Testing the sensory hypothesis of the early left anterior negativity with auditory stimuli☆

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Abstract

The sensory ELAN hypothesis states that the ELAN ERP component is a sensory component generated by very early detection of syntactic errors relying on predictions not only about grammatical category, but phonological form. This study extended previous findings on the sensory content of the visual ELAN by testing the effect of closed-class functional morphology on the processing of auditorily presented filled-gap sentences. Filled gap NPs with closed-class morphology elicited a Left Anterior Negativity (LAN), while those without were found to elicit a N400 component. The sensory ELAN hypothesis was partially supported, to the extent that differential ERP responses due to the presense or absence of closed-class morphology suggests that early parsing is sensitive not only to category, but to form, and that such morphology may increase the form-typicality of lexical items within their grammatical categories, speeding diagnosis of unexpected categories. In addition, the fact that filled gap NPs without closed-class morphology elicited a N400 component indicates that these items reach a semantic stage of processing, raising questions for serial/syntax-first models of processing.

Keywords: sentence processing, ERP, Early Left Anterior Negativity (ELAN), LAN, N400

1. Introduction

The Early Left Anterior Negativity (ELAN) is an event-related potential (ERP) component associated with syntactic processing and characterized by a negative-going wave in left anterior electrodes as early as 120ms after an unexpected of word category (Friederici et al., 1993; Friederici, 1995; Friederici et al., 1996; Hahne and Friederici, 1999; Neville et al., 1991). Friederici (2002) proposed a multi-stage model of processing in which syntactic structure is built

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based on grammatical categories, before a semantic phase in which semantic content and argument structure relations are computed. Under this model, the ELAN is assumed to be generated by left-anterior brain regions (e.g. superior temporal gyrus, BA 44) in the early syntax-only phase when an unexpected word category interferes with phrase structure building. Not yet fully explained is how a syntactic violation can be diagnosed so early by frontal brain regions, when the ELAN occurs in the same time range as early sensory processing (Bonte et al., 2006; Di Russo et al., 2002; Hickok and Poeppel, 2007).

Recent work (Lau et al., 2006; Dikker et al., 2009b,a) has led to a hypothesis that the ELAN has a greater basis in sensory processing than previously assumed. The present study aims to test this sensory hypothesis in the auditory domain. After reviewing existing evidence for the sensory hypothesis, results of two experiments designed to test predictions following from these findings are presented.

1.1. Background

1.1.1. ELAN and expectation

Lau et al. (2006) attempted to explain the very early occurrence of the ELAN as a function of expectancy. As the parser builds syntactic structure based on each word encountered in an utterance,upcoming grammatical categories are anticipated. Lau and colleagues manipulated the strength of the anticipation generated by the syntactic environment preceding a category violation. For the same violation, they found a greater ELAN response to those violations which occurred in strongly predicted environments than weakly predicted ones. The ELAN is stronger in these environments because the parser generates a strong prediction about the next category, making the unexpected category of the next word easier or faster to detect. In Friederici's model, wherein the ELAN reflects a general failure of structure building, this effect of the preceding context is unpredicted, because an unexpected word category results in failure of structure building in either case. Lau et al. (2006) conclude that the ELAN indexes a violation of expectation about a word's grammatical category based on the probability of that category given the preceding environment, rather than an ungrammatical syntactic structure *per se*.

Dikker et al. (2009b) extended the findings of Lau et al. (2006), proposing that because the ELAN occurs in the same time period as early sensory processing, it is in fact a response to physical properties of a grammatically unexpected item, and is generated by sensory areas rather than the higher-level structure-building areas in Friederici's model. That sensory areas may be sensitive to syntactic information is not entirely suprising. Hahne et al. (2002) found no topographical difference between the ERP responses to unexpected grammatical categories and those to acoustically unexpected items, and Pulvermüller and Shtyrov (2003) found that the ERP response to rare syntactic violations in a stream of frequent grammatical sequences was very similar to the Mismatch Negativity (MMN) response in both latency and topography Pulvermuller and Shtyrov (2006); Maess et al. (2009) localized this syntactic Mismatch Negativity (sMMN) to areas including the left auditory cortex. Taken together, these results are consistent with the hypothesis that the ELAN is generated in similar areas as the MMN, the auditory version of which is known to be generated by structures in and around auditory cortex by violations of expectations about the acoustic properties of a stimulus (Näätänen et al., 1997, 2001).

Dikker et al. (2009b) note that previous ELAN results had been demonstrated only with targets which include overt, closed-class functional morphology (Hahne and Friederici, 1999), such as (1) from Friederici et al. (1993), containing the German participle *ge-*. They also point out that closed-class lexical items have been shown to be privileged and processed more quickly in a variety of tasks in comparison to open-class lexical items (Bradley, 1983). Dikker et al. (2009b) proposed that closed-class morphemes speed word category identification, leading to earlier diagnosis of category violations when the illicit category is instantiated as closed-class functional morphology.

(1)	*Das	Baby	wurde	im	*gefüttert*
	the	baby	was	in the	fed

In order to test these hypotheses, Dikker et al. (2009b) measured the MEG response of frontal and occipital regions of interest following unexpected targets consisting of either an open-class (bare nominal (3)) item, open-class item with bound closed-class morphology (participle (5)), or closed-class function word (preposition (7); these responses comparing the response to that of their grammatical counterparts ((2), (4), and (6), respectively). Although the bound participle morpheme comes at the end of the word, the sentence was presented using a single word reading paradigm, meaning that the entire target could be read at once.

The visual M100, a response generated by occipital visual cortex in the ELAN time range in response to stimulation, was more negative after an unexpected item, but only when the unexpected item contained a closed-class morpheme; no response to unexpected items was found in anterior (non-sensory) regions. Dikker and colleagues concluded that the visual analogue of the ELAN in MEG is a negative amplitude deflection of the M100 component, which is indeed generated by sensory areas, specifically the visual cortex for visually presented sentences, and that it reflects the detection of visual properties of closed-class function morphemes which are unexpected in the context of a strong top-down anticipation of the a word's grammatical category.

(2) The discovery was *reported*

(3) *The discovery was *report*

(4) The discovery was in the *report*

(5) *The discovery was in the *reported*

(6) The boys heard Joe's *stories* about Africa

(7) *The boys heard Joe's *about* stories Africa

A second study by the same group (Dikker et al., 2009a) found that the presence of closed-class morphology was not strictly necessary to produce these

M100 effects. In addition to morphology, lexical items in a given grammatical category tend to share other perceptual features, such as phonological features. In a single-word reading task, Dikker et al. (2009a) found that unexpected targets which were highly typical of their class (8) increased M100 amplitude relative to expected items, while unexpected items which were less typical of their class (9) did not differ from expected items. Controlling for form typicality, there was no additional effect of closed-class morphology on the M100, suggesting that the effect of such morphology on processing seen in Dikker et al. (2009b) may be to increase the typicality of items which contain it.

(8) *The strongly *garlic* was used

(9) *The thickly *forest* was logged

The exact nature of the contrast between function and content lexical items has not yet been determined, but it seems that visual cortex is sensitive to grammatical category and lexical class distinctions at an early stage of processing. Pulvermüller et al. (1999) showed that nouns and verbs generate different ERPs by 200ms, and Pulvermüller et al. (2004) demonstrated differential MMN responses to individual words from different grammatical categories. Pulvermüller et al. (1995) showed that content and function words generate different ERP responses as early as 160ms after onset. Function words showed a hemispheric asymmetry, with greater negativity over the left than right hemisphere, while content words did not elicit such an asymmetry. The authors propose that content and function words are encoded differently: content words are represented by neuronal assemblies in both hemispheres, while function words are strongly left-lateralized.

In summary, two conditions appear to be necessary for the ELAN to occur: a strong expectation about the grammatical category of a target, and a target which is typical of an another, unexpected grammatical category. Closed-class morphology seems to increase this typicality. As the parser encounters the words of a sentence one by one, it fits them into a phrasal structure, and generates expectations about the structure of the rest of the sentence. These structural predictions are predictions about the categories of the upcoming constituents of the sentence, based on the rules of phrase structure and the structures allowed or likely given the words encountered so far; these expectations about category include information about form. Because of their small number and high frequency, items in the closed class of functional and derivational morphology, such as determiners, are strong indicators of phrasal category, and can be recognized quickly based on their phonological features. When the parser generates an expectation for some category other than a noun phrase, the sound or visual shape of the determiner *the* is enough to indicate an unexpected category. [1]

[1] This leads to an interesting prediction: if the physical features of morphology facilitate very early diagnosis of an unexpected category, then open class lexical items with features similar to those of a closed-class morpheme (2) might be expected produce an ELAN response as well, perhaps even if they are in fact of a licit category. Likewise, given the findings of

1.1.2. Auditory ELAN

Fewer studies have examined the ELAN using auditorily presented stimuli in a sentence processing task. Hestvik et al. (2007) found that an ungrammatically filled gap position in relative clause sentences (10) elicited an ELAN. When a word or a phrase is displaced from its canonical syntactic position, it must be associated with the correct verb in order to determine its semantic role. A phrase which has been identified as a potential filler must be held in verbal working memory until the parser encounters a verb with which it can associate the displaced phrase. Hestvik et al. (2007) demonstrated that the parser constructs traces in order to compute displacement dependencies at the purely syntactic level. A noun phrase occurring where a trace is expected generates an ELAN. It is notable that this ELAN does not necessarily reflect a violation of strictly local phrase structure, *per se*, in that the verbs used could have been followed by nouns in other kinds of sentences (11), but instead clearly reflects a violation of expectation about word category generated by the previous sentence environment, while some other studies contain targets which are violations of phrase structure under any circumstances, such as *was report* (3, Dikker et al. (2009b)) and *im gefüttert* (1, Friederici et al. (1993)). Hestvik et al. (2009) found that the same sentences did not appear to elicit an ELAN when presented at a higher frequency compared to grammatical sentences (15% in Hestvik et al. (2007) vs. 25% in Hestvik et al. (2009)). An increase in frequency of the ungrammatical condition raises the degree of expectancy of the target (Lau et al., 2006), which suggests that the ELAN is sensitive to the relative frequency of targets and standards within an experiment, much like the MMN. This is contrary to earlier findings (Hahne and Friederici, 1999) indicating that the occurence of the ELAN is unaffected by the frequency of ungrammatical sentences within the experiment, which was taken as evidence for an early, automatic stage of parsing.

(10) The zebra that the hippo kissed *the camel* on the nose ran far away

(11) The zebra said that the hippo kissed *the camel* on the nose

1.2. The auditory sensory ELAN hypothesis

The present study examined whether the presence or absence of functional morphology modulates the ELAN response to syntactic category violations during real-time auditory sentence processing. In the stimuli used by Hestvik et al. (2007) and Hestvik et al. (2009), all targets were noun phrases beginning with the function morpheme *the*. The present study aims to determine whether the

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Dikker et al. (2009a), a bare lexical item which is atypical of its class and more typical of another may give rise to an ELAN effect due to a 'misdiagnosis' of an unexpected category.

(1) *The dog bit my *the* leg

(2) The dog bit my *then* pain-free leg

auditory ELAN is sensitive to the closed-/open-class distinction found by Dikker et al. (2009b) using visual presentations by comparing auditorily presented sentences like (12) and (13). If auditory cortex differentiates between grammatical categories based on form typicality information enhanced by morphology, then the ELAN should occur for category violations which are signaled by a functional morpheme (12) and not for those which lack it (13). Those unexpected targets without such morphology cannot be diagnosed as quickly, and should be indexed by a syntactic violation component with a later onset latency than the ELAN.

(12) The dog that the cat kissed <u>the turtle</u> on the nose ran far away.

(13) The dog that the cat kissed <u>turtles</u> on the nose ran far away.

1.3. Current Predictions

Both sentences contain an unexpected noun phrase following the verb *kissed*. If the auditory ELAN indexes failure of syntactic structure building due purely to an unexpected category, then an identical or very similar ERP response to the onset of each underlined phrase would be expected. If, as proposed by Dikker *et al.* for visual cortex, the auditory cortex differentiates between syntactic categories based on form, allowing faster phrasal category identification for phrases marked by closed-class morphemes, then the ELAN should occur only for category violations which are signaled by an overt function morpheme, and the ELAN response should be present for sentences like (12) but not for those like (13) in comparison to an expected phrase category. Phrases like those in (13), with unexpected categories but which do not include functional morphology, cannot be diagnosed as quickly because their acoustic properties are not as strong an indicator of their category as the acoustic properties of function morphemes are for the category of their phrases. However, ungrammatical elements must still be recognized as such at some point, and should be reflected in a later syntactic component, such as the Left Anterior Negativity (LAN) (Friederici et al., 1993) in the 300–500ms latency range, and/or P600 (Osterhout and Holcomb, 1992; Hagoort et al., 1993), 600ms or more after onset of the unexpected target.

In order to test these predictions, two experiments were conducted in order to contrast the effects of unexpected phrases which contain closed-class functional morphology (Experiment 1) with those that do not (Experiment 2).

2. Experiment 1

Experiment 1 closely replicates the design of Hestvik et al. (2007).

2.1. Method

2.1.1. Participants

18 adults (10 female), ranging in age from 19 to 28, were recruited from the University of Delaware student community, and were compensated $15 for

their participation (one participant received course credit in lieu of monetary compensation). All participants gave informed consent, and all procedures were approved by the University of Delaware Human Subjects Review Board.

2.1.2. Design

Stimuli sentences were adapted from those used in Hestvik et al. (2007) and Hestvik et al. (2009), which were in turn adapted from Love (2007) and Love and Swinney (1997). Test sentences used by Hestvik et al. (2007) and Hestvik et al. (2009) contained an ungrammatical noun phrase (underlined) in the trace position of a relativized object (the Ungrammatical Object, or *UngramObj*, condition) (14):

(14) *The dog that the cat kissed <u>the turtle</u> on the nose ran far away.

The experiments by Hestvik et al. (2007) and Hestvik et al. (2009) included three additional conditions: the Grammatical Object Trace (*ObjTrace*) condition, in which a grammatical trace followed the verb (15), the Grammatical Object (*GramObj*) condition, in which a noun phrase following the verb was grammatical (16), and the Adjunct Relative (*AdjRel*, used only by Hestvik et al. (2009)) condition, in which a (grammatical) noun phrase follows the verb, and an adjunct has been relativized (17):

(15) The dog that the cat kissed <u>*t*</u> on the nose ran far away.

(16) The dog said that the cat kissed <u>the turtle</u> on the nose and then ran far away.

(17) The day that the cat kissed <u>the turtle</u> on the nose, they ran far away.

The *AdjRel* condition was introduced in order to control for the presence of a long distance dependency which is not present in the *Grammatical Object* condition, and target category (the category immediately following the verb in the *Object Trace* is not a determiner). The present study will compare only the *UngramObj* and *AdjRel* conditions. Both the *UngramObj* and *AdjRel* conditions contain a long-distance dependency, and the category of the phrase following the verb is a noun phrase in all cases. The other conditions used by Hestvik et al. (2007), plus a Grammatical Subject Trace (*SubjTrace*) condition, were retained as fillers in order to control participants' degree of expectancy both for relative clauses and ungrammatical sentences.

The 32 unique verbs used in Hestvik et al. (2007) were used to construct sentences by combining them with 32 unique sets of animal noun phrases; each animal noun phrase consisted of a singular animal name preceded by the determiner *the*. Each verb was used twice (*i.e.*, with two sets of animals) in each of the five conditions, resulting in 320 total sentences (see Appendix for the full set of stimuli.)

Sixty-four additional filler sentences (condition *Filler*) were added to further reduce the frequency of ungrammatical sentences in the experiment, based on the observation by Hestvik et al. (2009) that an increase in the frequency of

UngramObj	*The dog that the cat kissed the turtle on the nose ran far away.
AdjRel	The day that the cat kissed the turtle on the nose, they ran far away.
GramObj	The dog said that the cat kissed the turtle on the nose and then ran far away.
ObjTrace	The dog that the cat kissed *t* on the nose ran far away.
SubjTrace	The dog that *t* kissed the cat on the nose ran far away.
Filler	The mole reminded the gophers in the yard to stay away from the garden.
	The bobcat that had roared at the mountain lion near the river, walked along the bank.
	...

Table 1: Examples of sentence types in Experiment 1.

ungrammatical sentences in an experiment attentuates the ELAN response. The frequency of ungrammatical sentences in Experiment 1 was 16.7%. The filler sentences also increased the variety of sentence types heard by the subjects; filler sentences contained both relative clauses and other sentences structures, and included both plural and singular noun phrases. Stimulus conditions used in Experiment 1 are summarized in 1.

Comprehension questions were constructed for each filler and test sentence. Half of the comprehension questions were Yes/No questions (counterbalanced for correct answer), either about the action in the sentence (18), or its lexical content (19), and half were Wh-questions (20). These question types were selected to encourage attention to both the lexical (word recall) and semantic (computation of argument structure) content of the sentences. Question types were distributed equally across conditions. Although answering content questions about ungrammatical sentences is difficult or impossible, the same distribution of question types was used in the *UngramObj* condition in order to prevent participants from anticipating ungrammatical sentences, and to encourage the same attention and effort in parsing these sentences as for the grammatical conditions.

(18) Did the dog kiss the cat?

(19) Did you hear the word *kitten*?

(20) Who kissed the cat?

2.1.3. Stimuli

Sentences were created using the ModelTalker text-to-speech system Bunnell et al. (2005). Synthesized speech was chosen to afford control over intonational information and minimize confounding differences between conditions. ModelTalker is a concatenative synthesizer which constructs words and sentences from sampled speech units and combines them with synthesized F0, pitch contour, and stress.[2]

[2]Vogel et al. (2009) compared naturally-produced speech to that generated by ModelTalker. Although they observed lower overall accuracy in comprehension of synthesized speech, the

Questions consisted of natural speech, and were recorded by a female native speaker of American English. Questions and sentences were equalized for loudness.

2.1.4. Procedure

Task procedure. Participants were seated in front of an LCD screen and speakers. Stimuli were presented using E-Prime Software and responses collected via the Serial Response Box from Psychology Software Tools (Schneider et al., 2002).

Participants were informed that they were taking part in a test of sentence comprehension, and that they would be asked questions about sentences spoken by a synthetic voice, which would require their careful attention to understand. They were not told that some sentences would be ungrammatical, but were warned that some of the sentences would be difficult to understand, and were encouraged to do their best in answering the questions as accurately as possible.

Sentences were presented in 4 blocks of 96 trials (80 test sentences and 16 fillers), for a total of 384 trials per subject. Each trial began with a fixation cross. After a 500 millisecond delay, the sentence was presented. Following the sentence, a question-mark prompt appeared and the question was presented. Two possible answers (either two pictures, or the words *yes* and *no*, depending on the question type) appeared, and participants had two seconds in which to select an answer using a button box. After responding, feedback was given visually and a running accuracy score was displayed to encourage effort.

ERP acquisition. Participants were seated in a sound-attenuated, electrically shielded booth. EEG was acquired at 250Hz using the Electrical Geodesics 128-channel Geodesic Sensor Net. Impedances were held below 50 kΩ on each channel, and were re-checked halfway through the session.

2.1.5. Analysis

Behavioral analysis. Accuracy in response to questions following sentences in the conditions of interest (*AdjRel* vs. *UngramObj*) was analyzed using a mixed logit model. Correct Answer was regressed on fixed effects Condition and Question Type and random effect Participant; results were calculated in the `R` statistical environment (R Development Core Team, 2009) using the LME4 package Bates and Maechler (2009).

ERP analysis.

EEG preprocessing Continuous EEG data were segmented into 1000ms epochs with a 200ms baseline period synchronized to the onset of the first word following each relative clause verb. Trials containing eye blinks or other artifacts

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same pattern held between conditions in a stress discrimination task, suggesting that the synthetic speech is processed in a similar way to natural speech.

	AdjRel	UngramObj	
Wh-	89.06%	54.86%	71.96%
Yes-No	93.92%	92.36%	93.14%
	91.49%	73.61%	82.55%

Table 2: Response accuracy by Condition and Question Type for Experiment 1.

were removed, bad channels were replaced using spherical spline interpolation, and baselines corrected using Net Station software (Electrical Geodesics, Inc., 2003). An average of 20.2 trials (SD = 14.07) were eliminated for each subject across both experiements.

In order to reduce noise, participants who exhibited excessive artifacts were removed from further analysis. Only those who had at least 32 good trials (50%) in both the *AdjRel* and *UngramObj* conditions were included. Two participants were eliminated from Experiment 1, leaving $N = 16$ in subsequent analyses.

Components with spatial and temporal characteristics matching predicted components were selected for statistical analysis. Samples were averaged over 20ms time bins, and amplitudes of peak electrodes were entered into a Condition x Time Bin ANOVA.

2.2. Results

2.2.1. Behavioral results

Overall accuracy in response to all questions (including fillers) was above %80 (M = 82.55%), indicating that subjects were successfully comprending and responding to the sentence stimuli.

Questions following *AdjRel* sentences were answered correctly more often than those following *UngramObj* questions (Ms = 91.49% vs. 73.61% , respectively), and Yes-No Questions were answered correctly more often than Wh-questions (93.14% vs. 71.96%, respectively). The logit model revealed a significant main effects of Condition, Z = -12.323, p <.001, and Question Type, Z = 2.936, p <.001.

These effect was driven almost entirely by a significant interaction between Condition and Question Type, Z = 5.123, p <¡ .001. Yes-No questions following ungrammatical sentences were answered correctly 92.36% of the time, but Wh-questions were answered correctly only 54.86% of the time. This is unsurprising, because most Yes-No questions regarded the lexical content of their subject sentences, while Wh- questions addressed the action described by the sentence; lexical content can be easily assesed, even for ungrammatical sentences, while the violations of argument structure found in the ungrammatical sentences make understanding the sentence difficult or impossible.

Accuracy scores are summarized in Table 2; statistical results are summarized in Table 3.

2.2.2. ERP Results

Targets in the *UngrammObj* condition produced two components of interest: an anterior negativity, followed by a more central positivity.

	β	SE β	Z	p
Intercept	2.1904	0.1796	12.199	<.001 ***
Condition	-1.9835	0.1610	-12.323	<.001 ***
Question Type	0.6528	0.2223	2.936	0.003 **
Condition*Question Type	1.7340	0.2867	6.048	<.001 ***

Table 3: Summary of by-participant mixed logit analysis for Experiment 1; $N = 18$. ** indicates $p < .01$, *** indicates $p < .001$.

	df	SS	MS	F	p
Condition	1	44.6	44.6	4.6357	0.0320 *
Time Bin	1	0.5	0.5	0.0571	0.8113
Condition*Time Bin	1	8.7	8.7	0.9009	0.3432
Residual	348	3351.6	9.6		

Table 4: Analysis of variance for electrode 25, 250-400ms post-stimulus in Experiment 1. * indicates $p < .05$.

Anterior negativity. UngramObj targets elicited a more negative-going wave in anterior electrodes compared to *AdjRel* targets, which was bilaterally distributed (Figure 1), but strongest at left-frontal electrode 25 (Figure 2) and right-frontal electrode 1 (Figure 3). The waveforms of the two conditions diverge around 240ms after the target, reaching a peak around 300ms, followed by a sustained negativity lasting the duration of the epoch, peaking again around 700ms. Analysis of variance reveals a significant main effect of condition on the amplitude of electrode 25 between 240 and 440ms post-target ($F(1, 348) = 4.6357$, $p < .05$; statistical analysis is summarized in Table 4).

Central positivity. UngramObj targets also elicited a more positive-going wave in fronto-central electrodes near the vertex compared to *AdjRel* targets (Figure **??**), which was strongest at left-frontal electrode 7 (Figure **??**). The waveforms of the two conditions diverge around 500ms after the target, with the *UngramObj* waveform reaching a small peak around 600ms, but becoming more positive for the duration of the epoch. Analysis of variance reveals a significant main effect of condition on the amplitude of electrode 7 between 500 and 700ms post-target ($F(1, 1886) = 88.4656$, $p < .001$; statistical analysis is summarized in Table 4).

	df	SS	MS	F	p
Condition	1	25.22	25.22	11.0133	0.0010 **
Time Bin	1	7.04	7.04	3.0728	0.0805
Condition*Time Bin	1	3.31	3.31	1.4448	0.2302
Residual	348	796.93	2.29		

Table 5: Analysis of variance for electrode 7, 500-750ms post-stimulus in Experiment 1. ** indicates $p < .005$.

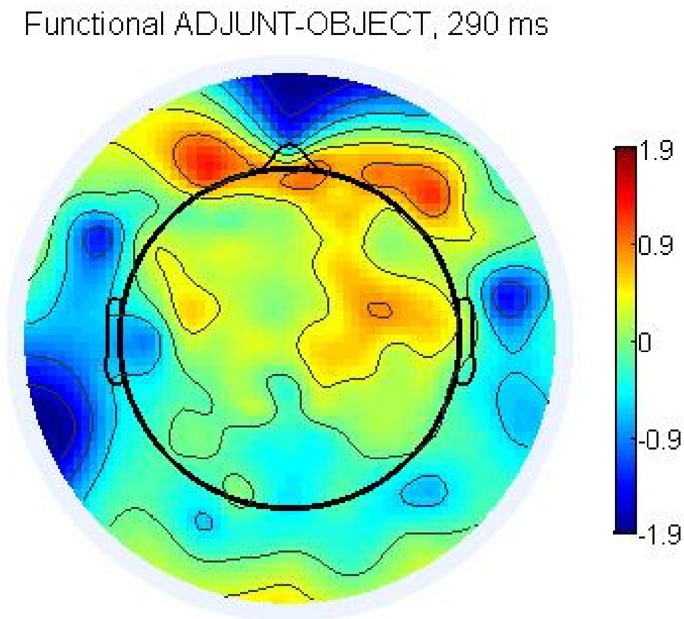

Figure 1: Scalp plot of *AdjRel*−*UngramObj* difference wave at 290ms post-target in Experiment 1.

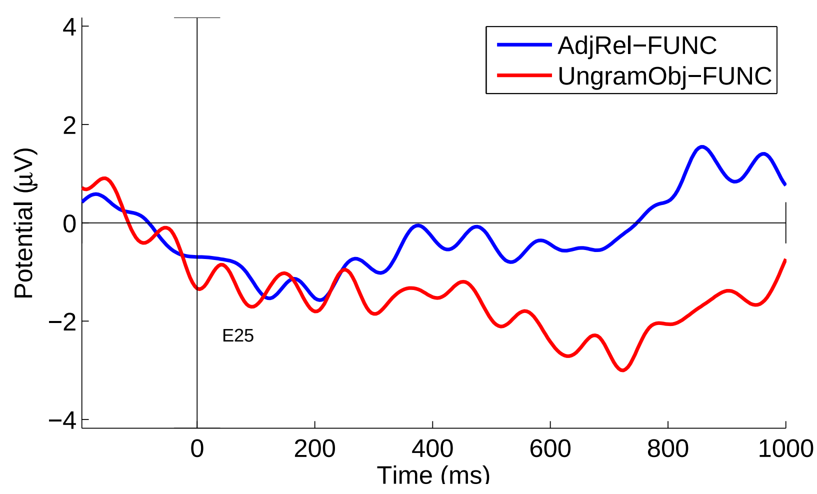

Figure 2: Waveform plot of electrode 25 (see Figure 4 for location) comparing *UngramObj* and *AdjRel* conditions in Experiment 1. Data are low-pass filtered at 15Hz for display.

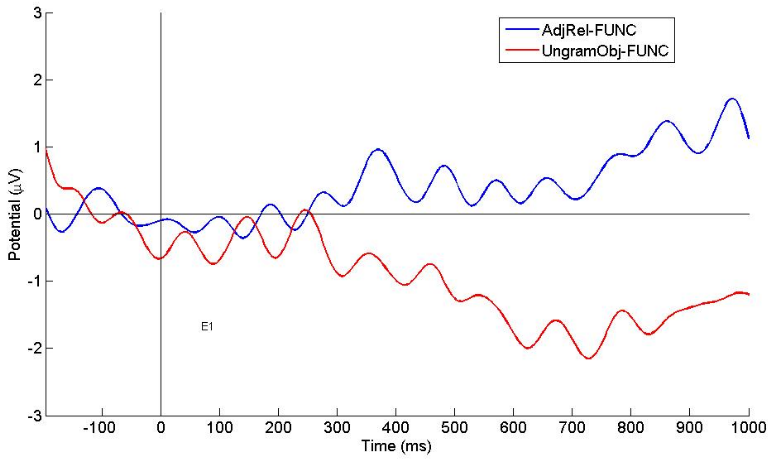

Figure 3: Waveform plot of electrode 1 (see Figure 4 for location) comparing *UngramObj* and *AdjRel* conditions in Experiment 1. Data are low-pass filtered at 15Hz for display.

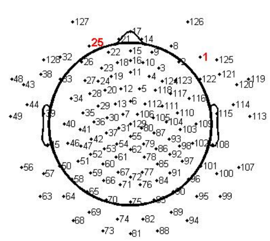

Figure 4: location of electrodes 1 and 25

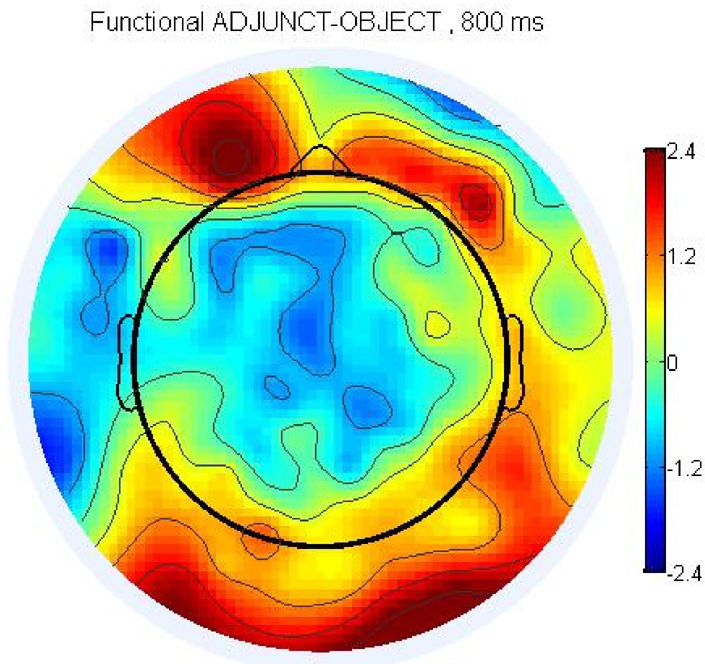

Figure 5: Scalp plot of $AdjRel - UngramObj$ difference wave at 800ms post-target in Experiment 1.

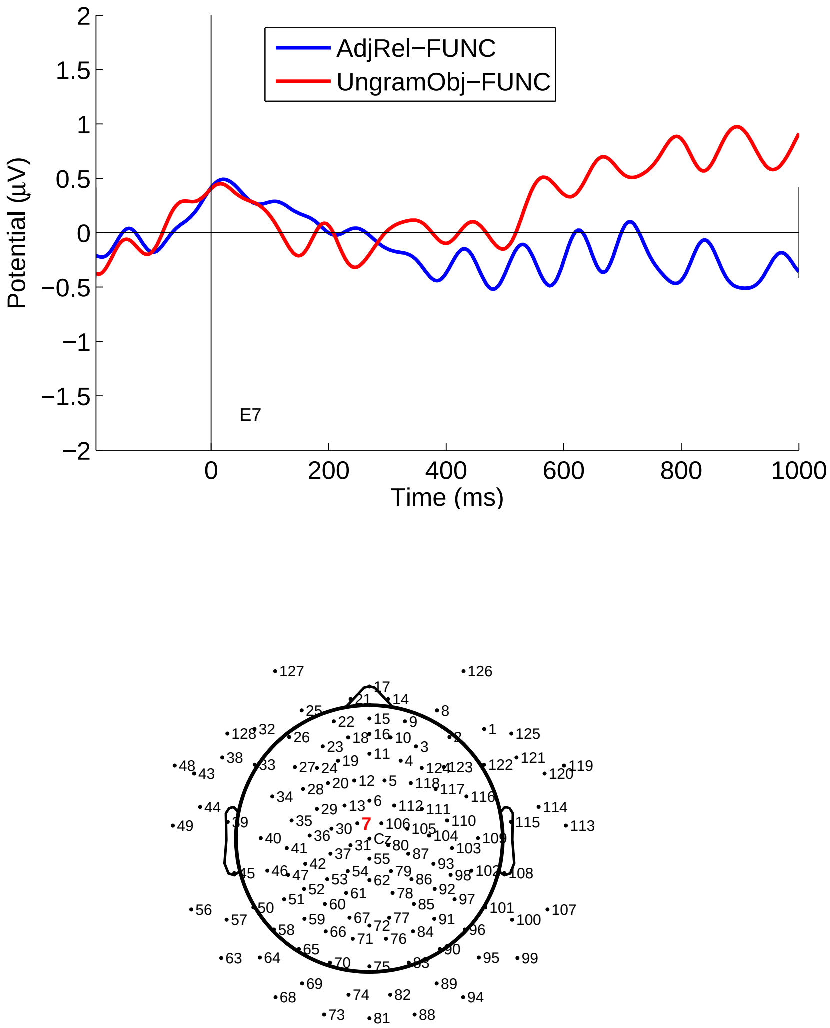

Figure 6: Waveform plot of electrode 7 (see inset for location) comparing *UngramObj* and *AdjRel* conditions in Experiment 1. Data are low-pass filtered at 15Hz for display.

2.3. Experiment 1 Discussion

Unexpected items containing closed-class functional morphology were expected to elicit an ELAN response, consistent with previous findings (Friederici et al., 1993; Hestvik et al., 2007; Dikker et al., 2009b). The anterior negativity observed in the current experiment occurs somewhat later than the typically described latency of 200ms or earlier (Friederici et al., 1993, 1996; Hahne and Friederici, 1999; Neville et al., 1991). A left anterior negativity (LAN) occuring after the ELAN time range has been associated with the resolution of syntactic dependencies (Kluender and Kutas, 1993), such as the relative clause structures employed here. Although the latency of the component observed in Experiment 1 more closely matches LAN, rather than ELAN, because the negativity appears to consist of two peaks, one around 250ms and one around 700ms (Figure **??**), it at least suggests the possibility of two underlying components; the first (ELAN) indexing an unexpected grammatical category, and the second (LAN) reflecting difficulty in computing the filler-gap dependency between the antecedent and the unexpected noun phrase (Hestvik et al., 2007). The failure to replicate previous results (Hestvik et al., 2007, 2009) could be due in part to the use of synthetic stimuli, which either reduced the amplitude or increased the latency (or both) of the ELAN, possibly because of the extra attentionpaid to the stimuli, which modulates the degree of expectation created by the sentences.

The positivity observed in fronto-central electrodes is consistent with the P600 component indexing syntactic difficulty and reanalysis (Osterhout and Holcomb, 1992; Hagoort et al., 1993). Kaan and Swaab (2003) found that frontal, as oppossed to posterior, P600 effects are associated with ambiguity resolution and discourse complexity, which is consistent with filled-gap sentences, wherein there are two many possible fillers for the gap, creating ambiguity as to which NP should fill this role.

The components found in Experiment 1 are consistent with a parser which generates a structural expectation and diagnoses an unexpected grammatical category at an early stage; the filler-gap dependency cannot be computed with this unexpected item (LAN), leading to attempted resolution of the ambiguity of having too many possible fillers at a late stage (P600). The results of Experiment 1 alone cannot directly support the sensory hypothesis, as the components found could be elicited either by a parser which has access to sensory information, or only to syntactic information. The sensory hypothesis predicts that characteristics of words and phrases, such as the presence of closed-class functional morphology, affects their processing. The effect of functional morphology on processing can be assessed by comparison with Experiment 2.

3. Experiment 2

3.1. Method

3.1.1. Participants

17 adults (10 female), ranging in age from 19 to 38, were recruited from the University of Delaware student community, and were compensated $15 for their

UngramObj	*The dog that the cat kissed turtles on the nose ran far away.
AdjRel	The day that the cat kissed turtles on the nose, they ran far away.
GramObj	The dog said that the cat kissed turtles on the nose and then ran far away.
ObjTrace	The dog that the cat kissed *t* on the nose ran far away.
SubjTrace	The dog that *t* kissed the cat on the nose ran far away.
Filler	The mole reminded the gophers in the yard to stay away from the garden.
	The bobcat that had roared at the mountain lion near the river walked along the bank.
	...

Table 6: Examples of sentence types in Experiment 2.

participation. All participants gave informed consent, and all procedures were approved by the University of Delaware Human Subjects Review Board.

3.1.2. Design

Stimuli sentences used in Experiment 2 correspond to those used in Experiment 1, but closed-class morphology on targets was removed ; instead of Determiner + Noun, targets were instead plural nouns (*ObjTrace* and *SubjTrace* sentences, which do not have a NP following the verb, were identical to those in Experiment 1). Although plural noun phrases do contain the plural morpheme, in the auditory presentation paradigm used this morpheme is not encountered until the entirety of the word has been encountered. Stimulus conditions used in Experiment 2 are summarized in Table 6

3.1.3. Stimuli

Sentences were generated using the same synthesizer, and questions recorded by the same speaker as in Experiment 1.

3.1.4. Procedure

Participants completed the same task, and EEG was acquired under the same conditions as in Experiment 1.

3.1.5. Analysis

Behavioral Analysis. Accuracy was assessed using a mixed logit model identical to that employed in Experiment 1.

ERP Analysis. Continuous EEG was processed in the same manner as Experiment 1.

In order to reduce noise, participants who exhibited excessive artifacts were removed from further analysis. Only those who had at least 32 good trials (50%) in both the *AdjRel* and *UngramObj* conditions were included. Three participants were eliminated from Experiment 2, leaving $N = 14$ in subsequent analyses.

	AdjRel	UngramObj	
Wh-	90.07%	63.42%	76.75%
Yes-No	91.91%	88.79%	90.35%
	90.99%	76.10%	83.55%

Table 7: Response accuracy by Condition and Question Type for Experiment 2.

	β	SE β	Z	p
Intercept	2.3894	0.2313	10.333	<.001 ***
Condition	-1.7619	0.1738	-10.137	<.001 ***
Question Type	0.2321	0.2164	1.072	0.284
Condition*Question Type	1.3884	0.2736	5.074	<.001 ***

Table 8: Summary of by-participant mixed logit analysis for Experiment 2; N = 17. *** indicates p <.001.

3.2. Results

3.2.1. Behavioral Results

Overall accuracy in response to all questions (including fillers) was again above %80 (M = 83.55%). Questions following *AdjRel* sentences were answered correctly more often than those following *UngramObj* questions (90.99% vs. 76.10%, respectively). The logit model revealed a significant main effect of Condition, Z = -10.137, p <.001. As in Experiment 1, this effect was driven by a significant interaction between Condition and Question Type, Z = 5.074, p <¡ .001. Yes-No questions following ungrammatical sentences were answered correctly 88.79% of the time, but Wh- questions were answered correctly only 63.42% of the time. The main effect of Question Type was not significant in Experiment 2

Accuracy scores are summarized in Table 7; statistical results are summarized in Table 8.

3.2.2. ERP Results

Comparison of *UngramObj* and *AdjRel* waveforms revealed no anterior negativity, nor a late positivity; instead *UngramObj* targets elicited a broad negativity in centro-parietal electrodes (Figure 7). In peak electrode 62, this negativity peaks around 400ms post-stimulus (Figure 8). Analysis of variance reveals a significant main effect of condition on the amplitude of four midline electrodes between 300 and 500ms post-target (F(1, 1424) = 158.2129, p <.001; statistical analysis is summarized in Table 4).

3.3. Experiment 2 Discussion

In Experiment 2, unexpected plural nouns did not elicit an ELAN. This is consistent with the sensory ELAN hypothesis (Dikker et al., 2009b,a), which links the early diagnosis of syntactic errors to predictions not only about category, but about form associated with said category. Closed-class morphology may increase the typicality of items within their grammatical category, speeding

	df	SS	MS	F	p
Condition	1	21.71	21.71	18.0929	<.001 ***
Time Bin	1	2.98	2.98	2.4820	0.1162
Condition*Time Bin	1	3.44	3.44	2.8676	0.0914
Residual	304	364.78	1.20		

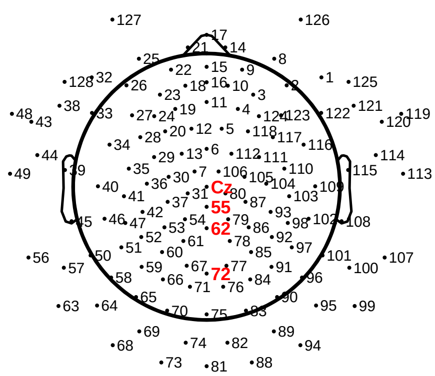

Table 9: Analysis of variance for four midline electrodes (see inset for locations), 300-500ms post-stimulus in Experiment 2. *** indicates $p <.001$.

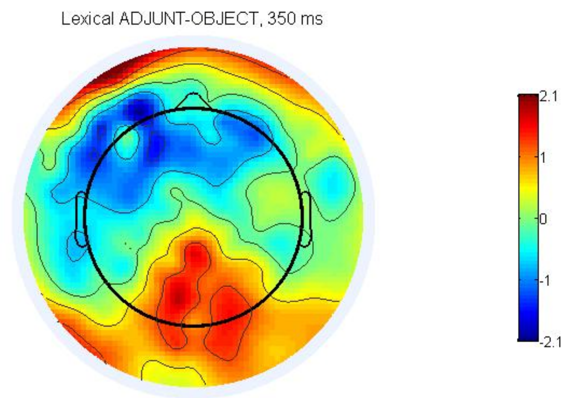

Figure 7: Scalp plot of *AdjRel−UngramObj* difference wave at 350ms post-target in Experiment 2.

category idenitification. Although the plural targets in Experiment 2 contain the plural morpheme, this does not appear to be sufficient to produce an ELAN, possibly because in auditory sentence processing, it is not encountered until the very end of the word[3].

Contrary to expectation, unexpected targets in Experiment 2 did not elicit later syntactic components (LAN or P600). It was predicted that because these unexpected NPs violate the rules of relative clause phrase structure, they should be indexed by syntactic components such as LAN and P600 even if the NPs lack the morphology to allow the early diagnosis indexed by the ELAN. Instead, unexpected plurals elicited a negative-going central-posterior peaking around 400ms after onset, similar to the N400 component associated with semantic incongruity (Kutas and Hillyard, 1980). This suggests that the content, as well as the structure of these sentences is processed, and that the N400 reflects difficulty incorporating the 'extra' NP into argument structure. In other words, the ungrammatical NP is not perceived as a structural violation during the earliest processing stage associated with the ELAN.

4. General Discussion

4.1. the sensory ELAN hypothesis revisited

Filled gap NPs with overt functional morphology elicited an anterior negativity, partially consistent with previous results, while filled gap NPs without functional morphology elicited no anterior negativity, instead giving rise to a later semantic component. This partially supports the sensory hypothesis of

[3]This line of reasoning leads to a number of interesting lexical and cross-linguistic predictions which bear further study.

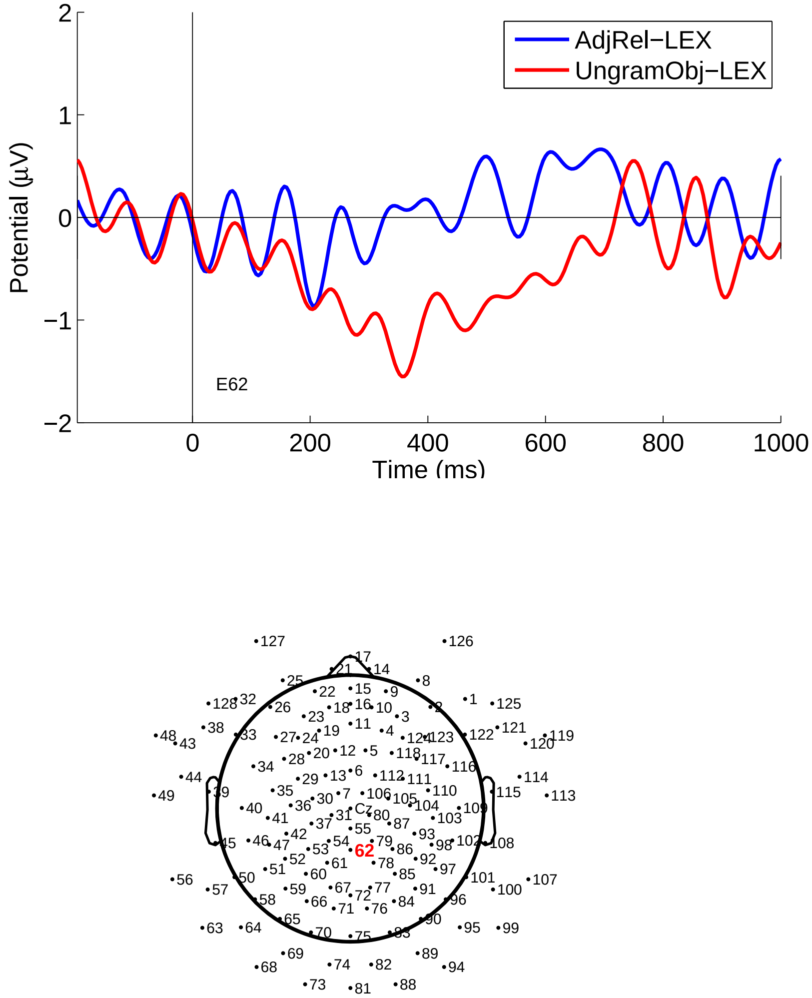

Figure 8: Waveform plot of electrode 62 (see inset for location) comparing *UngramObj* and *AdjRel* conditions in Experiment 2. Data are low-pass filtered at 15Hz for display.

the ELAN by showing that targets with functional morphology elicit a different response than those without, which is not predicted by the non-sensory account. We speculate that such morphology facilitates faster recognition of syntactic errors, so these sentences are abandoned as soon as offending morphology is encountered, with no attempt at argument structure integration. Without overt morphology, category is less extractable from form, so once the listener hears enough of the word to interpret category, the whole word can be understood, and semantic integration is attempted anyway (and fails).

4.2. Implications for processing models

The failure of filled-gap noun phrases without closed-class morphology to elicit an ELAN is a problem for models of processing which include a 'syntax only' phase, in which phrase structure is built purely from category information. Under such a model, grammatical category alone predicts the detection of errors. The current findings suggest that such serial models must be modified to accomodate additional information about form and morphology at or before this stage.

Even if serial models can be so modified, a further challenge arises from the fact that the ELAN and N400 are not simply two syntactic components differing in latency; rather, the qualitative difference between the ELAN (indexing syntactically primed form information) and the N400 (reflecting the interpretation of lexical and sentence meaning) indicates that closed-class morphology changes the way in which sentences are processed, and suggests that acoustic, syntactic, and semantic processing occur in parallel.

Based on the findings of Dikker et al. (2009b) that the visual ELAN is generated in occipital cortex, further research in this area should attempt to clarify the neural source of the auditory ELAN, as this would help to illuminate how and where syntactic information is encoded in the brain, as well as the role of morphology and form-typicality in early structural processing, and the modularity of parsing processes.

5. Conclusions

Two experiments were conducted to test the sensory hypothesis of the early left anterior negativity (ELAN) ERP component. The ERP response to ungrammatical targets was found to be sensitive to the presense of closed-class morphology on filled-gap NPs, which partially supports the sensory hypothesis and is not accounted for by syntax-only accounts of the ELAN.

Bates, D. and Maechler, M. (2009). *lme4: Linear Mixed-Effects Models Using S4 Classes*. R package version 0.999375-31.

Bonte, M., Parviainen, T., Hytonen, K., and Salmelin, R. (2006). Time course of top-down and bottom-up influences on syllable processing in the auditory cortex. *Cerebral Cortex*, 16(1):115–123.

Bradley, D. (1983). *Computational Distinctions of Vocabulary Type*. Indiana University Linguistics Club, Bloomington, IN.

Bunnell, H., Pennington, C., Yarrington, D., and Gray, J. (2005). Automatic personal synthetic voice construction. In *Proceedings of the Eurospeech 2005*, Lisbon, Portugal.

Di Russo, F., Martínez, A., Sereno, M. I., Pitzalis, S., and Hillyard, S. A. (2002). Cortical sources of the early components of the visual evoked potential. *Human Brain Mapping*, 15(2):95–111.

Dikker, S., Rabagliati, H., Farmer, T. A., and Pylkkänen, L. (2009a). Sensitivity to syntax in visual cortex: The role of form typicality. In *The 22nd Annual CUNY Conference on Human Sentence Processing*, Davis, CA.

Dikker, S., Rabagliati, H., and Pylkkänen, L. (2009b). Sensitivity to syntax in visual cortex. *Cognition*, 110(3):293–321.

Dixon, P. (2008). Models of accuracy in repeated-measures designs. *Journal of Memory and Language*, 59(4):447–456.

Electrical Geodesics, Inc. (2003). *Net Station Waveform Tools Technical Manual*.

Friederici, A. D. (1995). The time course of syntactic activation during language processing: A model based on neuropsychological and neurophysiological data. *Brain and Language*, 50(3):259–281.

Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences*, 6(2):78–84.

Friederici, A. D., Hahne, A., and Mecklinger, A. (1996). Temporal structure of syntactic parsing: Early and late event-related brain potential effects. *Journal of Experimental Psychology. Learning, Memory, and Cognition.*, 22(5):1219–1248.

Friederici, A. D., Pfeifer, E., and Hahne, A. (1993). Event-related brain potentials during natural speech processing: Effects of semantic, morphological and syntactic violations. *Cognitive Brain Research*, 1(3):183–192.

Hagoort, P., Brown, C. M., and Groothusen, J. (1993). The Syntactic Positive Shift (SPS) as an ERP-measure of syntactic processing. *Language and Cognitive Processes*, 8:439–483.

Hahne, A. and Friederici, A. D. (1999). Electrophysiological evidence for two steps in syntactic analysis: Early automatic and late controlled processes. *Journal of Cognitive Neuroscience*, 11(2):194–205.

Hahne, A., Schröger, E., and Friederici, A. D. (2002). Segregating early physical and syntactic processes in auditory sentence comprehension. *Neuroreport*, 13(3):305–309.

Hestvik, A., Bradley, C., Bradley, E., Kaufmann, M., Prescott, T., and Sparacino, L. (2009). An event-related potentials measure of the effect of low verbal memory span on gap-filling. In *The 22nd Annual CUNY Conference on Human Sentence Processing*, Davis, CA.

Hestvik, A., Maxfield, N., Schwartz, R., and Shafer, V. (2007). Brain responses to filled gaps. *Brain and Language*, 100(3):301–316.

Hickok, G. and Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience*, 8(5):393–402.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, 59:434–446.

Kaan, E. and Swaab, T. Y. (2003). Repair, revision, and complexity in syntactic analysis: An electrophysiological differentiation. *Journal of Cognitive Neuroscience*, 15(1):98–110.

Kluender, R. and Kutas, M. (1993). Bridging the gap: Evidence from ERPs on the processing of unbounded dependencies. *Journal of Cognitive Neuroscience*, 5(2):196–214.

Kutas, M. and Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, 207(4427):203–205.

Lau, E., Stroud, C., Plesch, S., and Phillips, C. (2006). The role of structural prediction in rapid syntactic analysis. *Brain and Language*, 98(1):74–88.

Love, T. (2007). The processing of non-canonically ordered constituents in long distance dependencies by pre-school children: A real-time investigation. *Journal of Psycholinguistic Research*, 36(3):191–206.

Love, T. and Swinney, D. (1997). Real time processing of object relative constructions by pre-school children. In *10th Annual CUNY Conference on Human Language Processing*, Los Angeles, CA.

Maess, B., Herrmann, B., Hasting, A. S., and Friederici, A. (2009). Localizing the auditory syntactic mismatch negativity using whole head magnetoencephalography. In *Fifth Conference on Mismatch Negativity (MMN) and its Clinical and Scientific Applications*, Budapest, Hungary.

Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., Vainio, M., Alku, P., Ilmoniemi, R., Luuk, A., Allik, J., Sinkkonen, J., and Alho, K. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature*, 385:432–434.

Näätänen, R., Tervaniemi, M., Sussman, E., Paavilainen, P., and Winkler, I. (2001). Primitive intelligence in the auditory cortex. *Trends in Neuroscience*, 24:283–288.

Neville, H., Nicol, J. L., Barss, A., Forster, K. I., and Garrett, M. F. (1991). Syntactically based sentence processing classes: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience*, 3(2):151–165.

Osterhout, L. and Holcomb, P. J. (1992). Event-related brain potentials elicited by syntactic anomaly. *Journal of Memory and Language*, 31(6):785–806.

Pulvermüller, F., Lutzenberger, W., and Birbaumer, N. (1995). Electrocortical distinction of vocabulary types. *Electroencephalography and clinical neurophysiology*, 94(5):357–370.

Pulvermüller, F., Lutzenberger, W., and Preissl, H. (1999). Nouns and verbs in the intact brain: Evidence from event-related potentials and high-frequency cortical responses. *Cerebral Cortex*, 9(5):497–506.

Pulvermüller, F. and Shtyrov, Y. (2003). Automatic processing of grammar in the human brain as revealed by the Mismatch Negativity. *NeuroImage*, 20(1):159–172.

Pulvermuller, F. and Shtyrov, Y. (2006). Language outside the focus of attention: The Mismatch Negativity as a tool for studying higher cognitive processes. *Progress in Neurobiology*, 79(1):49–71.

Pulvermüller, F., Shtyrov, Y., Kujala, T., and Näätänen, R. (2004). Word-specific cortical activity as revealed by the Mismatch Negativity. *Psychophysiology*, 41(1):106–112.

R Development Core Team (2009). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0.

Schneider, W., Eschman, A., and Zuccolotto, A. (2002). *E-Prime reference guide*. Psychology Software Tools Inc., Pittsburgh, PA.

Vogel, I., Hestvik, A., Bunnell, H. T., and Spinu, L. (2009). Perception of English compound vs. phrasal stress: Natural vs. synthetic speech. In *10th Annual Conference of the International Speech Communication Association*, Brighton, UK.