Brain responses to contextually ungrammatical verb inflection

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Abstract

The stem of a regularly inflected verb like "kick" must necessarily be stored in the mental lexicon, but the inflected version "kicked" need not be stored, because it can be composed in real time by general rule. A long-standing debate concerns whether irregular verbs have the same or a different status. The "dual route" model takes the view that they differ and that the inflected forms of irregular verbs (like "give-gave") are stored in memory and not derived by rule, whereas "single route" models assume that irregular verbs are also produced by rule, although more specific ones. During perception, therefore, dual route entails that an irregular verb is looked up in the lexicon as a whole, whereas the single route model entails that it is analyzed and decomposed into a stem and an abstract suffix. This computational difference can be tested by event-related potential measures. In the dual route model, inflection violations for irregular verbs should be perceived as lexical anomalies, and elicit N400 event-related potentials, in contrast to inflection violations of regular verbs, which should elicit Left Anterior Negativity (LAN), an ERP signature of morpho-syntactic rule violation. The single route model predicts that both irregular and regular verbs inflection violations should elicit LAN. Previous ERP studies have tested these predictions with visual (orthographical) stimulus presentation, and produced equivocal results. The current study tested these predictions for the first time with auditory stimuli. Simple sentences were presented, where the discourse context led listeners to expect a past tense verb, but a present tense verb was encountered. Both regular and irregular verbs elicited the same Left Anterior Negativity. This finding is consistent with the single route models of irregular verb inflection, and is not predicted by the dual route model.

Section: 7. Cognitive and Behavioral Neuroscience

Keywords: event-related potentials, language processing, dual-route model, irregular inflection, morphosyntax, left anterior negativity

1. Introduction

According to the dual route model—also known as the Declarative/ Procedural (DP) model (Pinker & Ullman, 2002; Ullman, 2001a, 2001b, 2004, 2006), the past tense of regular verbs is composed by rule during real-time processing (i.e., add *–ed* to the stem, forming e.g. *walk-ed*), but the past tense of irregular verbs is stored in memory (e.g., *sing, sang*). A related claim of the Declarative/Procedural model is that this difference between regular and irregular past tense formation has neurophysiological correlates. (Ullman, 2001a, 2001b, 2004) proposes that grammatical rule application in general is performed by structures supporting procedural memory, which includes the frontal basal ganglia, the parietal cortex, and superior temporal cortex, and left inferior frontal cortex, including portions of Broca's area. Lexical storage and look-up is argued to be dependent on declarative memory, supported by the medial temporal lobe and associated brain structures. If regular past tense is formed by rule whereas irregular past tense is not, then processing of regularly inflected verbs should activate both declarative memory circuits (for lexical look-up of stem) as well as procedural memory circuits (for computation of past tense form), whereas processing of irregularly inflected verbs should only activate declarative memory circuits. This predicts that different types of brain activity should be observed during processing of regularly inflected verbs versus processing of irregularly inflected verbs. (Note that this does not mean that regular verbs cannot be stored in their inflected form; this may be the case for high-frequent regular verbs, or regular verbs that bear strong analogical relationships to irregular verb classes; we finesse this issue in the current paper). In addition, the theory makes a wide range of predictions about neuropsychological dissociations (Ullman, 2004) as well as about sex differences in language processing (Ullman *et al.*, 2008).

In contrast to the dual route model, single route models (McClelland & Patterson, 2002; Rumelhart & McClelland, 1986) do not distinguish in principle between regular and irregular verbs, but account for all relationship between inflected forms of a verb by association networks. In this model, differences between regular and irregular verbs are expressed by degrees of phonological similarity between past and present tense forms. Crucially, no principled difference is assumed between the two verb classes. Finally, a third type of model, is represented by the Distributed Morphology (DM) model (Chomsky & Halle, 1968; Halle & Marantz, 1994), which stipulates that the past tense of irregular verbs is produced by specific stem changing rules applying to subsets of verbs. As in the dual-route model, there is a memory component for irregular verbs (i.e., the specific rule which applies to a specific set of verbs must be memorized), but unlike the dual-route model, the past tense form is still derived by rule. In the DM model, the phonetic surface form *taught* is decomposed into a stem and an abstract suffix, “teach”+[PAST] (Embick & Marantz, 2005). The feature is spelled out as a zero-suffix but triggering (partially idiosyncratic) stem-changing morpho-phonological rules.

Experiments testing for verb class differences during processing have produced equivocal results vis-à-vis the dual-route vs. single-route debate. For example, whereas it is uncontroversial that past tense versions of regularly inflected verbs should prime and be primed by their present tense forms in repetition priming experiments (because both contain the same stem), the different models make different predictions for irregular verbs. Specifically, because DM analyzes a past tense irregular as being represented by a stem and a zero suffix, priming is expected between inflected versions of irregular verbs (even between *gave* and *give*), whereas a weaker priming relationship is expected in the dual route model, because the two verb forms are morpho-phonologically distinct (Stockall & Marantz, 2006; Stockall *et al.*, 2004). However, as pointed out by (Kielar *et al.*, 2008), results for irregular verb priming is inconsistent across studies and methods.

Several studies using attenuation of the N400 event-related potential (ERP) as a measure of priming report that regular past tense verbs primed their present tense stems, but that irregular past tense forms did not (Münte *et al.*, 1999; Rodriguez-Fornells *et al.*, 2002; Weyerts *et al.*, 1996). On the other hand, (Marslen-Wilson & Tyler, 1998) report that both irregular and regular verbs showed form priming between inflected versions in a delayed repetition priming task, and also observed N400 priming by past tense form on present tense stems. Similarly, in a study using magneto-encephalographic (MEG) recordings of brain activity, (Stockall & Marantz, 2006) report that both regularly and irregularly inflected past tense verbs primed their present tense stems in a lexical decision task, as indexed by the M350 MEG component (sensitive to the time course of lexical activation), and take this as evidence that irregularly inflected verbs are decomposed into its root and an abstract past tense feature during processing. Thus, evidence from priming for a fundamental difference between regular and irregular verbs is mixed.

Another line of research probing for verb processing differences uses expectancy violations and measures which type of event-related potential is elicited by violations of regular vs. irregular verbs. This method is useful for testing Dual vs. Single route models because of the association that exists between distinct types of ERP responses and the general underlying linguistic processes. Specifically, violations of semantic or lexical expectancies typically lead to a central/posterior negativity occurring around 400ms after the processing of the stimulus—the N400 (Kutas & Hillyard, 1984; Kutas & Iragui, 1998; Kutas *et al.*, 1988). Violations of syntactic phrase structure rules, syntactic category expectancies, morphosyntactic and morpho-phonological rules, elicits a left-lateralized anterior negativity (LAN) peaking between 300ms and 500ms post-onset (Friederici *et al.*, 1993; Gunter *et al.*, 2000; Hahne & Friederici, 1999; Kluender & Kutas, 1993; Rösler *et al.*, 1993). Additionally, a late positivity at central/posterior electrode sites, the P600 is related to various aspects of syntactic processing, ranging from complexity effects to reanalysis (Hagoort & Brown, 2000; Hagoort *et al.*, 1993; Kaan *et al.*, 2000; Kuperberg, 2007; Osterhout & Nicol, 1999).

As proposed by (Ullman, 2001b), the N400 can be taken to reflects declarative memory processes in general, and that the LAN as reflecting procedural memory processes in general. Processing violations involving regular verbs should therefore be indexed by LAN (which generally index morphosyntactic violations), whereas processing of violations involving irregular verbs should be indexed by the N400 (Ullman, 2001a). Previously, two different types of violation paradigms have been used to study verb inflection: experiments that violate morphological rules per se, and experiments that violate expectancies about tense on an otherwise morphologically well-formed verb. The former type of studies examine the effect of violating morphological structure by combining irregular verbs with regular inflectional suffixes, and vice versa by combining regular verbs with irregular inflection. Incongruent “regularized” irregular verbs and nouns has consistently elicited a LAN response in these studies (Krott *et al.*, 2006), whereas “irregularizing” regular verbs and nouns (putting irregular suffixes on regularly inflected words) show either no effect or weaker priming responses (Gross *et al.*, 1998; Penke *et al.*, 1997; Rodriguez-Fornells *et al.*, 2001; Weyerts *et al.*, 1997). These authors concluded that a difference in response between the two verb classes itself supported the dual route model. Similarly, (Morris & Holcomb, 2005) also examined morphological tense violations with English verbs, and observed the same LAN response for both regular and irregular verbs (although the effect was more "pronounced" for irregulars). Morris and Holcomb interpreted their findings as evidence against the dual-route model. The findings from morphological "mixing" paradigms therefore do not clearly speak to the issue of dual vs. single route vs. distributed morphology. Furthermore, the results from "mixing" paradigms are difficult to interpret precisely because they create processing situations that forcibly blend two (hypothetical) systems, whereas the goal should be to study how they differ under "natural" processing conditions (see also (Ullman, 2001a) for discussion of this point).

An alternative violation paradigm, where the normal processing of the morphological form itself is not disturbed by experimental manipulations, is to measure ERPs in response to violations of contextual expectancies of otherwise morphologically well-formed verb inflections. (Steinhauer & Ullman, 2002a) compared regular and irregular verbs in visually presented ungrammatical sentences like "*Yesterday, we eat Peter's cake in the kitchen*", and furthermore examined sex differences, based on the expectation that women should be more likely to exhibit N400 responses to both irregular and regular verbs, whereas men should be more likely to exhibit LAN for regular verbs and N400 for irregular verbs only. This is in turn related to findings that women rely more on declarative memory processes than men, who rely more on procedural memory processes (Ullman *et al.*, 2008). They found that during the 300-400ms time window, ungrammatical irregulars elicited an N400 response in both men and women, whereas ungrammatical regular verbs elicited a LAN in men, but an N400 in women. During the 400-500ms time window, all verbs then elicited a LAN for both men and women (followed by a P600 in the 600-900ms window). They interpreted the early transient N400 as evidence for a sex difference in morpho-phonological processing, reflecting the fact that women are more likely to store even inflected regular verbs, whereas men only store inflected irregular verbs. The ERP effects arise as follows: When a verb is first encountered, the processing system determines what word it is and what features the morphological form expresses. The N400 reflects an unexpected form resulting from lexical look-up, whereas the LAN reflects a violation of expected morphological rule application. The subsequent LAN during 400-500ms, followed by a P600, was interpreted by Steinhauer and Ullman to reflect the morphosyntactic aspect of the violation computation. During this stage, the violation is equal for both regular and irregular verbs, which was why both verb types elicited a LAN response in both men and women.

(Newman *et al.*, 2007) report a study employing the same contextual violations as in (Steinhauer & Ullman, 2002a). This study observed a LAN response only for violations involving regular verbs, and a P600 response for both regular and irregular verbs. As pointed out in (Newman *et al.*, 2007), the single route model of (Halle & Marantz, 1994) predicts the same LAN response to both irregular and regular verbs in the contextual tense violation paradigm in (Newman *et al.*, 2007), whereas the dual route model predicts a LAN response only to regulars; their findings support the dual route model inasmuch as a LAN effect was only observed for regulars. However, this study did not observe an N400 response to contextually ungrammatical inflection on irregular verbs, which would be expected under the dual-route view that irregular tense violations amounts to an unexpected word form being pulled out of the lexicon. However, the finding of a difference ERP response to regular vs. irregular verbs is also inconsistent with single route models as well as the Distributed Morphology models, which expect the same response for both verb classes.

(Allen *et al.*, 2003) presented subjects with more local contextual tense expectancy violations by altering the tense of a preceding auxiliary (i.e., “will ate”, “can walked”). This study only observed a P600, similar to a P600 finding by (Osterhout & Nicol, 1999) for violations like “won’t eating” and “can flying”. However, they also found that the onset latency of this ERP showed an interaction with frequency for irregular verbs, but not for regular verbs, and interpreted this finding as support for the dual route model. The authors suggested that tense information coded in the stem of a stored lexical item is accessed faster than information about tense on regular verbs, which must be composed in real time by suffixation.

Previous studies of contextual verb tense violations have therefore showed a range of different results: transient N400 to irregulars (women only) followed by LAN for both verb classes (Steinhauer & Ullman, 2002a), LAN only to regulars followed by P600 to both verb types (Newman *et al.*, 2007), and P600 only, but irregular and regulars differentiated by latency (Allen *et al.*, 2003). Note that these previous studies all used visual/orthographic presentation of stimuli, i.e. processing was measured via reading.

The purpose of the current study was to extend the empirical basis for deciding between the Dual Route model versus alternative models by replicating (Newman *et al.*, 2007; Steinhauer & Ullman, 2002b) but using auditory stimulus presentation rather than visual presentation. In the past context condition, we compared auditory comprehension of "Yesterday, I ate a banana" to "Yesterday, I eat a banana" (irregular verbs), and "Yesterday, I walked to school" vs. "Yesterday, I walk to school" (regular verbs), and examined the prediction that the irregular violation should elicit an N400 violation and the regular violation should elicit a LAN. In addition, (Newman *et al.*, 2007; Steinhauer & Ullman, 2002b) only compared grammatical past tense verbs to ungrammatical present tense verbs (i.e., "Yesterday, he froze/freeze a streak"). This grammatical/ungrammatical comparison is confounded by the past/present difference. We therefore added a null context control condition where both tenses were grammatical, by simply removing the word "Yesterday" from the sentence, resulting in e.g. "I walk/walked after lunch". This allowed us to verify that the ERP in the past tense incongruent context is due to ungrammaticality alone, and not to the difference between past and present tense by itself. EEG was recorded while subjects categorized the sentences as occurring in the past, present, or "didn't make sense."

2. Results

2.1. Behavioral results

We first analyzed behavioral results in the null context condition, and then in the past context condition. In the null context trials, three subjects scored at or below chance on the judgment task in one or two cells of the design, and also had a relatively high number of missing responses in the same conditions. However, these subjects exhibited the same main ERP patterns that were present in the grand average. These subjects were not excluded from the ERP analysis, because all trials from all subjects were included in the ERP data, whether or not subject responded correctly or not. They were however treated as behavioral outliers and excluded from the behavioral analysis.

Accuracy and reaction time was analyzed using Hierarchical Linear Modeling (Raudenbush & Bryk, 2002), using the predictors Verbtype and Tense. The mean accuracy for the intercept in the HLM model was 92%. There was a main effect of Verbtype, such that regular past tense verbs had 5% higher accuracy than irregular past tense verbs ($t(19) = 4.415$, $p < .001$). This main effect was again driven by an interaction between Tense and Verbtype, such that accuracy for present tense judgments were 5% better than past tense judgments for regular verbs only ($t(19) = -4.049$, $p < .001$), with no difference for irregular verbs. This interaction can be seen in Figure 3, upper left panel. Adding subject's sex as a predictor at level 3 for intercept, Tense slope, Verbtype slope and Tense X Verbtype interaction was not significant.

Note that subjects gave a delayed response, and the task was therefore not a speeded reaction time task. The predicted mean reaction time for past tense irregular verbs (554ms) was used as the intercept. There was a main effect of Verbtype such that regular verbs were responded to 47ms faster than irregulars ($t(19) = -2.86$, $p = .01$), and a main effect of Tense, such that present tense verbs were responded to 88ms slower than past tense verbs ($t(19) = 4.192$, $p = .001$). Figure 1, upper right panel illustrates these two main effects. Adding sex as a subject-level predictor was not significant. To summarize, subjects were slightly better at judging past tense regulars than present tense regulars and irregulars in the null context condition. Subjects were also faster at making correct judgments for regular than for irregular verbs, and past tense was responded correctly to faster than present tense for both verb classes.

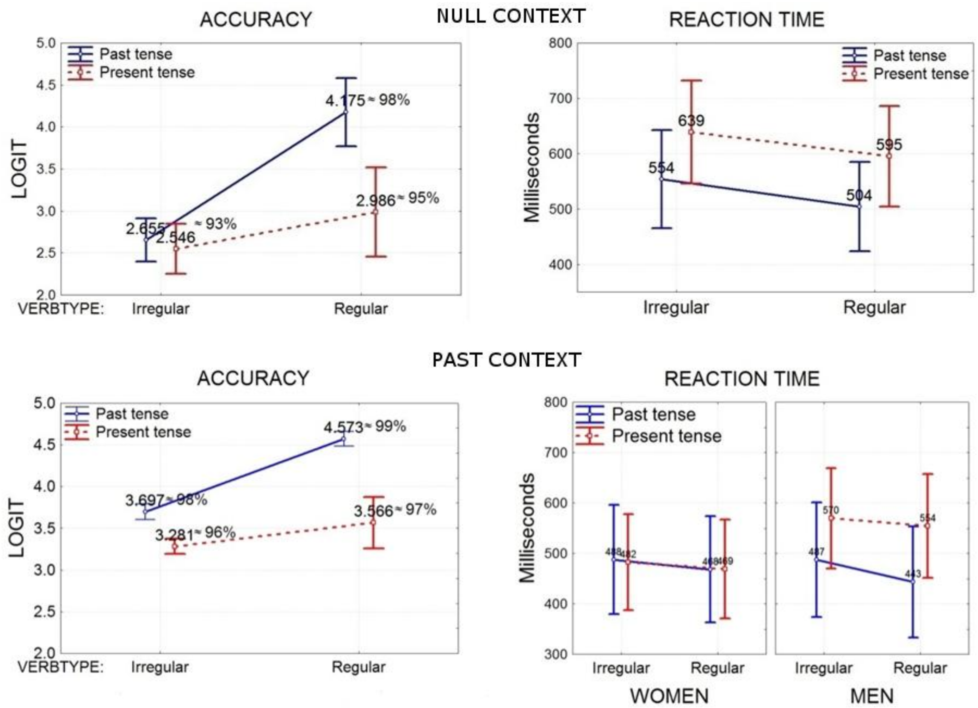

Figure 1. Main effects and interactions for accuracy and reaction time. Upper panel: Null context condition; lower panel: Past tense context condition. Accuracy is shown in logits in order to accurately represent the 95% confidence intervals.

In the past tense context, each sentence is preceded by “Yesterday”, which makes past tense verbs grammatical but present tense verbs ungrammatical. One subject scored below chance on present tense irregulars, while another subject scored below chance on present tense regulars. These two subjects were excluded from behavioral analysis of the past tense context condition (but again included in the ERP analysis, because they exhibited the same pattern of ERP responses observed in the mean, and because trials were generally included in the ERP independently of behavioral responses). The predicted mean accuracy for past tense irregulars in the HLM analysis was 98%. There was a very small but statistically significant main effect of Verbtype, such that regular past tense verbs were more accurate than irregular past tense verbs ($t(20) = 3.09$, $p = .006$), and an interaction between Verbtype and Tense, such that a small difference between present and past tense was significant for regular verbs only ($t(20) = -2.435$, $p = .025$). This was the same interaction as observed in the null context condition. However, the differences were so small (~2%) that they were not interpretable as practically significant. Adding Sex as a predictor for intercepts and slopes did not result in significant coefficients.

In the HLM analysis of reaction time, using the mean for past tense irregulars (487ms) as intercept, there was a marginally significant main effect of Verbtype, such that regulars were 31ms faster than irregular ($t(20) = -1.788$, $p= .088$) and a marginally significant main effect of tense, such that present tense verbs were 36ms slower than past tense ($t(20) = 1.792$, $p = .088$). When sex was added as a predictor for all level 2 coefficients, a three-way interaction between Verbtype, Tense and Sex emerged. Male subjects were 83ms slower in reacting to present tense (ungrammatical) verbs than past tense verbs ($t(19) = 2.19$, $p = .041$) irrespective of verb type, whereas women showed no reaction time difference (cf. Figure 1, lower right panel).

2.2 ERP results

The results from the two different context conditions were analyzed separately, because the past and present verbs occurred under different discourse context (with and without “Yesterday”). We first discuss the results of the past context conditions, where ungrammatical present tense is compared to grammatical past tense, and then we turn to discussion of the null context control condition, where both past and present tense verbs are grammatical.

2.2.1 Past tense context: description

Visual inspection of the grand average waveforms in the past context condition ("Yesterday,…") revealed that ungrammatical present tense verbs elicited a left anterior negativity for both irregular and regular verbs. This effect occurred after the completion of the verb. There was no apparent ERP effect related to experimental conditions during processing of the verb.

In order to pin-point the topographical distribution of the effect, difference waveforms were calculated. Figure 2 illustrates the distribution of the difference waveform for regular verbs. (Here and in the following, we generally use topographical plots to illustrate results rather than single electrode waveform line plots, due to high number of channels in high-density electrode arrays). The difference plot shows a negativity developing from 900ms after verb onset. Recall that the ERP is time-locked to the onset of the verb. The mean duration of regular verbs was 548ms (SD=89ms), whereas the mean duration of irregular verbs was 513ms (SD = 95ms). Regular verbs mark their tense at the end of the word, and grammaticality cannot therefore be determined until after the offset of the verb. Given the variance in verb durations, any effect in the grand average is therefore not expected to be seen until about 600ms past verb onset. With this in mind, observe in Figure 2 that the left anterior negativity, focused around electrode AF7 (EGI 14) starts to develop 900-1000ms past the verb onset, which corresponds to 300-400ms past verb offset. The effect inverts in polarity at right anterior electrodes. The difference wave continues to increase in amplitude and reaches maximum amplitude at the end of the epoch.

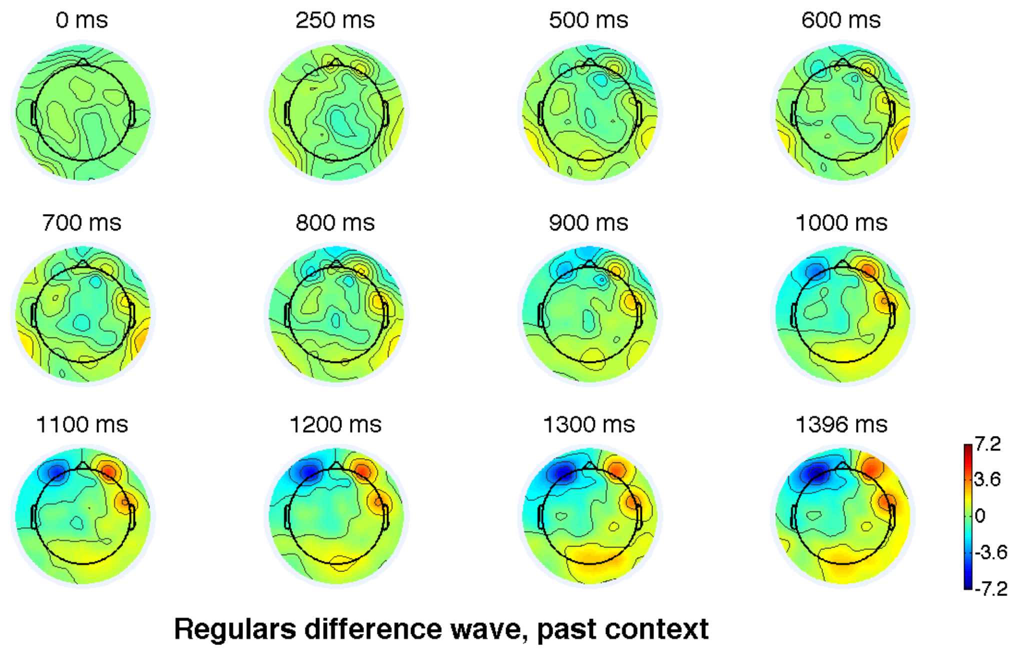

Figure 2. Present minus past tense difference waveform topoplot for regular verbs, past context.

The difference plots for irregular verbs showed a similar effect, although the negativity started earlier for irregulars, cf. Figure 3. This earlier effect is expected, because irregular verbs mark tense stem internally, and the phonetic signal of past tense is therefore temporally available at an earlier stage. As can be seen in Figure 3, the difference waveform starts to become negative 800ms past verb onset, which corresponds to about 200ms past verb offset. The difference effect is more spread out than for the regular verbs, and peaks 1200-1300ms past verb onset (roughly 600-700ms past verb offset). The focus of the effect for both regulars and irregulars is at electrode AF7 (EGI 14), which is typically the locus of the LAN (Friederici, 2002).

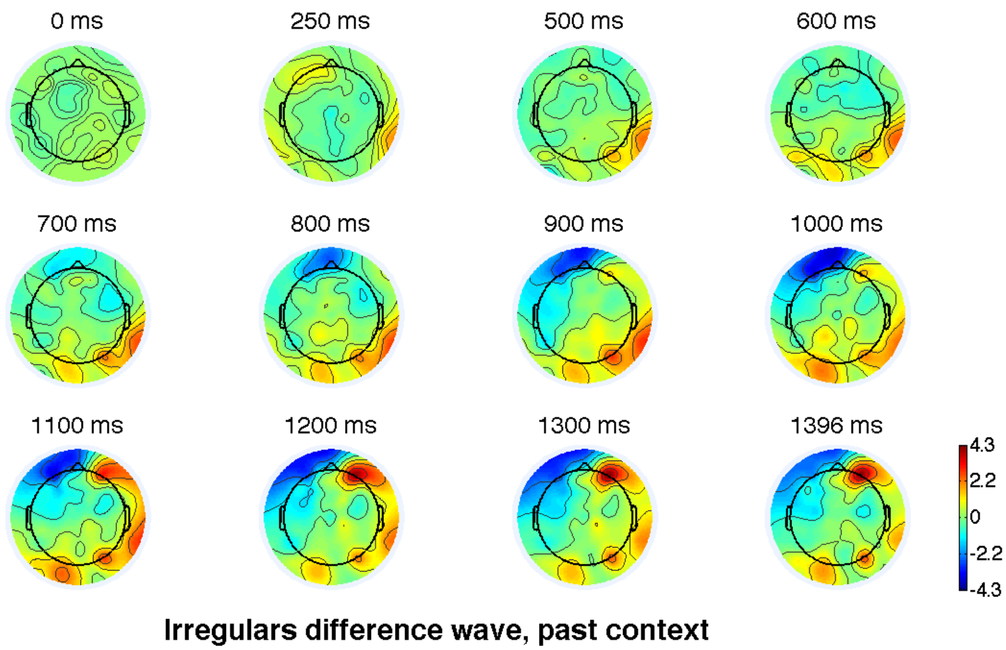

Figure 3. Present minus past tense difference waveform for irregular verbs, past tense context.

2.2.2 Past tense context: analysis

We followed the analysis path in (Newman *et al.*, 2007) to facilitate comparison between these two very similar studies. In the following we only report interactions involving the TENSE factor, because the experiment was designed to measure the grammaticality effect involving past vs. present tense verbs.

We first analyzed the EEG data recorded during the processing of the verb itself, by computing mean voltages for each of the four quadrants defined by anterior-posterior (ANTPOS) and Left-Right hemisphere (LAT), for each 100ms time window from 0-600ms, and each cell in the VERBTYPE x TENSE design. These measures were submitted to a mixed factorial repeated measures ANOVA, with TIME(6) x VERBTYPE x TENSE x ANTPOS x LAT. The ANOVA revealed no main effects or interactions involving TENSE and VERBTYPE during this early time window (i.e., during the processing of the verb), except a marginal TIME x TENSE interaction ($F(5,110)=2.68$, $\varepsilon=0.25$, $p=.088$). (Here and below we reported the Greenhouse-Geisser corrected p-value for the TIME interaction terms.) Inspection of the interaction plot indicated that it was related to the present tense waveform starting out more positive that past tense during 0-300ms, and then changing to more negative than the past tense waveform during the 400-600ms time window. Orthogonal contrast analysis showed that the TENSE difference was not significant in any single time window. We also ran a second ANOVA with sex added as a between-subjects factor; this did not result in any different statistics. In other words, we observed no sex, verb type or tense (grammaticality) related effects during processing of the verb itself.

We next analyzed the time region following the offset of the verb itself, i.e., after the auditory word had been completed. Mean voltages were computed for each quadrant for nine 100ms time windows from 500-1400ms; by tense condition and verb type. These measures were submitted to a mixed factorial repeated measures ANOVA, with TIME(9) x VERBTYPE x TENSE x ANTPOS x LAT as within-subject factors. This resulted in a TENSE x ANTPOS interaction ($F(1,22)=7.33$, $p=0.013$), such that present tense was more negative than past tense in the anterior region, and with this difference inverted in the posterior region. A significant TENSE x LATERALITY interaction observed ($F(1,22)=4.58$, $p=0.044$) indicated that the present tense was more negative compared to past tense in the left hemisphere and more positive than past tense in the right hemisphere. This interaction further interacted with time, by a significant TIME x TENSE x LATERALITY interaction ($F(8,176)=28.10$, $\varepsilon=0.186$, $p<.00001$). Finally, the four-way interaction TIME x TENSE x ANTPOS x LATERALITY was significant ($F(8,176)=25.78$, $\varepsilon=0.295$, $p<.00001$).

These interactions indicated that the TENSE effect differed over time among the four quadrants, and was followed up by orthogonal contrast analysis of the grammaticality factor (TENSE) for each 100ms time window in each of the four quadrants. In the left anterior quadrant, present tense was significantly more negative than past tense starting with the in 800-900ms time window ($t=2.66$, $p=.014$), and in every following time window (statistics are not reported for subsequent windows because the differences always became systematically greater in amplitude, hence by transitivity they are significant). Given that the mean verb duration was 548ms with a standard deviation of 89ms; this means that the negativity actually started around 200ms past verb offset, consistent with a Left Anterior Negativity (with latency calculated from estimated verb offset; see below for confirmation by analysis of offset epoched data).

In the right anterior quadrant, the TENSE difference was significant in the later time windows, from 1000ms past onset; i.e. about 400ms past offset ($t=-2.55$, $p=.017$) and on. The direction of the difference was here that present tense was more *positive* than past tense, i.e. an inversion of the waveforms in the left anterior region (cf. Figures 4-5). In the left posterior quadrant, the present tense waveform was significantly more positive than the past tense waveforms during 600-700ms time window only. Inspection of the grand average waveform plot revealed that this was caused by only two electrodes at the inferior posterior band. Due to the limited distribution and narrow time range, this effect was not further analyzed. In the right posterior quadrant, the present tense waveforms were also significantly more positive that the past tense waveforms starting with the 900-

1000ms window (t=-2.54, p=.018) and every subsequent time window. In summary, the analyses showed negativity to ungrammatical present tense verbs in the left anterior quadrant, with inversion in the right anterior and right poster quadrants. The apparent difference between regulars and irregulars in the difference waveform topoplots in Figures 2 and 3 did not reach significance in this analysis.

In addition, following the analysis strategy of (Newman *et al.*, 2007), given the *a priori* hypothesis that we should observe a difference between regulars and irregulars with respect to the LAN, and that there should be a difference between men and women, we also ran an ANOVA on just the left anterior quadrant data, for the 500-1400ms time range, with TIME (9) x VERBTYPE x TENSE x SEX. This again only revealed a main effect of TENSE (F(1,21)=6.93, p=.015), and a TIME x TENSE interaction (F(8,168)=23.38, e=0.31, p < .00001), and no interactions involving grammaticality effect and verb type.

2.2.3 Analysis of data time-locked to verb offset

Although the effect of ungrammaticality appears to be later than typical LAN effects, it is important not to confuse the relative timing of this LAN with its absolute timing. I.e., even though the effect starts as late as 1000ms after verb onset, it is early relative to verb offset. Note that if the ERP had been time-locked to the offset of the verb, it should by this reasoning have an onset latency around 200-300ms. This was verified by constructing a data set with the same ERPs time-locked to the offset of the verb. Figure 4 compares the effect at AF7 (EGI 14) for the offset vs. onset computed ERPs for both verb classes.

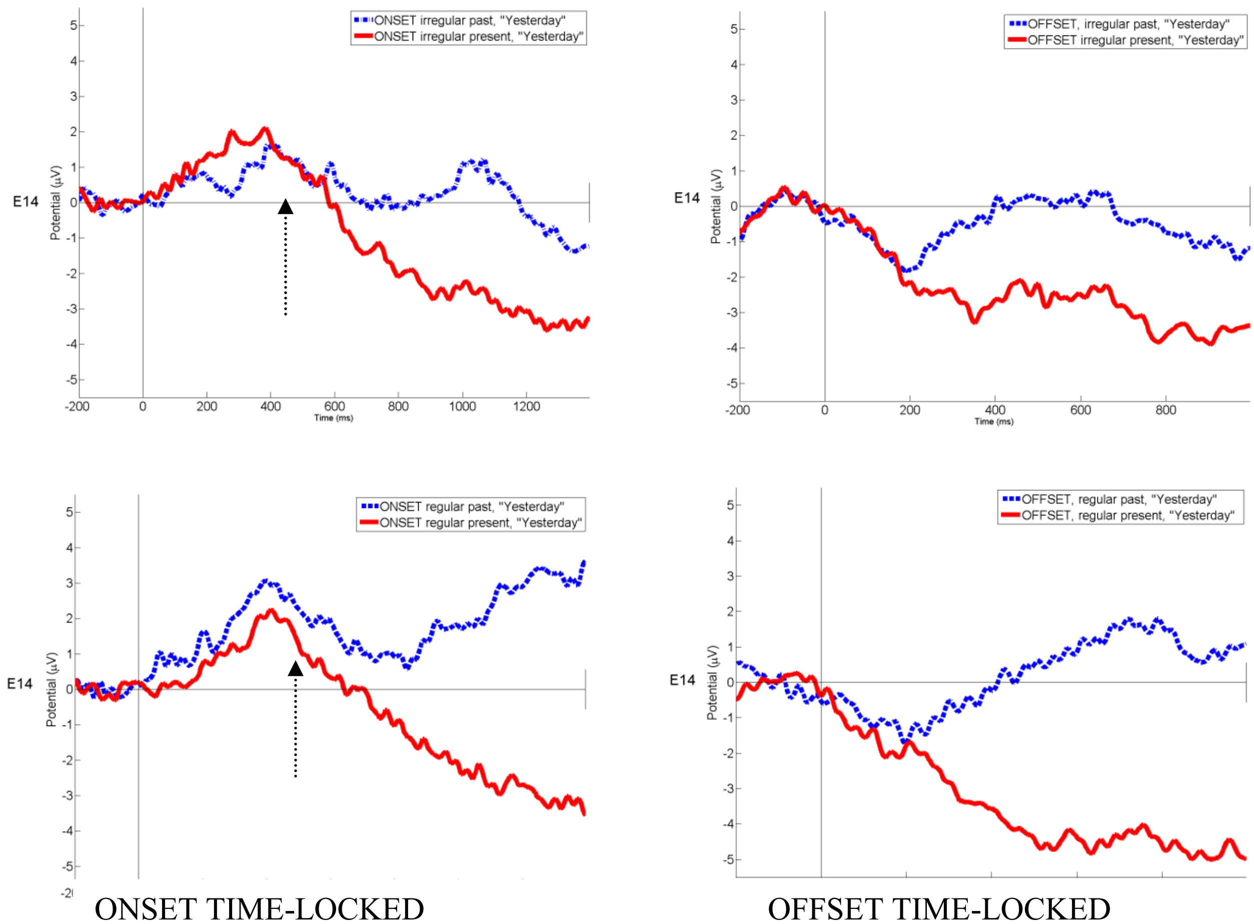

Figure 4. Comparison of onset computed vs. offset computed ERPs, electrode AF7. Left panel: ERPs time-locked to verb onset, irregular vs. regular verbs. I.e., 0ms = beginning of verb; arrows indicate approximate mean verb offset latency. Right panel: ERPs time-locked to verb offset, irregular vs. regular verbs. Here, 0ms = end of verb.

As can be seen in Figures 5 and 6, the offset time-locked ERP starts around 200 ms after the verb offset for both irregulars and regulars, and is present from 300ms—consistent with a LAN. Note that time-locking the ERP to verb offset provides a more accurate mean estimate of the ERP latency for regular verbs, because the offset point will be equated for all the regular verbs. On the other hand, it will provide a less precise time course estimate for irregular verbs, because the grammaticality effect with irregulars is likely to manifest in the EEG before the end of the verb. In order to statistically compare both verb classes, it is necessary to compute the ERPs in the same way. In order to confirm that the ERP analysis was not biased by examining the entire epoch time-locked to verb onset, we conducted an analysis of the data produced by time-locking 1000ms epochs to verb offset.

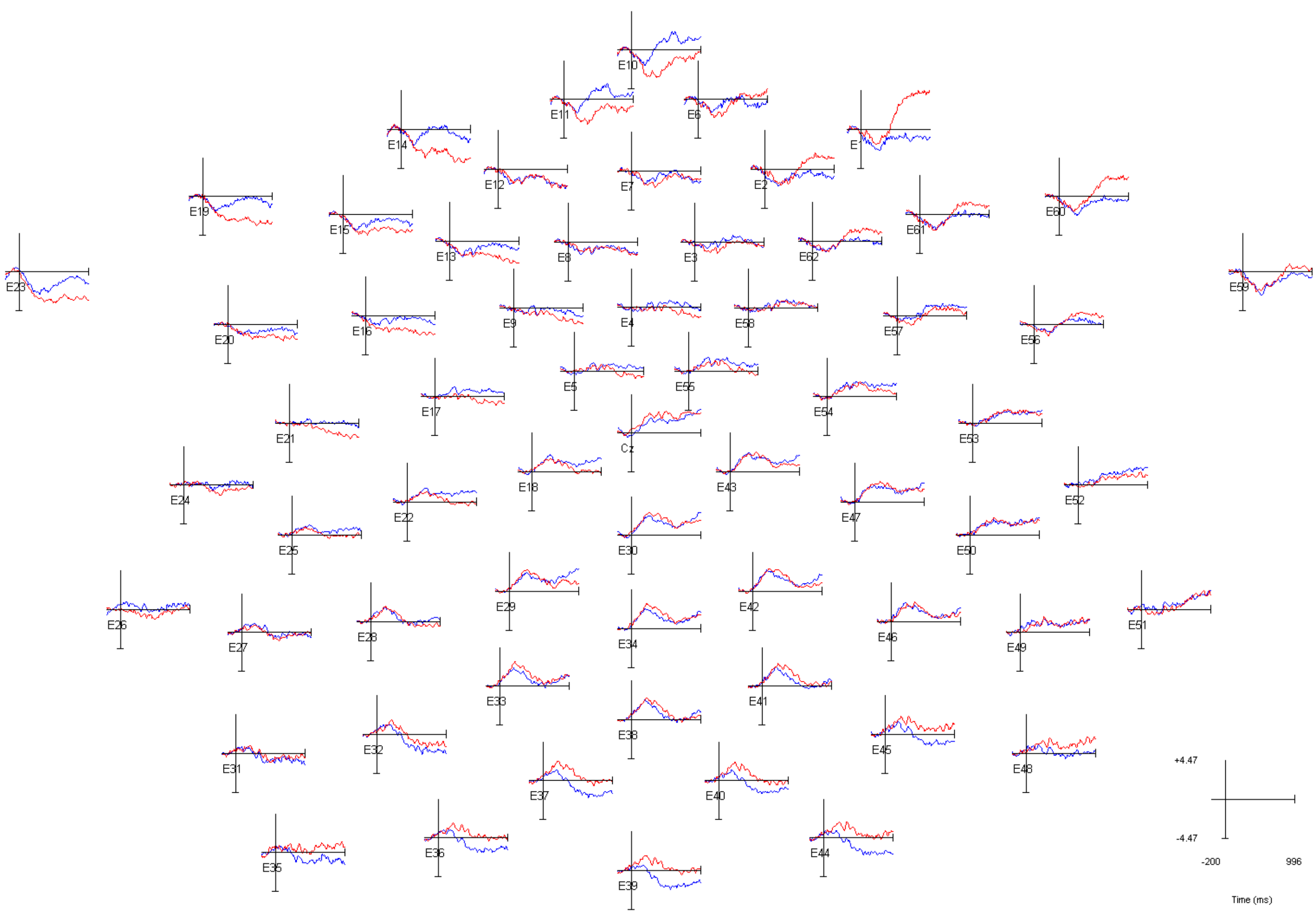

Figure 5: Grand average waveform for irregular verbs, offset computed ERPs in the past context condition.

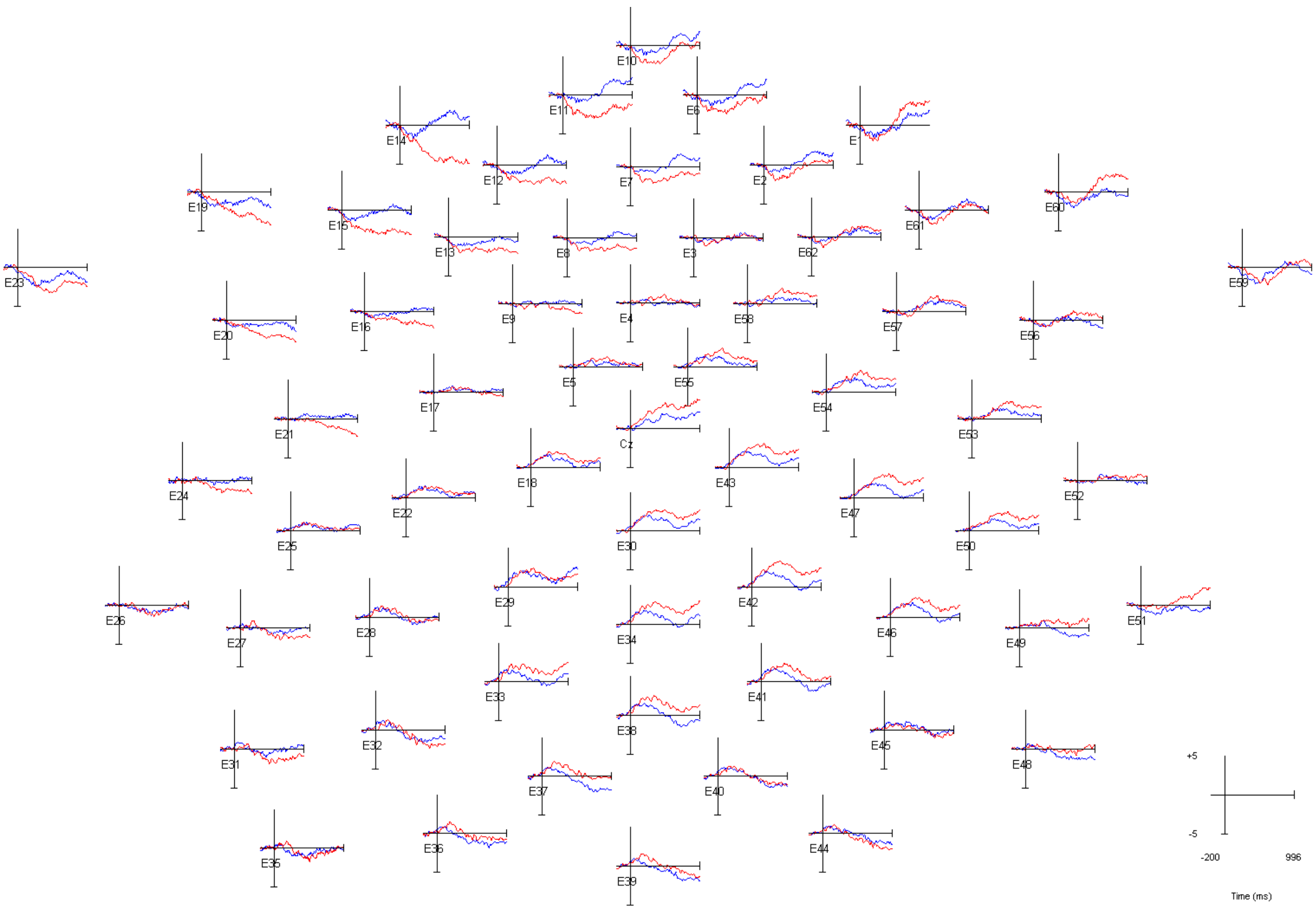

Figure 6: Grand average waveform for regular verbs, offset computed ERPs in the past context condition.

We again computed the mean voltage for each of the four quadrants by verb type and tense, and calculated mean voltages for 100ms time windows starting with the 0-100ms window, and submitted these dependent measures to a TIME (10) x VERBTYPE x TENSE x ANT/POS x LAT(reality) repeated measures ANOVA. This revealed the following 2-way interactions: a TENSE and ANTPOS interaction such that the present tense was more negative than past tense in the anterior region and more positive in the posterior region ($F(1,22)=5.59, p<.05$), and a TENSE x LAT interaction, such that present tense was more negative than past tense in the left hemisphere and more positive in the right ($F(1,22)=12.59$, $p<.005$), i.e. a left-right inversion. The related 3-way interaction TIME x TENSE x ANTPOS (reflecting inversion of the past-present difference in anterior and posterior regions) was also significant ($F(9,198)=4.96$, e=0.28, $p=.0056$), as was the TIME x TENSE x LAT ($F(9,198)=15.9, \varepsilon=0.23$, $p<.0001$), reflecting a negative difference between present and past in the left hemisphere and a positive difference in the right hemisphere. Finally, the TENSE x ANTPOS x LAT interaction was significant ($F=13.7$, $p < .05$), reflecting that the left hemisphere showed an anterior difference between past and present not observed in the right hemisphere. No main effects or interactions involving TENSE x VERBTYPE were observed. Finally, the 4-way TIME x TENSE x ANTPOS x LAT was significant ($F(9,198)=12.94$, e=0.215, $p < 0.0001$). Inspection of interaction plots suggested that this 4-way interaction was driven by an earlier and greater difference between past and present tense in the left anterior quadrant.

The 3-way interaction between TENSE, ANTPOS and LAT was followed up with orthogonal contrast analyses of the grammaticality (TENSE) effect in each of the four electrode region (across the entire 1000ms epoch). The contrast between past and present tense was highly significant in the left anterior quadrant ($t=4.95$, $p<.0001$), but not significant in the right anterior quadrant ($F(1,22)=1.4$, $p=.24$). The inversion (i.e., present more positive than past) was significant in the right posterior quadrant ($t=-2.8$, $p=.01$). Inspection of waveform plots showed that the effect in the right posterior region had a similar time course as the effect in the left anterior region, and is therefore due to the inversion in polarity of the left anterior effect as a consequence of average referencing.

The left posterior quadrant did not show any significant effect ($F(1,22)=.22$, $p=.63$). Contrast analysis in the left anterior region in each 100ms time bin showed that the contrast was significant from the 200-300ms time window ($t=3.23$, $p=.004$) and in all subsequent time windows.

In addition, given the *a priori* hypothesis of a LAN effect in the left anterior quadrant for regular verbs but not for irregular verbs, as well as the hypothesis that men should show a greater LAN effect than women, we again followed (Newman *et al.*, 2007) and performed a repeated measures ANOVA for the left anterior quadrant only, with the factors TIME, VERBTYPE and TENSE x SEX in the left anterior quadrant only. This revealed a main effect of TENSE ($F(1,21)=31.2$, $p<.0001$) and a TIME x TENSE interaction ($F(9,198)=24.5$, $\varepsilon=0.33$, $p<.00001$; the now familiar LAN)—the basic grammaticality effect. It also revealed a TENSE x SEX interaction ($F(1,21)=8.3$, $p< .01$) and a TIME x TENSE x SEX interaction ($F(9,198)=4.73$, $e=0.33$, $p=.005$); such that the difference between past and present was greater for women than for men (and over time). No main effects or interactions involving VERBTYPE was observed.

The interactions involving SEX in the left anterior region was examined by orthogonal contrast analysis of each time window of the TENSE effect separately for women and men. This revealed that the TENSE difference was significant for men only in the late time windows; 700ms ($t=2.28$,$p=.03$), 800ms ($t=2.76$,$p=.011$) and 900ms ($t=2.24$, $p=.035$). For women, it was significant in every time window from 300ms ($t=4.98$, $p<.00001$) and every following time window (cf. Figure 10). In other words, the offset analyzed data brought out a sex difference: the women among the subjects exhibited a LAN with earlier onset latency and greater amplitude than men.

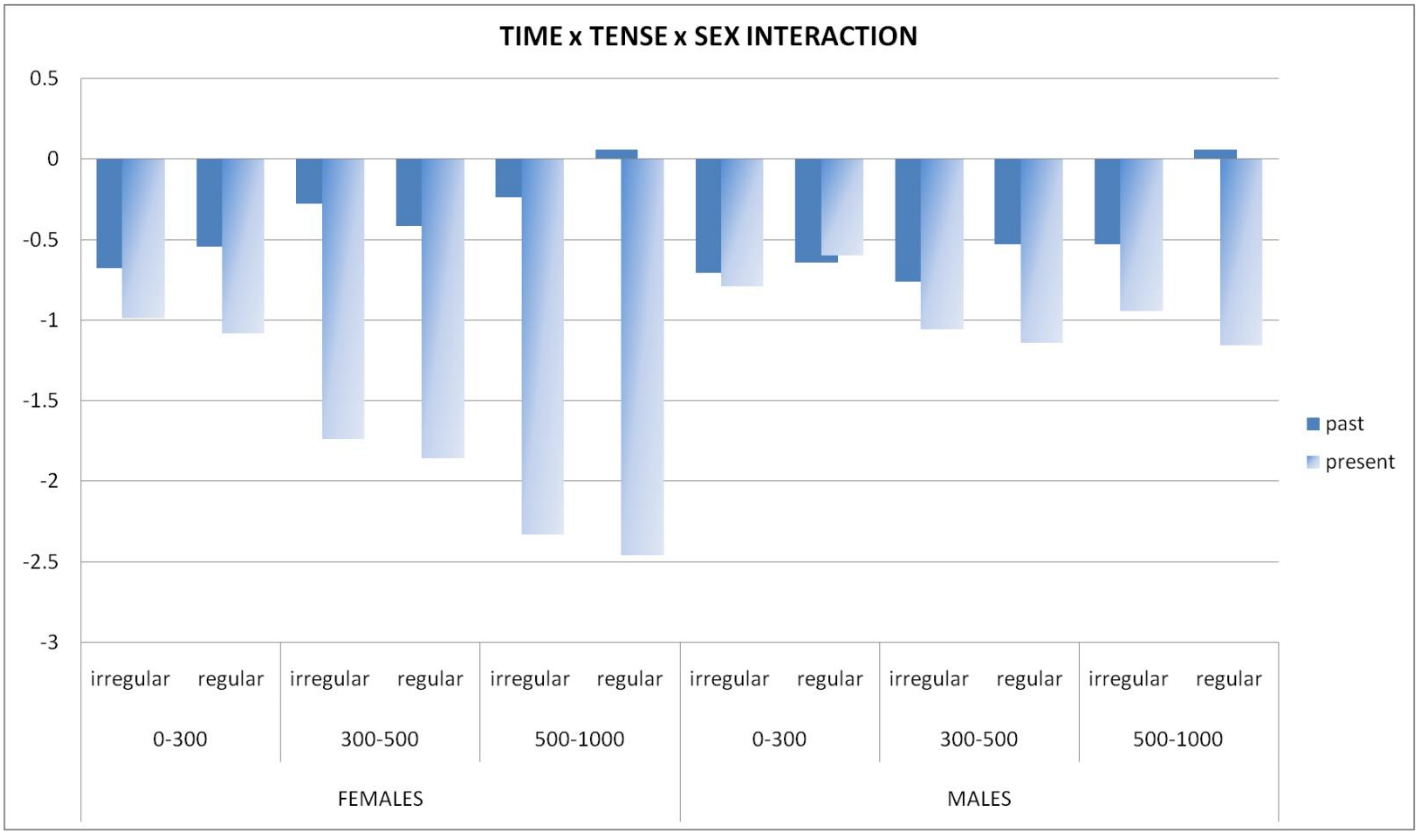

Figure 7: Sex difference in ungrammaticality effect over time, left anterior region (ERPs computed from verb offset). Y-axis shows mean microvolt. X-axis shows irregular vs. regular verbs, by time windows.

2.2.4 Null context condition

In the null context condition, where both tenses were grammatical, present tense verbs generally elicited a left anterior positivity in comparison to past tense. In other words, the voltage difference was the opposite of what was observed when present tense verbs were ungrammatical. As in the past context condition, the amplitude of the tense difference for irregulars started earlier than for regulars, had a greater amplitude and was more spread out topographically. The present tense positivity for regular verbs was focused at AF7 and showed an inversion at right anterior inferior electrodes, as in the past tense context, and started at 1000ms (roughly 400ms past the mean verb offset). Figure 8 shows the time series of topographical plots of the difference waveforms calculated by subtracting the past tense voltage from the present tense voltage.

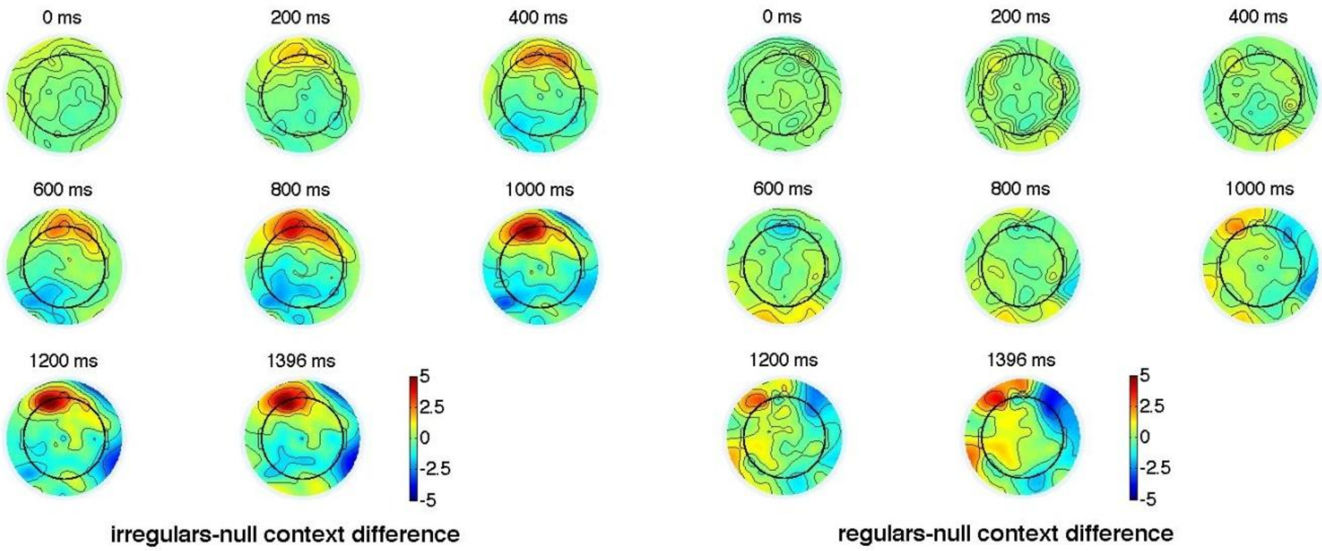

Figure 8. Present tense – past tense difference waveform topoplot, null context condition; both tenses are grammatical. Note that scale is equated for both plots to illustrate magnitude difference.

The same analysis path was followed as for the past context condition. We first analyzed the time region during the processing of the verbs, by computing mean voltages for each of the quadrants and 100ms time windows from 0-600ms, by verb condition and tense condition. These dependent measures were submitted to a TIME(6) x VERB x TENSE x ANTPOS x LAT repeated measures ANOVA. This revealed no interactions involving TENSE, but a VERB x LAT (hemisphere) interaction, such that the mean amplitude difference between left and right hemisphere was bigger for regulars than for irregulars ($F(1,22)=8.93$, $p=.007$).

We next analyzed the post-verbal time region, from 500-1400ms, with a TIME (9) x VERB x TENSE x ANTPOS x LAT repeated measures ANOVA. Again, a VERB x LAT interaction ($F(1,22)=9.2$, $p<.01$) was observed such that the amplitude difference between left and right hemisphere was bigger for regulars than for irregulars (reflecting stronger inversion between left and right anterior electrodes for regulars, cf. Figure 8). A TIME x TENSE x ANTPOS interaction was observed ($F(8,176)=11.9$, $e=0.32$, $p < .00001$). Inspection of interaction plots revealed that this interaction was due to present tense waveforms becoming more different from past tense waveforms during the second half of the epoch (around 1000ms past verb onset and around 400ms past verb offset; with present tense going positive relative to past tense in the left hemisphere and negative in the right hemisphere. Orthogonal contrast analysis of the each successive 100ms time window in the left anterior quadrant revealed that this difference was only significant in the last 100ms window ($t=-2.43$, $p=.02$).

3. Discussion

The ERPs observed in the past context condition clearly showed a left anterior negativity to the ungrammatical present tense verbs in comparison to past tense verbs. Although the difference waveforms started earlier for irregular verbs than regular verbs, the time course of the difference effect was not statistically different. No statistical difference between irregular verbs and regular verbs was observed: both verb types elicited a LAN. We computed the ERPs both by time-locking to verb onset and to verb offset; no difference in verb type and grammaticality effect was observed under the two epoch schemes. A sex difference was brought out by the offset epoched data, such that the LAN effect started earlier and had greater amplitude for women compared to men. However, assuming that the LAN reflects the application of a morphosyntactic computation involving tense; this sex difference is the opposite of what would be expected under the hypothesis that women should show less reliance on computing tense by rule and more reliance of retrieving stored forms from the lexicon. It is not clear whether this effect is due to sampling error or reflects a deeper difference. However, the weak and late LAN effect for men can be interpreted to be related to their slower reaction time to ungrammatical present tense compared to women (cf. Figure 3, lower right panel). In other words, if they were slower at computing that the present tense verbs were ungrammatical, this should result in slower reaction times at making that judgment behaviorally, which we observed.

The null context condition showed that *grammatical* present tense elicited a more *positive* going waveform in comparison to grammatical past tense. This provides support for interpreting the ERP in the *past* context condition as only related to grammaticality: When present tense is ungrammatical (past tense condition), the voltage is more negative that past tense (past context condition); but when present tense is grammatical (null context condition), it has a more positive voltage than past tense. This shows that the difference observed in the ungrammatical condition is not confounded by a grammaticality-independent difference between past and present verbs in general, because the past-present difference has opposite sign under the two conditions.

The Procedural/Declarative model entails that the inflected forms of irregular verbs are stored in the lexicon. Hearing an irregular verb with an unexpected tense should therefore be akin to hearing an unexpected lexical item, which should generate an N400 response under the model of (Ullman, 2001a). On the other hand, for regularly inflected verbs, the stem is identical in both the past tense and the present tense, and tense is computed by rule. Hence, encountering a regular verb in the wrong tense does not require retrieving another form from the lexicon for comparison, but should activate the procedural system where inflectional rules are stored, because it involves recognizing that the wrong inflectional process has produced the word. Computing present tense when past tense is expected should therefore generate a LAN. However, these differential predictions were not matched by the results of the current study: Both irregular and regular verbs with incorrect present tense generated a strong and sustained LAN response, and no N400 response. On the other hand, the finding that both irregular and regular verbs elicit a Left Anterior Negativity is consistent with the Single Route model, as well as Distributed Morphology (Halle & Marantz, 1994). The latter theory entails that both regular and irregular verbs should activate rule computation, and that both regular and irregular verbs are decomposed into a stem and an abstract tense feature (Stockall & Marantz, 2006).

However, these conclusions could be tempered by the following considerations. Current syntactic theory posits that sentences contain an independent syntactic projection of an abstract "Tense" category, which dominates the phrase containing the verb. The inflected verb must combine with this abstract tense node, either through movement "up" in the tree, or by the feature of the Tense node "lowering" to the verb (Chomsky, 1995) (the choice of direction is orthogonal to the current argumentation). The value of this abstract tense node can be determined by adverbs and other tense-bearing elements in the discourse. Specifically, when a listener hears "Yesterday, I…", this causes the tense feature in the abstract tense node to be specified as [+PAST] before the actual verb is encountered, because sentence comprehension and structure building is left-to-right incremental. If the verb itself is morpho-syntactically specified as [-PAST], a feature conflict will result only when the two features bundles are combined by the merging of the T and V node, as depicted in Figure 9.

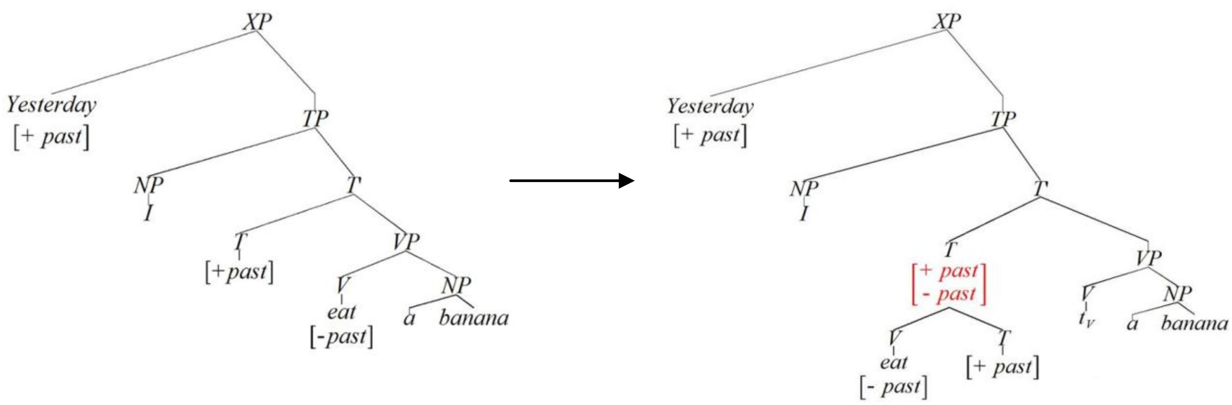

Figure 9. Sequence of parsing operations. Left panel: A past tense adverb induces a +PAST specification in the abstract Tense node. Right panel: A feature conflict occurs when the abstract Tense node is unified with the verb and its tense feature.

An alternative to Distributed Morphology, where syntactic affixation is done at the syntactic level, is that verbs are retrieved from the lexicon and inserted into a syntactic tree with its tense make-up fully specified (Chomsky, 1995). If so, then the resulting conflict can be viewed as occurring at a purely syntactic level of representation, where the origin of the [-PAST] feature, whether it comes from morphological rule or specified as part of a lexical item, is immaterial. In this model, no difference between regular and irregular verbs is expected at the level of processing where a context-induced tense specification conflicts with the morphologically determined tense on a verb. The conflict would be purely at the abstract syntactic feature level, and not at the level of lexical items. If so, the same LAN effect would be expected in both cases because only a syntactic feature combination rule is violated. Indeed, this is roughly the model assumed by (Steinhauer & Ullman, 2002a). They assumed a model where verb processing first go through a morpho-phonological stage, involving recognition of the word form; followed by a morpho-syntactic stage, where that verb form is compared to the constraints imposed by its syntactic environment. (Steinhauer & Ullman, 2002a) reported observing an N400 to ungrammatical irregular verbs in women only (and a LAN in men) during the early morphophonological stage (400 after visual presentation of a word form), followed by a LAN during the 500ms time window, for both men and women. Thus, it could be that the difference between a morpho-phonological and morphosyntactic stage is not observed with our auditory stimulus presentation, because the variance in verb durations and the different points in time that the tense coding is detectable in irregulars vs. regulars makes that transient period statistically undetectable. If so, the LAN common to irregulars and regulars that we observe is the same morphosyntactic verb type independent LAN that (Steinhauer & Ullman, 2002a) observed.

A different objection that can be raised to the conclusions drawn from the current study (as well as (Newman *et al.*, 2007)) is that only violations of past tense morphology, and not present tense morphology, should be used to interpret brain signatures of lexical vs. rule-based inflection violations. This is because present tense in English is not derived by overt suffixation, only past tense is; present tense verbs occur in their stem form. In other words, one could argue that the brain response to an ungrammatical present tense verb does not reveal anything about whether the *past* tense of the same verb is derived by rule or not. In order to address this criticism, the current study would have to be replicated with a condition where it is the past tense version that is unexpected, as in the ungrammatical past tense "*Tomorrow, I will ate a banana" compared to grammatical stem form in "Tomorrow, I will eat a banana", and comparison of "Tomorrow, I will kicked a ball" with "Tomorrow, I will kick a ball". This would be similar to the study in (Allen *et al.*, 2003) but with auditory stimulus presentation. Such an experiment would then directly measure violations of past tense rather than present tense, and might provide a more direct measure of whether irregular past tense is derived by rule or stored. If this experiment were to yield the same LAN effects for irregular and regular ungrammatical verbs, the conclusion would clearly favor a single-route model over a dual route model. On the other hand, a dual route model would be strongly supported if the past tense ungrammatical irregular resulted in an N400 whereas a present tense irregular resulted in a LAN.

4. Methods

4.1. Participants

Thirty adults (15 men and 15 women) participants were recruited in Manhattan via an internet bulletin board for volunteering. All subjects gave informed consent and were reimbursed $10/hour for participation. After data collection, one subject was excluded because of left-handedness (as determined by self-report) and age range restrictions; three subjects were excluded because of experiment errors, and three subjects were excluded because of excessive artifacts during recording. The remaining 23 subjects (12 women and 11 men) had a mean age of 31 years (SD = 6, range 20 - 40 years). All subjects were native speakers of English, with no knowledge of a second language before the age of 7. All reported normal hearing and normal to corrected vision, right-handedness, and no history of neurological impairments.

4.2 Materials

56 regular verbs and 56 irregular monosyllabic verbs were used to form 112 simple declarative sentence structures, introduced by the pronoun "I", followed by the verb, and then followed by verb phrase material, e.g. "I walked after lunch." From each of these structures, four sentences were constructed by varying two conditions: whether the verb was in the past tense or present tense, and whether the sentence was preceded by "Yesterday" or not. The resulting 448 sentences constituted a 2 (past vs. null context) x 2 (past vs. present tense) x 2 (irregular vs. regular) design of the within-subject factors. The null context level was included to examine the difference between past and present tense verbs in the absence of ungrammaticality and will be analyzed separately. Thus, each level of the CONTEXT factor constitutes a 2 x 2 design, as summarized below. In the "null" context condition, both past and present tense sentences are grammatical, cf. Table 1:

TABLE 1

Null context.

	VERBTYPE	
TENSE	*Irregular*	*Regular*
Past	I **ate** a banana	I **walked** after lunch
Present	I **eat** a banana	I **walk** after lunch

In the past tense context, where each sentence is preceded by the adverb “Yesterday,” the present tense verb sentences are ungrammatical, cf. Table 2:

TABLE 2

Past tense context; * indicates ungrammaticality.

	VERBTYPE	
TENSE	*Irregular*	*Regular*
Past	Yesterday, I **ate** a banana	Yesterday, I **walked** after lunch
Present	*Yesterday, I **eat** a banana	*Yesterday, I **walk** after lunch

The conditions in Table 2 constitute the critical comparisons and is identical to the visual presentation design in (Newman *et al.*, 2007), except for having 56 trials instead of 32 in each cell. To summarize, the questions asked by the study is: Does the comparison of past and present tense verbs elicit a different ungrammaticality-related ERP response for regular vs. irregular verbs, and is there an interaction with subjects’ sex? The null context conditions act as a control for the grammaticality-independent past-present difference.

The stimulus sentences were recorded by a female speaker with a moderate speech rate, using 16-bit resolution and 22kHz sampling frequency. The recording was manipulated so that there was a period of complete silence of about 100ms before and after each word, cf. Figure 10.

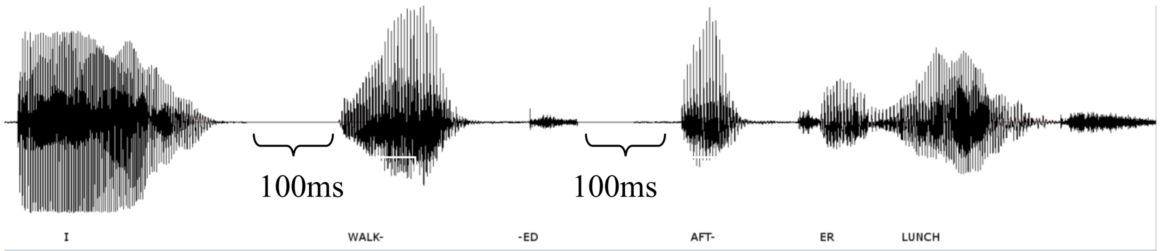

Figure 10: An auditory stimulus. Note the 100ms silence before and after the verb.

The purpose of inserting pauses was to acoustically isolate the beginning and end of each verb, in order to reduce overlap of obligatory auditory ERPs with other effects. A pause of 300ms was inserted after “Yesterday”. Because the same recorded sentences were used in both context conditions, there were no prosodic differences during the verb regions of the stimuli sentences dependent on “Yesterday.” All the 448 sentences from the two context conditions combined were presented in a single experimental session, resulting in 1:4 ratio of ungrammatical to grammatical sentences.

4.3. Procedure

Subjects were seated in an electrically shielded International Acoustics Company audiometry booth, with a PST Serial Response Box placed in front of them on a tabletop. The subjects were instructed to listen to each sentence for meaning, and determine whether it was about something in the present; or something in the past, or didn’t make sense. They were told to use all the cues in the sentence to make the decision, both the tense on the verb as well as the sentence initial adverbial.

Four lists of 112 stimuli sentences were constructed, such that each verb occurred only once in each list. In a given list, the verb would occur in one of the four possible combinations of tense and context. The order of sentences was pseudo-randomized within each list. Regular and irregular verbs and grammatical and ungrammatical sentences from the two context conditions were counter-balanced across the lists. All subjects heard the stimuli in the same order. A set of six sentences were initially presented to train the subjects in the task. The four lists of trials were then presented successively, with eight blocks of 14 trials within each list. Each block was followed by a brief pause, and each list of 112 sentences was followed by a longer break.

Each stimulus sentence was presented auditorily via two speakers, one placed in front of the subject and one placed behind. A single trial was introduced by the sound of a bell, followed by a 300ms pause, followed again by auditory presentation of the sentence. Upon completion of the verb in the sentence, a 1000ms pause ensued. After this pause, the response box buttons would light up, followed by a 2000ms response window. The purpose of this delayed response window was to prevent subjects from responding prematurely during the processing of the verb itself, as well as to prevent subjects from responding during the period after the verb during which the ERPs of interest was measured. Subjects were instructed to press “button 1” if the sentence was about something in the present; “button 2” if the sentence was about something in the past, or “button 3” if the sentence didn’t make sense or was ungrammatical. All subjects used the right hand to respond. The subjects received no other visual input than the button box lights. After the subject responded (or timed out), a 1500 ms pause followed before the next trial. The entire recording session took between 1.5 and 2 hours.

4.4. EEG acquisition and off-line processing

Stimulus presentation and experimental control was programmed in *E-Prime* (Schneider *et al.*, 2002) with the *Netstation Biological Add-Ons*. Accuracy and reaction time of the behavioral responses were recorded by E-Prime on a PC. EEG data was collected using an Electrical Geodesics 200 system, with a 65 channel Geodesic Sensor Net with silver/silver-chloride (Ag/AgCL) plated electrodes contained in electrolyte-wetted sponges. One electrode was placed under each eye to monitor eye movements and eye blinks. EEG was sampled at 250Hz, referenced to Cz online, and band-pass filtered between 0.1-30.3Hz. Impedances were kept below 60kΩ, which is appropriate for high-impedance amplifiers (Ferree *et al.*, 2001).

After recording, the continuous EEG was divided into epochs containing the verb and the following sentence material for each trial, using two different schemes: (i) by time-locking the ERP to the onset of the verb, and (ii) by time-locking the ERP to the offset of the verb. Thus, two different time-locking data sets were created. Under the onset scheme, the epoch was 1400ms long, and under the offset scheme, the epoch was 1000ms long. Trials where the subject had given the incorrect behavioral response were included, in order to avoid extra loss of trials and power.

Each epoch was submitted to the following artifact detection procedures: A channel in a single recording was marked as a bad channel if the fast average amplitude exceeded 200 μV, if the differential amplitude exceeded 100 μV, or if it had zero variance. Bad channels were deleted and replaced with data using the spherical spline interpolation. A trial was marked for exclusion from single subject averages if it contained more than 10 bad channels, or if it contained lateral eye movements or eye-blinks. This procedure removed on the average 26% of the trials per subject (SD = 14%, range = 4% - 49%), with roughly equal number of trials per condition (on the average, around 36 trials per cell in each experiment). Three subjects with an average of more than 50% bad trials were removed from analysis. All good EEG trials were used for analysis, irrespective of behavioral response, in order avoid further reduction in the number of trials per cell and subject and avoid poor signal-to-noise ratio. Each epoch was then baseline corrected relative to a 200ms baseline period, and the average for each condition per subject was computed. The resulting averages were then re-referenced to the average voltage.

4.5 Behavioral data analysis

The data from the past tense and the null context conditions were examined in separate analyses. The behavioral data (accuracy and reaction time) were analyzed with Hierarchical Linear Modeling (HLM) (Raudenbush & Bryk, 2002; Raudenbush *et al.*, 2005). For each of the two context conditions, every verb was presented twice, once in the past tense and once in the present tense. Each verb can therefore be viewed as nested within the TENSE factor, which constitutes the repeated measures level (level 1). The following level 1 equation was used for accuracy, with the predicted probability of correct response represented as logits:

$$\log\left(\frac{p}{1-p}\right) = \pi_0 + \pi_1(PRESENT)$$

The same model was used for reaction time. Because each verb only occurs twice in each context condition (analyzed separately) there is no error term at this level. The 112 intercepts and slopes for each verb are then modeled by two higher order regression equations (level 2), where the mean intercept constitutes the new intercept for the intercepts, and the mean slope coefficient constitutes the intercept for the level-1 slopes. In addition, because each verb is nested within one of the verb classes (irregular and regular verbs), verb class was entered as coefficients for each of the level 2 equations, using regular verbs as intercepts.

$$\pi_0 = \beta_{00} + \beta_{01}(IRREG) + r_0; \quad \pi_1 = \beta_{10} + \beta_{11}(IRREG) + r_1$$

β_{00} represents the mean for regular past tense verbs; β_{01} represents the difference between irregular and regular past tense verbs, and r_0 represents the error term for an individual verb relative to its inflection class. β_{10} represents the mean difference between regular past tense and regular present tense verbs, and β_{11} represents the cross-level interaction term between tense and verb type, i.e. how much the score is predicted to change between an irregular present tense and a regular present tense verb (with r_1 the error term for each individual verb). Finally, because this set of equations is constructed for every subject, the set of level 2 coefficients can be predicted by two more regression equations, where the intercepts represents the mean for all subjects for the intercepts and coefficients at level 2. Subject-level properties (i.e. between-subjects factors) can then be entered as predictors for each level 2 equation.

$$\beta_{00} = \gamma_{000} + \gamma_{001}(MALE) + u_{00}; \beta_{01} = \gamma_{010} + \gamma_{011}(MALE) + u_{01}$$

$$\beta_{10} = \gamma_{100} + \gamma_{101}(MALE) + u_{10}; \beta_{11} = \gamma_{110} + \gamma_{111}(MALE) + u_{11}$$

γ_{001} represents how much the mean accuracy for the intercepts (past tense regular verbs) changes as a function of subject's sex; γ_{011} represents the effect of sex on the irregular/regular verb accuracy (the 2-way interaction between VERBTYPE and sex); γ_{101} is the effect of sex on the mean accuracy for the past/present tense distinction (the 2-

way interaction between TENSE and sex), and finally, γ_{111} represents how sex modulates the VERBTYPE x TENSE interaction (the 3-way interaction between VERBTYPE, TENSE and sex). The error terms represent how much a single subject deviated from the predicted values at level 3. The data were modeled with and without sex as predictors at level 3.

4.6 ERP analysis

For analyzing the ERPs, voltage averages in electrode regions and time bins were used as dependent measures. Electrode regions were defined as recommended by (Dien & Santuzzi, 2005) for high-density electrode arrays. Electrodes were grouped on the basis of ANTERIORITY (anterior vs. posterior electrodes), LATERALITY (left vs. right hemisphere, excluding the midline electrodes), and DORSALITY (inferior vs. superior electrodes). Figure 2 shows the resulting eight electrode regions for the 64 electrodes used in the recording. For example, the left anterior inferior region contained electrodes 11, 12, 14, 15, 19, 20, 23; and the left anterior superior region contained electrodes 5, 8, 9, 13, 16, 17, 21 Electrodes 63 and 64 monitored eye activity.

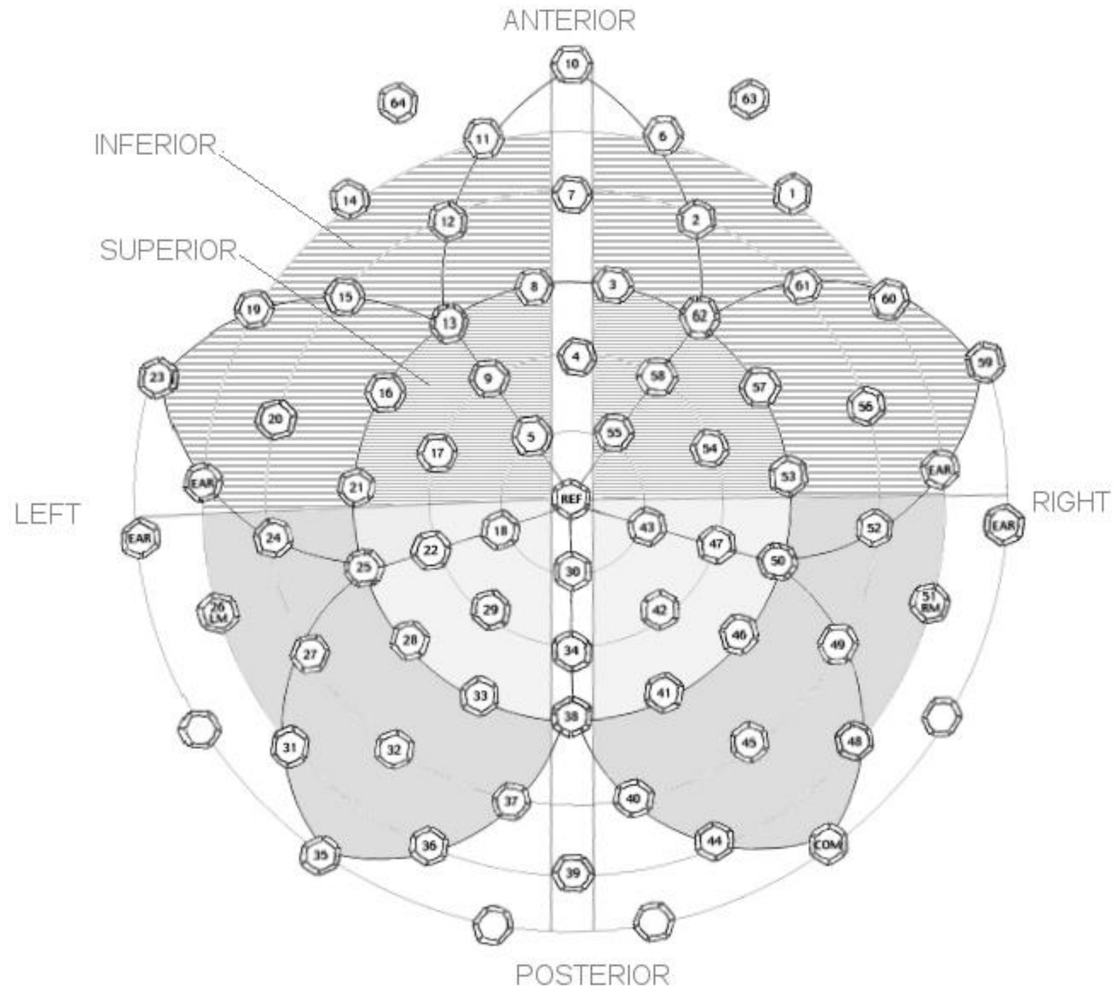

Figure 11. Electrode regions defined for averaging the 65 electrodes used in the recording. (See Luu & Ferree (2000) for the correspondence between electrode placements and the International 10-10 system.)

By combining inferior and superior regions, 4 major regions defined by left/right hemisphere x anterior/posterior regions can be constructed. In the time dimension, the mean amplitude over 100ms time-windows was computed for each electrode region, by subject and condition. The resulting means were used as the dependent measures in mixed factorial repeated measures ANOVA, with electrode region, time window and condition as the within-subject factors, and sex as a between-subject factor. For analyses involving factors with more than two levels, we report *p*-values based on ε-adjusted degrees of freedom (Greenhouse & Geisser, 1959) along with the original F-values. Significant interactions between the experimental conditions and temporal and topographical factors were followed up by planned orthogonal contrast analyses.

Irregular verbs typically mark inflection in the vowel immediately following the onset consonant, whereas regular verbs mark inflection with a suffix. This raises a potential problem for comparing ERPs to inflection in the two verb classes. Ideally, the ERP should be time-locked to the moment in time when tense information becomes available for each verb. However, inflection is marked at the end of the verb for regulars, but inside the stem for irregulars—possibly already at the onset consonant because it will assimilate to the following vowel (i.e., the /s/ in "see" is phonetically different from the /s/ in "saw"). Therefore, time-locking to the offset might reduce variability in the ERP latencies for regulars, but might also increase latency jitter for irregulars (because they are not all of the same duration). On the other hand, time-locking to the onset will likely reduce variability for irregulars but increase it for regulars. There is therefore no single way to directly compare the time course of irregulars and regulars (except for time-locking each irregular verb to its individual "gating" point, which we did not undertake to do). In order to assess whether this difference affects the interpretation of the data, we also constructed epochs from the offset of all verbs and compared the resulting data from the onset-based epochs.

Acknowledgements

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Appendix: Stimuli

A1. Irregular verb sentences

Number	*Prefix*	*Present tense*	*Prefix*	*Past tense*
1	(Yesterday,)	I bend a spoon	(Yesterday,)	I bent a spoon
2	(Yesterday,)	I bleed on it	(Yesterday,)	I bled on it
3	(Yesterday,)	I break a glass	(Yesterday,)	I broke a glass
4	(Yesterday,)	I bring an apple	(Yesterday,)	I brought an apple
5	(Yesterday,)	I build a castle	(Yesterday,)	I built a castle
6	(Yesterday,)	I buy one shoe	(Yesterday,)	I bought one shoe
7	(Yesterday,)	I catch a trout	(Yesterday,)	I caught a trout
8	(Yesterday,)	I choose a shirt	(Yesterday,)	I chose a shirt
9	(Yesterday,)	I deal a card	(Yesterday,)	I dealt a card
10	(Yesterday,)	I dig a hole	(Yesterday,)	I dug a hole
11	(Yesterday,)	I drive around town	(Yesterday,)	I drove around town
12	(Yesterday,)	I eat a banana	(Yesterday,)	I ate a banana
13	(Yesterday,)	I feed our eagle	(Yesterday,)	I fed our eagle
14	(Yesterday,)	I feel an earthquake	(Yesterday,)	I felt an earthquake
15	(Yesterday,)	I fight with Larry	(Yesterday,)	I fought with Larry
16	(Yesterday,)	I fly over Disney Land	(Yesterday,)	I flew over Disney Land
17	(Yesterday,)	I freeze a steak	(Yesterday,)	I froze a steak
18	(Yesterday,)	I give an answer	(Yesterday,)	I gave an answer
19	(Yesterday,)	I grow an inch	(Yesterday,)	I grew an inch
20	(Yesterday,)	I hear a story	(Yesterday,)	I heard a story
21	(Yesterday,)	I hide a coin	(Yesterday,)	I hid a coin
22	(Yesterday,)	I hold our baby	(Yesterday,)	I held our baby
23	(Yesterday,)	I keep a dime	(Yesterday,)	I kept a dime
24	(Yesterday,)	I lose a key	(Yesterday,)	I lost a key
25	(Yesterday,)	I make a cake	(Yesterday,)	I made a cake
26	(Yesterday,)	I meet a friend	(Yesterday,)	I met a friend
27	(Yesterday,)	I read a story	(Yesterday,)	I read a story
28	(Yesterday,)	I ride a horse	(Yesterday,)	I rode a horse
29	(Yesterday,)	I ring our bell	(Yesterday,)	I rang our bell
30	(Yesterday,)	I run a mile	(Yesterday,)	I ran a mile
31	(Yesterday,)	I sell a car	(Yesterday,)	I sold a car
32	(Yesterday,)	I send a letter	(Yesterday,)	I sent a letter
33	(Yesterday,)	I shoot an arrow	(Yesterday,)	I shot an arrow
34	(Yesterday,)	I sing in bed	(Yesterday,)	I sang in bed
35	(Yesterday,)	I sink a ship	(Yesterday,)	I sank a ship
36	(Yesterday,)	I sit in bed	(Yesterday,)	I sat in bed
37	(Yesterday,)	I sleep in bed	(Yesterday,)	I slept in bed
38	(Yesterday,)	I slide on ice	(Yesterday,)	I slid on ice
39	(Yesterday,)	I speak with Betty	(Yesterday,)	I spoke with Betty
40	(Yesterday,)	I spend a dollar	(Yesterday,)	I spent a dollar
41	(Yesterday,)	I spin on ice	(Yesterday,)	I spun on ice

42	(Yesterday,)	I steal a pie	(Yesterday,)	I stole a pie
43	(Yesterday,)	I stick around him	(Yesterday,)	I stuck around him
44	(Yesterday,)	I sting an eye	(Yesterday,)	I stung an eye
45	(Yesterday,)	I strike a nail	(Yesterday,)	I struck a nail
46	(Yesterday,)	I swear at school	(Yesterday,)	I swore at school
47	(Yesterday,)	I sweep our floor	(Yesterday,)	I swept our floor
48	(Yesterday,)	I swim a mile	(Yesterday,)	I swam a mile
49	(Yesterday,)	I swing a bat	(Yesterday,)	I swung a bat
50	(Yesterday,)	I take a penny	(Yesterday,)	I took a penny
51	(Yesterday,)	I teach a class	(Yesterday,)	I taught a class
52	(Yesterday,)	I tell a story	(Yesterday,)	I told a story
53	(Yesterday,)	I think about Mary	(Yesterday,)	I thought about Mary
54	(Yesterday,)	I weep with joy	(Yesterday,)	I wept with joy
55	(Yesterday,)	I win a prize	(Yesterday,)	I won a prize
56	(Yesterday,)	I write you poetry	(Yesterday,)	I wrote you poetry

A2. Regular verb sentences

Number	*Prefix*	*Present tense*	*Prefix*	*Past tense*
57	(Yesterday,)	I ask a question	(Yesterday,)	I asked a question
58	(Yesterday,)	I beg in town	(Yesterday,)	I begged in town
59	(Yesterday,)	I call a friend	(Yesterday,)	I called a friend
60	(Yesterday,)	I cause a riot	(Yesterday,)	I caused a riot
61	(Yesterday,)	I change a diaper	(Yesterday,)	I changed a diaper
62	(Yesterday,)	I clear a debt	(Yesterday,)	I cleared a debt
63	(Yesterday,)	I crawl into bed	(Yesterday,)	I crawled into bed
64	(Yesterday,)	I cry with joy	(Yesterday,)	I cried with joy
65	(Yesterday,)	I drop a plate	(Yesterday,)	I dropped a plate
66	(Yesterday,)	I dry a flower	(Yesterday,)	I dried a flower
67	(Yesterday,)	I fail an exam	(Yesterday,)	I failed an exam
68	(Yesterday,)	I fan our king	(Yesterday,)	I fanned our king
69	(Yesterday,)	I file a lawsuit	(Yesterday,)	I filed a lawsuit
70	(Yesterday,)	I fire a rifle	(Yesterday,)	I fired a rifle
71	(Yesterday,)	I gain a pound	(Yesterday,)	I gained a pound
72	(Yesterday,)	I glue one stamp	(Yesterday,)	I glued one stamp
73	(Yesterday,)	I help a stranger	(Yesterday,)	I helped a stranger
74	(Yesterday,)	I hire a nanny	(Yesterday,)	I hired a nanny
75	(Yesterday,)	I look after Sue	(Yesterday,)	I looked after Sue
76	(Yesterday,)	I move a chair	(Yesterday,)	I moved a chair
77	(Yesterday,)	I owe a dollar	(Yesterday,)	I owed a dollar
78	(Yesterday,)	I pass one test	(Yesterday,)	I passed one test
79	(Yesterday,)	I pay a fine	(Yesterday,)	I paid a fine
80	(Yesterday,)	I plan a party	(Yesterday,)	I planned a party
81	(Yesterday,)	I play an instrument	(Yesterday,)	I played an instrument
82	(Yesterday,)	I pour one gallon	(Yesterday,)	I poured one gallon

83	(Yesterday,)	I pray in bed	(Yesterday,)	I prayed in bed
84	(Yesterday,)	I prove a point	(Yesterday,)	I proved a point
85	(Yesterday,)	I pull a tooth	(Yesterday,)	I pulled a tooth
86	(Yesterday,)	I raise a hand	(Yesterday,)	I raised a hand
87	(Yesterday,)	I reach a conclusion	(Yesterday,)	I reached a conclusion
88	(Yesterday,)	I roar with laughter	(Yesterday,)	I roared with laughter
89	(Yesterday,)	I roll a marble	(Yesterday,)	I rolled a marble
90	(Yesterday,)	I sail a ship	(Yesterday,)	I sailed a ship
91	(Yesterday,)	I save a quarter	(Yesterday,)	I saved a quarter
92	(Yesterday,)	I score a point	(Yesterday,)	I scored a point
93	(Yesterday,)	I scrape our floor	(Yesterday,)	I scraped our floor
94	(Yesterday,)	I share a cake	(Yesterday,)	I shared a cake
95	(Yesterday,)	I sign a letter	(Yesterday,)	I signed a letter
96	(Yesterday,)	I slip on ice	(Yesterday,)	I slipped on ice
97	(Yesterday,)	I spy on Chris	(Yesterday,)	I spied on Chris
98	(Yesterday,)	I stare around me	(Yesterday,)	I stared around me
99	(Yesterday,)	I stay after school	(Yesterday,)	I stayed after school
100	(Yesterday,)	I step on gum	(Yesterday,)	I stepped on gum
101	(Yesterday,)	I stir our soup	(Yesterday,)	I stirred our soup
102	(Yesterday,)	I stop a cab	(Yesterday,)	I stopped a cab
103	(Yesterday,)	I talk with Elbert	(Yesterday,)	I talked with Elbert
104	(Yesterday,)	I tie a ribbon	(Yesterday,)	I tied a ribbon
105	(Yesterday,)	I try her soup	(Yesterday,)	I tried her soup
106	(Yesterday,)	I use a map	(Yesterday,)	I used a map
107	(Yesterday,)	I view a movie	(Yesterday,)	I viewed a movie
108	(Yesterday,)	I walk after lunch	(Yesterday,)	I walked after lunch
109	(Yesterday,)	I weigh a package	(Yesterday,)	I weighed a package
110	(Yesterday,)	I whip an egg	(Yesterday,)	I whipped an egg
111	(Yesterday,)	I wish you joy	(Yesterday,)	I wished you joy
112	(Yesterday,)	I work with Fred	(Yesterday,)	I worked with Fred

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