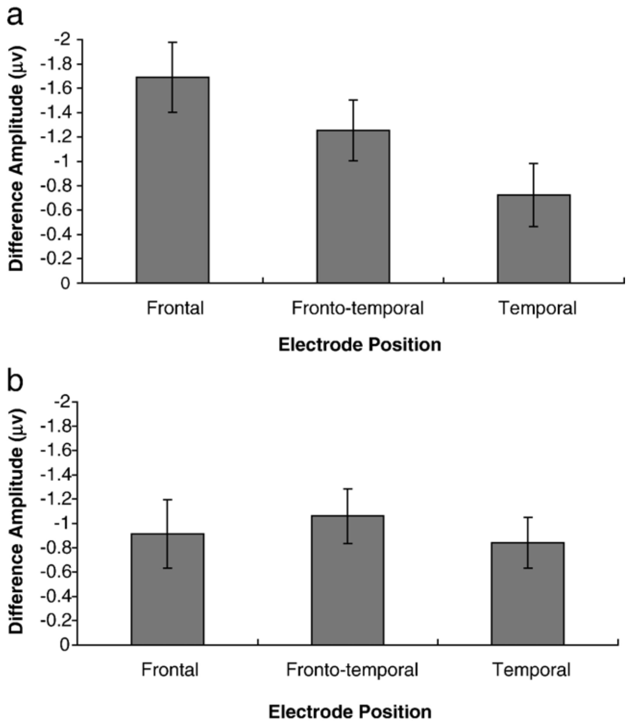

Fig. 4 – Amplitude of the negative grammaticality effect between 180 and 250 ms for (a) English and (b) Jabberwocky. The measurement for each electrode position in the figures is the mean of amplitude differences between the ungrammatical and grammatical conditions measured at four electrodes (lateral and medial sites over left and right hemispheres).

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[4] Unlike the N1 component, the N320 does not show clear peaks at all 12 anterior electrode sites in the grand-average ERP waveforms, thus mean amplitude around the N320 peak (300–340 ms) was also measured and submitted to ANOVAs. These analyses yielded similar results as the analyses on local peak amplitude measurement (Hemisphere: *English* — $F(1,33) = 37.48$, $p < 0.001$; *Jabberwocky* — $F(1,33) = 12.98$, $p < 0.005$; Sentence Type × Hemisphere: $F(1,33) = 9.23$, $p < 0.01$).

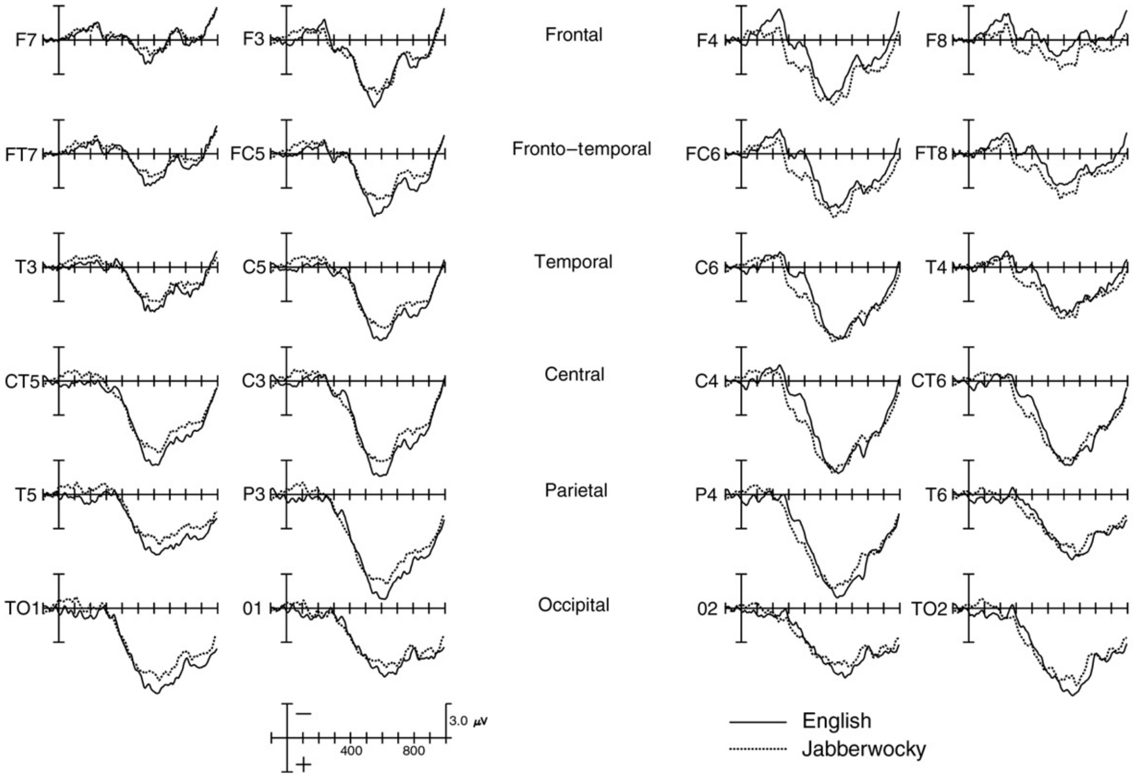

Fig. 5 – Grand-average ERP difference waveforms for English and Jabberwocky sentences. Each waveform represents the difference in voltages between the grammatical and ungrammatical conditions. The differences were computed by subtracting the voltage in the grammatical condition from the voltage in the ungrammatical condition at each electrode site.

Overall, the amplitude of the grammaticality effects at the N1 did not differ between English and Jabberwocky, but they tended to exhibit different distributions. While, for English, the effect was largest over the frontal electrode sites and decreased in amplitude toward temporal and central sites, the effect observed for Jabberwocky was distributed evenly from frontal to central sites. A significant difference in distribution was observed for the grammaticality effects elicited during the 180-250 ms time window. Syntactic violations in English elicited a greater effect over frontal sites than Jabberwocky. Over temporal sites, the amplitude of the effects did not differ between the two sentence types. Therefore, the topographical difference was unlikely attributable to an earlier and/or more robust P600 in English canceling the negative effect at temporal sites. Rather, the current data suggest that syntactic processing in normal English sentences recruits additional neural systems or that some subsystems within the same neural network are recruited to a greater degree during

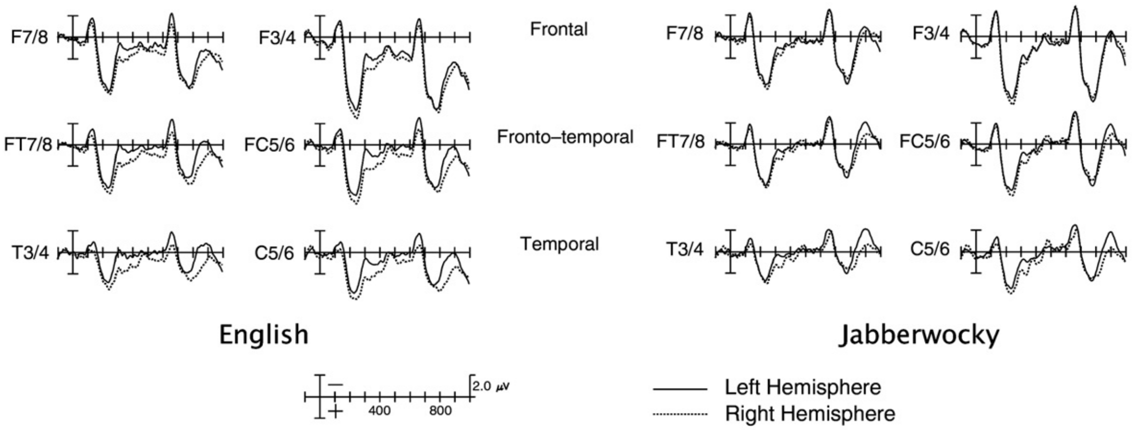

Fig. 6 – Grand-average ERP waveforms for critical words in grammatical sentences. ERPs recorded at left and right hemisphere homologous sites are overlaid.

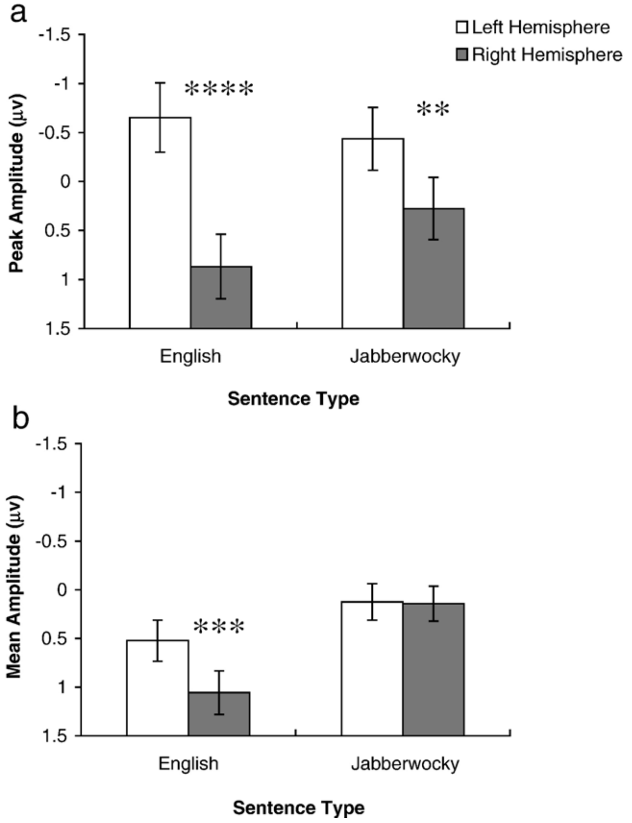

Fig. 7 – Hemispheric laterality. (a) Local peak amplitudes of the N320 as a function of Hemisphere and Sentence Type and (b) mean amplitudes of the N400–550 as a function of Hemisphere and Sentence Type (b). ($^{**}p<0.01$, $^{***}p<0.005$, $^{****}p<0.001$).

processing of English sentences. These results suggest that, although early (<300 ms) syntactic processes are executed in the absence of semantic context, semantic information, or a lack thereof, affects how the processes are carried out. Therefore, the present findings cast doubts to the validity of strict serial, syntax-first models of sentence comprehension and provide evidence for a more interactive view of sentence comprehension in which previous semantic context could affect early syntactic processes.

The frontal maxima observed for English sentences in the present study may be a reflection of neural activity associated with ongoing syntax–semantics interaction. Findings from a number of neuroimaging studies suggest that parts of the network involved in syntactic and semantic processing are in close proximity with each other within the inferior frontal region of the left hemisphere. A functional magnetic resonance imaging (fMRI) study by Dapretto and Bookheimer (1999) has found that semantic processing activates areas in the inferior frontal region adjacent and anterior to the areas activated during syntactic processing—pars orbitalis (BA 47) for semantic processing and pars triangularis (BA 45) for syntactic processing. Activations related to semantic processing have also been observed in the anterior portion of the left inferior frontal region (BA 45/47) in other studies (e.g., Devlin et al., 2003; Hagoort et al., 2004), whereas the areas associated with syntactic processing have been reported to be slightly more posterior (BA 44/45) within the same region (e.g., Embic et al., 2000; Sakai et al., 2002) (for a summary of relevant studies, see Bookheimer, 2002). Using the fMRI technique, Keller et al. (2001) found that the activation in the left inferior frontal gyrus (IFG) was modulated by interaction of syntactic complexity and word frequency. The change in signal intensity in the left IFG, encompassing Brodmann's areas 44, 45, and 47, showed interactive, rather than additive, effects of the two factors. Findings from a number of studies have led to the observation that the areas within the left inferior frontal region may be organized into smaller subsystems, each specialized for semantic, syntactic, and phonological processing (Bookheimer, 2002). The proximity of these subsystems in this area has resulted in the hypothesis that the left inferior frontal region is the area where syntactic and semantic information are integrated to achieve sentence comprehension (Hagoort, 2005; Sakai, 2005), and the present findings support this hypothesis.

The interpretation of the present results, that syntactic and semantic information are integrated even during the early stages of syntactic processing indexed by the anterior negativities, may seem to contradict the conclusion drawn in previous studies which used doubly anomalous sentences (Friederici et al., 1999; Gunter et al., 2000, 1997; Hahne and Friederici, 2002). These studies compared the ERP effects elicited by words that violate both syntactic and semantic constraints (doubly anomalous condition) to those elicited by words that violate only a syntactic constraint (syntactic violation condition). Their conclusion was that the early stages of syntactic processing are independent of semantic processing since the ELAN and LAN (putative indices of early syntactic processing) did not differ between the doubly anomalous and syntactic violation conditions. However, as discussed in the introduction, there is a critical difference between the double-anomaly studies, on one hand, and the Jabberwocky studies, on the other hand, in terms of when the relevant differences in semantic information arise. In the double-anomaly studies, the semantic context is equally coherent up to the point where the critical words are presented. In both the syntactic violation condition (e.g., **Das Eis wurde im gegessen*. [The ice cream was in–the eaten]) and double-anomaly condition (e.g., **Der Vulkan wurde im gegessen*. [The volcano was in the eaten]),[5] it is only at the critical words (underlined in the German examples) that semantic coherence differs between the two conditions. In contrast, in Jabberwocky sentences, the difference in semantic information (i.e., presence vs. absence of semantic information) is present well before syntactic violations occur; therefore, the state of the neural systems for syntactic processing (e.g., whether or not these systems have been interacting with semantic processing systems) may differ between normal and Jabberwocky sentences when critical words that violate a syntactic rule are presented. The present findings raise the hypothesis that pre-existing semantic information, or semantic context, may affect how the initial syntactic processing is carried out.

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[5] In these German examples, *gegessen* (eaten) violates syntactic (word-category) violation since it is preceded by *im* (in–the). These example sentences will be syntactically acceptable if *im* is absent.

In the present study, the grammaticality effect of the negative polarity elicited over the anterior scalp region during the 180-250 ms time window was larger over the right hemisphere as compared to left hemisphere sites in English, whereas a hemispheric asymmetry was not observed for Jabberwocky. These results were unexpected. A lack of left lateralization of anterior negativities, while rare, is not unprecedented. Bilateral (Hahne and Friederici, 2002; Münte and Heinze, 1994; Vos et al., 2001) and right-lateralized (Osterhout and Nicol, 1999) anterior negativities for (morpho-)syntactic violations have been observed in other studies; however, no attempt has been made to systematically investigate experimental conditions which elicit bilateral and right-lateralized anterior negativities. The present study provides additional data that anterior negativities are not always left-lateralized; however, it is not possible to determine the factor that affects the distribution based on the present data.

3.1.2. *P600*

The syntactic violation used in the current study elicited robust P600s in both English and Jabberwocky sentences. However, during the 500-900 ms time window, the P600 elicited in Jabberwocky was attenuated relative to the P600 elicited in English over the left hemisphere. This result is in line with the hypothesis that the P600 reflects in part a semantic-based process (Canseco-Gonzalez, 2000; Canseco-Gonzalez et al., 1997; Münte et al., 1997), but it was not predicted by the Timing Hypothesis (Hahne and Jescheniak, 2001). Since the negative grammaticality effects in this study were elicited early (<300 ms), and since critical words in the present study were closed-class words, thus their occurrences should not be perceived as semantic errors (Münte et al., 2001; Neville et al., 1992; Nobre and McCarthy, 1994); the present data demonstrate that, contrary to the prediction of the Timing Hypothesis, the attenuation of P600 does not require error detection in both syntactic and semantic domains. Unlike the violations in the studies by Canseco-Gonzalez (2000), Canseco-Gonzalez et al. (1997), and Münte et al. (1997), the violations in the study by Hahne and Jescheniak (2001) were at the end of the sentence. The absence of P600 attenuation in Jabberwocky sentences in the latter study may be related to the position of syntactic violation within the sentence. It has been repeatedly observed that, while sentence-medial (morpho-)syntactic violation elicits the P600, the sentence-final words in these ungrammatical sentence elicits negative-going ERPs relative to the sentence-final words in grammatical sentences (McKinnon and Osterhout, 1996; Osterhout and Holcomb, 1992, 1993; Osterhout and Mobley, 1995; Osterhout and Nicol, 1999). Therefore, the amplitude of the P600 elicited by sentence-final syntactic violations may overlap with the sentence-final negativity. If this negativity were larger for normal sentences than for Jabberwocky sentences, a larger portion of the P600 would be masked by the negativity in normal sentences, resulting in the P600s of similar amplitudes for the two types of sentences.

Compared to the studies by Canseco-Gonzalez (2000), Canseco-Gonzalez et al. (1997), and Münte et al. (1997), the P600 attenuation in the present study was small. We are unable to answer why this was so in this study beyond speculation that the type of syntactic violation used in this study might have triggered or required less semantic-based processes in normal English sentences. The large positivity remaining in the Jabberwocky condition suggests that semantic-based processes comprised only a part of those underlying the P600 in the present study, and a question remains as to what other processes underlie the P600. It has been reported that the amplitude of the P600 is modulated by factors besides absence of semantic content. Two factors investigated extensively are the proportion of sentences with (morpho-)syntactic violations and the relevance of violations to the performance of an experimental task. These studies have found that the amplitude of the P600 is reduced when the proportion of ungrammatical sentences is high (≥75%) (Coulson et al., 1998; Gunter et al., 1997; Hahne and Friederici, 1999a) or when participants were not asked to make grammaticality judgments (Gunter and Friederici, 1999; Hahne and Friederici, 2002; Osterhout et al., 2002b; Osterhout and Mobley, 1995). Hahne and Friederici (2002), for example, presented both syntactically and semantically anomalous sentences and asked participants to judge the semantic coherence of each sentence while ignoring syntactic errors. Compared to the P600 elicited in participants who were asked to judge both semantic coherence and syntactic well-formedness, the P600 was greatly reduced in participants who made judgments only on semantic coherence.

The findings from a few lesion studies (Frisch et al., 2003; Kotz et al., 2003) provide evidence that the absence of a P600 correlates with poor grammaticality judgment accuracy. In these studies, patients with lesions in the basal ganglia failed to show a P600 to argument structure (subcategorization) violations although they showed an N400-like negativity. In contrast, patients with a lesion outside the basal ganglia showed a P600 to the same violations, but no negativity. Behaviorally, the basal ganglia patients (who showed no P600) made twice as many errors in making grammaticality judgments as the non-basal ganglia patients (who showed a P600). Using the same stimulus materials as the present ones, we have conducted a study to examine to what extent the P600 is reduced in English and Jabberwocky sentences when participants do not perform a grammaticality judgment task (Yamada and Neville, in preparation). A large reduction in amplitude was observed for both English and Jabberwocky. These results suggest that the processes underlying the P600 elicited in the present study are related to making grammaticality judgments.

3.2. *Closed-class word effects*

An additional interest in the present study was to explore whether the closed-class words in Jabberwocky sentences are processed in a similar manner as the closed-class words in English sentences. The ERPs elicited by critical words (determiners and possessive pronouns) in the grammatical sentences were analyzed for this purpose. The latency of the first negative peak after the anterior N1–P2 complex was approximately 320 ms (N320). The N320 was larger over the left hemisphere relative to the right hemisphere for both sentence types. Left lateralization of the N320 is not likely to be related to syntactic integration processes since it has been observed for closed-class words presented not only in normal sentences (Brown et al., 1999; Neville et al., 1992; Osterhout et al., 1997, Experiment 1) but also in word lists and random sentences (i.e., sentences in which words are scrambled in order) (Nobre and McCarthy, 1994; Osterhout et al., 1997, Experiment 2; Pulvermüller et al., 1995) which do not have syntactic structures into which closed-class words are integrated. Pulvermüller (1996) and Pulvermüller et al. (1995) have argued that the ERPs elicited by closed-class words were left-lateralized because neuronal assemblies representing closed-class words are located in the left hemisphere peri-Sylvian cortices. Therefore, the left-lateralized N320 may reflect lexical-level processing of closed-class words such as word search and/or identification within the closed-class (Brown et al., 1999; Neville et al., 1992). The present results suggested that this process is similarly performed for closed-class words in normal and Jabberwocky sentences.

The late negative component (N400–550) elicited by closed-class words differed between English and Jabberwocky in terms of hemispheric lateralization in the present study. The N400–550 was larger over the left hemisphere in English while it was symmetrical in Jabberwocky. Left lateralization of this component seems to be related to the context in which closed-class words are embedded. When closed-class words are presented in normal sentences, the late negativity has been larger over the left hemisphere (Brown et al., 1999; Münte et al., 2001, Experiment 2; Neville et al., 1992), whereas, when closed-class words are presented in word lists, no hemispheric asymmetry has been observed (Münte et al., 2001, Experiment 1; Pulvermüller et al., 1995). It has been hypothesized that this late negative component reflects expectancy for upcoming meaningful words since closed-class words are frequently followed by meaning-bearing open-class words in sentences (Brown et al., 1999). A lack of hemispheric asymmetry for closed-class words in Jabberwocky sentences in the present study, along with the previous studies in which closed-class words were presented in word lists, suggests that such expectancy is indexed by left lateralization of this late negative component.

3.3. *Conclusion*

The findings in the present study provide evidence that the early syntactic processing indexed by anterior negativities is not entirely independent of what is or is not taking place in the semantic domain during on-line processing. This finding illustrated that the processing of syntactic information of a newly incoming word interacts with previous semantic context at earlier stages of processing, suggesting that syntactic and semantic processing begin to interact earlier than that has been proposed by serial, syntax-first models. As discussed above, differences in the semantic domain between English and Jabberwocky sentences were present before syntactic information of the critical words became available in the present study. Although previous findings from the double-anomaly studies suggest that, when relevant syntactic and semantic information are presented simultaneously, initial syntactic processing is unaffected by semantic information; a more recent study (van den Brink and Hagoort, 2004)[6] provided evidence that this may not be the norm during on-line comprehension of spoken sentences. In the auditory modality, different types of information for a particular lexical item do not necessarily become accessible simultaneously, and semantic processing for a lexical item could precede syntactic processing if semantic information becomes available earlier than syntactic information. These findings suggest that sentence comprehension involves continuous interaction of information processing in different domains and that processing systems are flexible with respect to the timing at which different types of linguistic information are processed and utilized during comprehension.

The present findings with respect to the P600 were in line with the hypothesis that at least a part of the processes indexed by this effect requires semantic content. These results also generate questions regarding other processes indexed by the P600. The P600 has been reported to be modulated by more than one factor and is likely to index multiple cognitive processes. However, the exact nature of the processes underlying the P600 has not yet been fully identified. Further studies that systematically parcel out contributions of various cognitive processes generating this late effect are necessary to better understand ERP indices of on-line language processing.

Neural systems subserving syntactic and semantic processing may interact with each other continuously during sentence processing although how the two subsystems affect each other may not be the same for earlier and later stages of sentence comprehension. In particular, it was not ascertainable what the exact nature of the early interaction is in the present study. These questions are left for future investigation.

4. Experimental procedures

4.1. *Participants*

Thirty-four monolingual native English speakers (18 females) were recruited at the University of Oregon to participate in this experiment. The mean age of the participants was 21.6 years (SD = 3.7). All participants were right-handed as assessed by the Edinburgh Inventory for handedness (Oldfield, 1971). They reported having no known neurological disorder and having normal or corrected-to-normal vision. They were paid for their participation.

4.2. *Materials*

Stimulus materials consisted of 240 sentences. There were 54 experimental sentences in each of the following four categories: (1) grammatical English sentences, (2) ungrammatical English sentences, (3) grammatical Jabberwocky sentences, and (4) ungrammatical Jabberwocky sentences (see Table 1 for examples). In addition to these experimental sentences, 24 distracter sentences, each sentence being one of the four types listed above, were included in the stimulus set. Ungramma-

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[6] We would like to thank an anonymous reviewer for bringing this study to our attention.

tical versions of the experimental sentences were created by inserting an extra closed-class word, either a demonstrative (e.g., *this*, *that*) or possessive pronoun (e.g., *his*, *my*), in the sentence-final prepositional phrase. Presence of an extra closed-class word caused a violation of English phrase structure rules. Ungrammatical versions of the distracter sentences were created by switching the positions of the verb and an article or demonstrative in the direct object noun phrase immediately following the verb. The distracter sentences, specifically the ungrammatical versions, were included so that participants would not simply attend to the sentence-final prepositional phrase to detect syntactic violations.

Jabberwocky sentences were constructed by replacing all open-class words in the English sentences with pseudo-words while keeping closed-class words and inflectional morphemes intact. Pseudo-words in Jabberwocky sentences were created by substituting each phoneme in the original open-class words with a different phoneme. Each consonant was replaced by another consonant with the same manner of articulation whenever possible. That is, when this procedure yielded consonant clusters which are not permissible in English or produced real words, the above restriction was relaxed, and consonants with different manners of articulation were selected as substitutes. Each vowel was also replaced by another vowel. The word-initial phonemes in the original words were always retained regardless of whether they were consonants or vowels.[7]

4.3. *Procedure*

All participants gave written consent and filled out a language experience questionnaire before participating in the ERP experiment. The purpose of administering the questionnaire was to ensure that participants had not had extensive experience with languages other than English. After application of a cap with electrodes, participants were seated in a dimly lit and acoustically and electrically shielded booth. They were asked to read each sentence silently and judge whether or not it was grammatically correct. As a part of the instructions, participants were told that some of the sentences would be English, and some of the sentences would be English-like, and they were given an example of each type of sentences. Participants were also told that their judgments must be based on grammaticality of the sentences and not on whether the sentences made sense.

English and Jabberwocky sentences were intermixed and presented visually, one word at a time, in a fixed pseudo-randomized order on a cathode-ray monitor situated approximately 140 cm away from participants. Words were printed in white against a black background. The visual angle of words subtended 0.4 to 4.2° horizontally and 0.4 to 1° vertically. At the beginning of each trial, the monitor displayed a black background. A second after participants pressed a button to initiate a trial, a white rectangular border (subtending $6.4 \times 4.2°$ visual angle) appeared on the monitor. The first word of a sentence appeared at the center of the border 750 ms later. Each word in a sentence was presented for 300 ms with an inter-stimulus interval of 233 ms. After the offset of the last word of a sentence, the border remained on the monitor for 2233 ms. Participants waited until the border disappeared to make a response. Responses were made by pressing either the right or left button, one for a "yes" (grammatical) judgment response and the other for a "no" (ungrammatical) judgment response, with the index finger of the corresponding hand. A subsequent trial was initiated by pressing one of the two buttons. The sides of the initiation and response buttons were counterbalanced across participants.

Ten percent of the stimulus sentences (12 English and 12 Jabberwocky) were followed by a probe word which appeared on the monitor upon making a grammaticality judgment response. Participants were asked to judge whether the probe word was one of the words in the immediately preceding sentence. Responses were made by pressing the "yes" (present) button or the "no" (absent) button. The probe words as well as the distracter sentences were included to encourage participants to attend to the entire span of sentences.

Before experimental trials, the participants had 12 practice trials. Half of the practice trials were in English, and the rest were in Jabberwocky. Half of the sentences in each type were ungrammatical. The practice trials also included four probe words. Participants received feedback on the accuracy of their judgments on each practice sentence and probe word. No feedback was given during the experiment. Throughout the experiment, participants were encouraged to stay still and not to blink or move their eyes while the rectangular border was displayed on the monitor.

4.4. *ERP recording and analysis*

The EEG was recorded from 29 tin electrodes attached to an elastic cap (Electro-Cap International). Locations of the scalp electrodes are shown in Fig. 8. The electrooculogram was also recorded from electrodes placed at outer canthi of both eyes and below the right eye. All scalp electrodes were referenced to the right mastoid during recording and re-referenced to the average of the left and right mastoid off-line. The EEG was amplified with a bandpass of 0.01–100 Hz and digitized at the sampling rate of 250/second (i.e., every 4 ms).

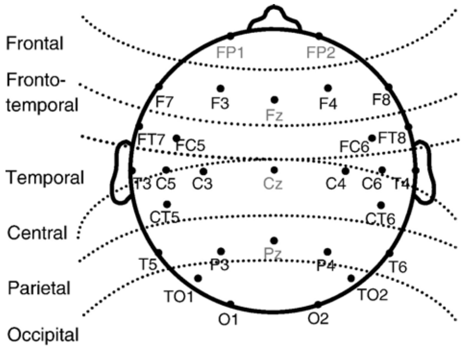

Fig. 8 – Approximate electrode locations. Electrodes labeled in black are those included in analyses.

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[7] The word-initial phonemes were retained in order to achieve consistency in coding word onset in the auditory version of the same stimulus sentences.

The EEG was averaged to the onset of the critical words with a 100 ms pre-stimulus baseline. Trials that were judged incorrectly and/or contained ocular artifacts were excluded from averages. Analyses included ERPs recorded at 24 scalp electrodes (F7/8, F3/4, FT7/8, FC5/6, T3/4, C5/6, CT5/6, C3/4, T5/6, P3/4, TO1/2, O1/2).

For the analyses of the grammaticality effects, repeated-measures analyses of variance (ANOVAs) were conducted for each sentence type (English or Jabberwocky) separately with four factors (Grammaticality [grammatical, ungrammatical], Hemisphere [left, right], Anterior/Posterior [frontal, fronto-temporal, temporal, central, parietal, occipital], and Lateral/Medial [lateral, medial]). For the analysis of the peak amplitudes between 75 and 175 ms, only four levels (frontal, fronto-temporal, temporal, central) were included in the Anterior/Posterior factor since the negative peaks around 100 ms after the onset of critical words (N1) were not reliably measurable over parietal and occipital electrode sites. For the analyses of closed-class word effects, ERPs elicited by the critical words in the grammatical condition were examined separately for English and Jabberwocky by conducting a three-factor repeated-measures ANOVAs (Hemisphere [left, right], Anterior/Posterior [frontal, fronto-temporal, temporal], Lateral/Medial [lateral, medial]). The factor Sentence Type (English, Jabberwocky) was included in ANOVAs when direct comparison of the two sentence types was called for. The Greenhouse–Geisser correction was applied to all main effects and interactions involving factors with more than two levels.

In order to carefully examine differences in distribution of grammaticality effects, ERP data were normalized as follows: difference ERPs were computed by subtracting the ERPs elicited in the grammatical condition from those in the ungrammatical condition, and mean amplitudes within time windows of interest were measured on the difference ERP waveforms. Subsequently, the data were normalized by the following procedure recommended by McCarthy and Wood (1985): the grand mean amplitude and standard deviation of all the electrode sites and all the participants were computed for each condition. The grand mean amplitude was subtracted from the amplitude at each electrode site for each participant, and the difference was divided by the standard deviation.

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