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Research Report

# Event-related potentials to violations of inflectional verb morphology in English

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**Abstract**

Event-related brain potentials were recorded to morphologically correct and incorrect regular and irregular past tense verb forms presented in sentences and in lists. In the sentence context, all incorrect verb forms elicited a broadly distributed late posterior positivity, as well as a left anterior negativity (LAN) that was particularly pronounced for the incorrect irregulars. Using a single-word paradigm, we did not find a LAN for any of the incorrect verb forms but found an N400-like effect for all irregular verbs. In the sentence context, only the incorrect irregulars elicited a long-lasting, broadly distributed late positivity, reminiscent of the P600. For regular verbs, responses to incorrect forms produced smaller, more time restricted effects. These data show that morphological and syntactic violations produce similar patterns of brain activity, suggesting that these two systems engage cognitive processes with similar underlying neural substrates.
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*Theme:* Neural basis of behavior
*Topic:* Cognition

*Keywords:* Morphology (language); Irregular inflection; N400; P600; Left anterior negativity

## 1. Introduction

Much of the research at the morphological level of linguistic representation has focused on delineating the balance between computation and storage in the processing of morphologically complex words. Some theories posit that all words, including those that are morphologically complex, are stored as full forms in the mental lexicon, while other theories propose that some complex words undergo decomposition into their constituent morphemes during processing.

### 1.1. The representation of morphologically complex words

Studies on morphological decomposition suggest that some complex words may be represented and accessed decompositionally, but exactly which words are so represented is subject to much debate. Taft [38,39] argues that both derived and inflected words are subject to decomposition via affix stripping prior to lexical access; Burani and Caramazza [2] suggest that familiar words activate whole word units, while unfamiliar complex words are processed decompositionally. For Colé et al. [3], the nature of the affixation determines whether words will be decomposed, i.e., suffixed, but not prefixed, words are accessed via their root morpheme. Meunier and Segui [21] argue that high-frequency affixed words are represented both as full forms and as decomposed morphemes, while low-frequency affixed words are represented only in a decomposed form. Stanners and colleagues [36,37] propose that the property of a word that determines whether or not it will be represented and/or processed decompositionally is its status as a derived versus inflected form; inflectionally related forms share a lexical entry and therefore can be accessed via a common root morpheme after decomposition, but derivationally

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related forms are merely lexical neighbors and thus must each be accessed via their own lexical entries.

There is also disagreement about the level of lexical representation at which morphological decomposition occurs. Some researchers propose that morphologically complex words are represented as whole units at the level of form, but that morphological relatives are linked to common morphological representations at a different, more abstract level of linguistic structure [5,6,8]. Thus, there is little consensus on either the type of morphological complex word that undergoes decomposition or the level of lexical representation at which that decomposition takes place.

### *1.2. The neurophysiology of morphological processing*

Hypotheses about the representation and processing of complex words have been difficult to test using only reaction time paradigms as it is difficult to tease apart the influence of semantic, phonological, orthographic and morphological and mnemonic properties on reaction time data. The limitations of behavioral data have led some researchers to turn to other methodologies such as scalp recorded event-related potentials (ERPs).

ERPs are well suited to the study of language processing because they have good temporal resolution which allows for the tracking of perceptual and cognitive processes in real time without requiring subjects to produce overt responses that may interfere with the cognitive events related to stimulus processing. Moreover, if it is assumed that distinct processes are mediated by different underlying neurophysiological and neuroanatomical mechanisms, then differences in patterns of ERPs, particularly scalp topography, can provide evidence for distinct brain and by extension cognitive mechanisms [24]. This property of ERPs has been useful for researchers trying to disentangle the role of syntactic versus semantic processes in language comprehension and is used in the present study to investigate the extent to which morphologically complex words are processed decompositionally.

#### *1.2.1. Language-related ERP components*

In recent years, several ERP components have also been found that are sensitive to both semantic and syntactic processes during language comprehension. The component most associated with semantic processing has been the N400, a negative going component which typically has a central–posterior maximum. A substantial number of studies have shown that the amplitude of this component is primarily sensitive to the process whereby a word is semantically integrated with the preceding context (larger N400s being associated with more integration difficulty [12]).

The LAN is a negativity in the same time window as the N400 but with a left anterior distribution. It has been observed in response to violations of syntactic rules such as errors of subcategorization and to morphological agreement violations, e.g., subject–verb agreement [7,35].

A final component that has been shown to be sensitive to syntactic violations is the P600. The P600 typically has a centro-parietal distribution, an onset between 300 and 500 ms and a duration of several hundred milliseconds. A disparate set of syntactic violations have been shown to enhance the amplitude of the P600. These include violations of constraints on phrase structure [10,23,25], verb subcategorization [10,25,28,35], subject–verb agreement [4,10,27], reflexive pronoun–antecedent agreement and anaphor binding [11,27] and subjacency [20,23], as well as grammatical but non-preferred continuations [14,15].

### *1.3. ERPs to morphological violations*

Both morphology and syntax are systems that govern the expression of linguistic form, as opposed to meaning; both systems are combinatorial and rule governed. If morphologically complex words must be decomposed during comprehension and combined during production, it may be that the cognitive processes responsible for the decomposition and/or combination of both morphological and syntactic units share a single underlying brain mechanism. If they do, it may be possible to use the modulation of components such as the LAN and P600 that have been shown to be associated with syntactic processing, as evidence for decompositional accounts of morphological representation. Alternatively, if morphologically complex words are represented as whole words (i.e., in undecomposed form), then ERPs sensitive to syntactic processes might prove insensitive to morphological manipulations, while some other ERP component(s), perhaps one that reflects lexical or semantic possessing (e.g., the N400) might reveal morphological effects.

Thus far, at least three published studies have examined the brain responses to violations of morphological form. Penke and colleagues [29] examined violations of regular and irregular verb inflection in German. They used regular, irregular and nonsense verb forms and varied the correctness of the forms, by regularizing the irregular verbs and irregularizing the regular verbs. They also varied the context in which the stimuli were presented—in list form, embedded in a single sentence context and embedded in a short story. Subjects performed a noun detection task in the single word condition, a sentence recognition judgment task in the sentence condition and a memory task in the discourse condition. They found a LAN (a negative waveform in the 250–500 ms window at the left fronto-temporal sites) for regularized irregular verbs, i.e., the -t participle applied to an irregular verb (e.g., **aufgeladet* instead of *augeladen*) but not for irregularized regular verbs, i.e., the -n participle applied to a regular verb (e.g., **durchgetanzen* instead of *durchgetanzt*). In a previous study, Weyerts and colleagues [40] found the same effect with regular and irregular noun plurals. They interpreted the presence of a LAN for irregular verb and noun forms with the regular past tense or plural affix as being consistent with regular affixation occurring by rule. In the case of irregular verbs, the stored inflected form of a verb interferes with the application of the rule to that verb [32]. In other words, it is the violation of this rule that results in a LAN. If it was the case that the ERP effect was merely due to a conflict between the presented word and the "real" past tense representation (e.g., '*ran*' vs. '*runned*'), then brainwave responses indicative of a lexical or semantic problem (e.g., that item is a non-word) in a sentence context (i.e., an N400) would have been obtained. Hence, Penke et al. interpret the similarity of the ERP effects for morphological and syntactic violations (LAN) as evidence of morphological decomposition for regularly inflected nouns and verbs but not for irregulars.

Gross and colleagues [9] examined ERPs to over-regularizations of past participles in Italian to see if the effects found for German would generalize to a typologically different language. They used Italian verbs and presented them in list form. Italian is a Romance language in which regular past tenses are formed by affixing the particle -t to a verb stem and then adding a gender/number marker; -o is the default masculine singular inflection. Verbs stems consist of a root and a "theme" vowel that determines the conjugation class into which the verb falls. Thus, regular verbs can be decomposed into a root, theme vowel and inflection. The formation of a regular participle involves two processes, the concatenation of a root and theme vowel to form a stem and the attachment of the inflectional ending (e.g., *parl-a-re* ⇨ *parl-a-to*). Irregular participles, in contrast, are formed by phonologically modifying the stem and cannot be decomposed into root, theme vowel and past tense inflection (e.g., *prendere* ⇨ *preso*). Thus, if stem formation and affixation are processes that engage different brain systems, we might expect languages that rely on stem formation processes in addition to affixation, such as Italian, to elicit different patterns of brain activity than those that depend on affixation alone.

In a noun detection task, using single word stimuli, Gross et al. [9] found a broadly distributed, slightly right lateralized negativity to over-regularization errors involving affixation. There was also a smaller negativity with a right anterior distribution to verb stem formation errors involving regular verbs. These two negative components differed from the negativity – characterized as a LAN – found by Penke et al. [29] in that they were both more broadly distributed and lateralized to the right as opposed to the left. Hence, they appear to be more reminiscent of the N400 that has been often been associated with lexical processing than of a true LAN. These findings are more consistent with a whole word account of morphological processing than with a compositional account. Gross et al. [9] hypothesized that the difference between the German and Italian findings may be due to differences in the kinds of morphological processes that are predominant in each language. It may be that languages with stem-based inflection may rely more heavily on lexical processes than those that depend principally on affixation.

Rodriguez-Fornells and colleagues [34] investigated morphological violations in Catalan, which like Italian, is a Romance language in which inflection is stem based. Violations were embedded in discourse contexts, and subjects were asked to remember and answer questions about the content of the discourse. They found both a LAN, albeit one with a more posterior distribution than has typically been found, and a P600 to both verb stem formation errors, and past tense inflectional over-regularization errors. Despite the fact that Catalan is a Romance language with stem-based inflection, they did not find any N400-like responses to violations, suggesting that the differences in findings for the German and Italian studies described above may not wholly depend on the differences between stem-based and affix-based inflectional systems.

Rodriguez-Fornells et al. [34] suggest that their study may have yielded a P600 effect, whereas the Italian and German studies did not because they used sentences embedded in discourse, as opposed to Penke et al. [29], who used lists as well as sentences and stories, and Gross et al. [9], who used just lists. If the P600 reflects reanalysis or repair processes on a sentential level, then it should be absent in word-list studies, such as those conducted by Penke et al. and Gross et al.

Another possibility is that Penke et al. presented their critical verbs as the final word of a simple declarative sentence. Prior studies [25] have shown that sentence final words from semantically difficult to interpret sentences (e.g., with a syntactic anomaly earlier in the sentence) often have somewhat larger N400s. This effect has been interpreted as reflecting a sentence-level closure or wrap-up process whereby the degree of coherence of the entire sentence is evaluated [26]. A large N400 to the incorrect irregulars in the Penke study, especially if temporally extended, may have obscured any potential P600 effect.

This hypothesis is bolstered by the findings of Linares, Rodriguez-Fornells and Clahsen [17] who observed a LAN and P600 to violations of verb stem formation and suffixation in Spanish. In their study, violations were embedded in sentence contexts, and the critical verb form was always the fourth word of the sentence.

### *1.4. The current set of studies*

The current set of studies aims to further investigate the question of whether morphologically complex words are decomposed during processing. In particular, we had three main goals. Our first aim was to investigate brain responses to morphologically violations with the goal of clarifying whether combinatorial processes at the word and sentence level may share common brain mechanisms. If so, we would expect to find that morphological violations elicit ERP components similar to those that are elicited by syntactic violations (LAN and/or P600). On the other hand, if combinatorial processes are not used in processing morphologically complex words, then syntactically sensitive ERP components should not be modulated by morphological violations, and instead, some other ERP component might prove sensitive to these effects. The N400, which has been shown to reflect later semantic processing and to be sensitive to earlier lexical processes (e.g., [13]) might prove sensitive to morphological violations.

A second goal of this study was to examine ERPs to correct and incorrect verb forms in both single-word and sentence contexts. If the P600 reflects reanalysis or repair processes on a sentential level, and if the LAN reflects thematic role assignment, these components may be sensitive to morphological violations only in the presence of a sentence context.

A third goal was to look for similar patterns of effects between the studies in German, Italian and Catalan data and this study in English. In contrast to verbal inflectional morphology in Catalan and Italian, English morphology, like German, is word- rather than stem-based, and some researchers have claimed that this difference might lead to different processing mechanisms or strategies. If this is true, then we would expect the data from English to resemble more closely the German data, as opposed to the data from Italian and Catalan. In particular, we would expect to see an ERP component associated with syntactic or combinatorial processing, such as the LAN or P600 in response to morphological violations rather than a component associated with lexical processing such as the N400.

## 2. Experiment 1: sentence acceptability judgment task

In Experiment 1, we compared ERP responses to (a) regular and (b) irregular past tense verbs, (c) incorrect irregular verbs, i.e., those that had the regular past tense morpheme incorrectly applied (e.g., bring *bringed, instead of brought) and (d) incorrect regular verbs that had undergone stem vowel changes similar to those of irregular past tense verb forms (e.g., seep ⇨ *sept instead of seeped). English regulars and irregular past tense verb forms differ in terms of their morphological composition. Whereas regular verbs are comprised of a stem and segmentable affix, irregular verbs form the past tense in a variety of ways, often by means of a vowel change to the stem (e.g., run ⇨ ran). Thus, it is not possible to completely match regular and irregular verb forms.

The critical words were presented as the main verbs of simple declarative sentences. We predicted that the incorrect irregular verbs, which contained violations of morphological structure in the form of incorrect combinations of separable bound morphemes (morphological violations), would elicit ERP responses indicative of combinatorial processing such as the LAN and/or P600, and that the morphologically simple incorrect regular verbs (lexical anomalies or non-words) would elicit responses indicative of lexical processing, such as the N400.

### 2.1. Method

#### 2.1.1. Subjects

The subjects for this study were 24 adults (9 men and 15 women). The data from 3 subjects, one male and two females, were excluded from analysis, one because of failure to complete the study and two for excessive eye movement artifact. All subjects were recruited from the Tufts University community and paid for their participation. The subjects ranged in age from 17 to 23 years (mean 19.9 years). All were right-handed native English speakers with normal or corrected-to-normal vision, and none reported any linguistic or neurological impairment.

#### 2.1.2. Stimuli

The stimuli were 80 regular and 80 irregular verbs matched for both frequency and length, divided into two lists each containing 40 regular and 40 irregular verbs. Each verb appeared in infinitive and in past tense form. The infinitive forms were included for the purposes of another study and will not be discussed further here. Regular and irregular verbs were matched for log frequency of both uninflected ($t(1,158) = 1.4$, $P > 0.2$ and past tense forms ($t(1,158) = 0.27$, $P > 0.8$) and length of the uninflected form ($t(1,158) = 1.8$, $P > 0.07$). The items on the two lists also did not differ in log frequency ($t(1,318) = 0.2$, $P = 0.8$) or length ($t(1,318) = 0.2$, $P = 0.8$). Irregular verbs also appeared in a regularized form in which the regular past tense ending -ed was attached to the infinitive, e.g., 'bringed'. Each list also included 80 regular verbs that were made irregular by means of a vowel change and sometimes the addition of an unvoiced alveolar stop (e.g., 'peep' became 'pept' on analogy with 'creep/crept' and 'sweep/swept'). Because these "irregularized" verbs had to be selected from specific phonological neighborhoods, i.e., phonological neighborhoods that allowed generalization by analogy to new forms, they were not the same verbs as those that appeared in correct regular past tense from and were not matched in frequency. They did not differ in length ($t(1,158) = 1.68$, $P > 0.1$). The order in which the different forms of verbs appeared was counterbalanced across subjects.

In each list, the 280 experimental items were supplemented by 40 fillers. Fillers consisted of 40 additional irregular verbs that were regularized by the addition of the regular past tense ending. These were included to ensure that each list contained equal numbers of well-formed and ill-formed verbs, but the data for these fillers items were not analyzed. Each list of 320 was divided into five blocks of 64 items each.

#### 2.1.3. Procedure

Each verb was presented as the main verb of a simple declarative sentence of the following form:

"The police warn drivers about speeding."

After reading each sentence, subjects were instructed to press one of two buttons of a game controller if the sentence was ungrammatical or in any way unacceptable, and another if the sentence was correct. The hand that subjects used to press the buttons was counter-balanced across subjects. Words were presented for duration of 350 ms with a 150-ms blank screen pause after each word. Subjects responded 1200 ms after the presentation of final word in each sentence, and they were given a short break after each block.

### 2.1.4. Recording procedure

EEG activity was recorded from 29 scalp locations using tin electrodes attached to an elastic cap (Electrocap International) according the international 10–20 system (Fig. 1).

Vertical eye movements and blinks were monitored by means of an electrode placed beneath the left eye and horizontal eye movements, by an electrode placed at the outer canthus of the right eye. These 31 channels were referenced to an electrode placed over the left mastoid, while the activity over the right mastoid was actively recorded. EEG signals were amplified with a bandpass of .01 to 40 Hz by a SA Bioamplifier system. The data were digitized online at 200 Hz and stored on disc for later analyses.

### 2.1.5. Data analysis

We calculated the mean voltage in each of two time windows (300–500 ms and 600–1000), relative to a 100 ms pre-stimulus baseline. These time epochs were chosen because they correspond to the latency ranges that have been typically found for the LAN, the N400 and the P600. Trials characterized by excessive EOG artifact were rejected, resulting in 1.45% of trials being discarded. This percentage did not vary significantly across experimental conditions ($P > 0.34$).

Mean amplitude data were analyzed with four separate repeated measures ANOVAs. One ANOVA included the midline sites; the three other analyses included sites located at three bilateral columns running along the rostral–caudal axis (see Fig. 1). All four ANOVAs included the factors REGULARITY (regular, irregular), CORRECTNESS (correct, incorrect) and ELECTRODE. The three lateral analyses also included the factor HEMISPHERE (right, left). For the midline ANOVA, the factor ELECTRODE had five levels (FPZ, FZ, CZ, PZ, OZ), for the Inner Lateral ANOVA, 3 levels (FC1/2, C3/4,CP1/2), for the Mid-lateral ANOVA, 4 levels (F3/4, FC5/6,CP5/6,P34) and for the Outer Lateral ANOVA, 5 levels (FP1/2, F7/8, T3/4, T5/6, O1/2). The Geisser–Greenhouse correction was applied when evaluating effects with more than one degree of freedom. Finally, as suggested by McCarthy and Wood [19], analyses with significant interactions of stimulus variables with a topographic factor (e.g., Electrode Site or Hemisphere) were repeated after amplitude values were normalized (using $z$ scores) separately within each level of the Word- or Sentence-type factor. Only interactions significant after normalization are reported.

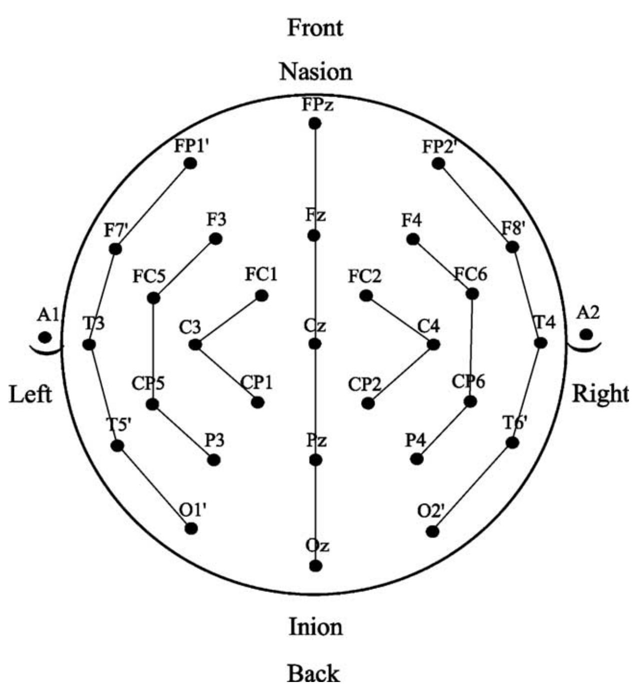


Fig. 1. The 32-channel montage. The lines connecting the electrode sites show the locations of the midline and bilateral parasagittal columns used in the statistical analysis of the data.

## 2.2. Results

### 2.2.1. Grammaticality judgments

Participants judged the correct regular and irregular past tenses to be grammatical on 85.8% and 88.3% or the trials respectively. Incorrect irregular verb forms (e.g., bringed) were judged to be grammatical on 9.6% of all trials, and the incorrect regular verb forms (e.g., pept) were judged grammatical on 3.6% of trials. There was no significant REGULARITY × CORRECTNESS interaction ($F(1,20) = 3.4$, $P > 0.05$).

### 2.2.2. 300–500 ms epoch

Analyses of data in this time window yielded a significant CORRECTNESS by HEMISPHERE by ELECTRODE interaction at the Mid Lateral column ($F(3,60) = 7.2$, $P = 0.002$). Separate analyses for the right and the left hemispheres showed that there was a significant CORRECTNESS × ELECTRODE interaction in the left hemisphere ($F(3,60) = 5.8$, $P = 0.008$) but not in the right. In the left hemisphere, separate analyses for correct and incorrect forms revealed a significant effect of ELECTRODE for incorrect forms ($F(3,60) = 8.0$, $P = 0.004$) but not for correct forms ($P > 0.1$). For the incorrect forms, orthogonal polynomial contrasts revealed a significant linear trend $F(1,20) = 9.6$, $P = 0.006$) with anterior electrodes sites more negative than posterior ones (see Fig. 2).

There was also a REGULARITY by CORRECTNESS × HEMISPHERE interaction at the Inner Lateral sites

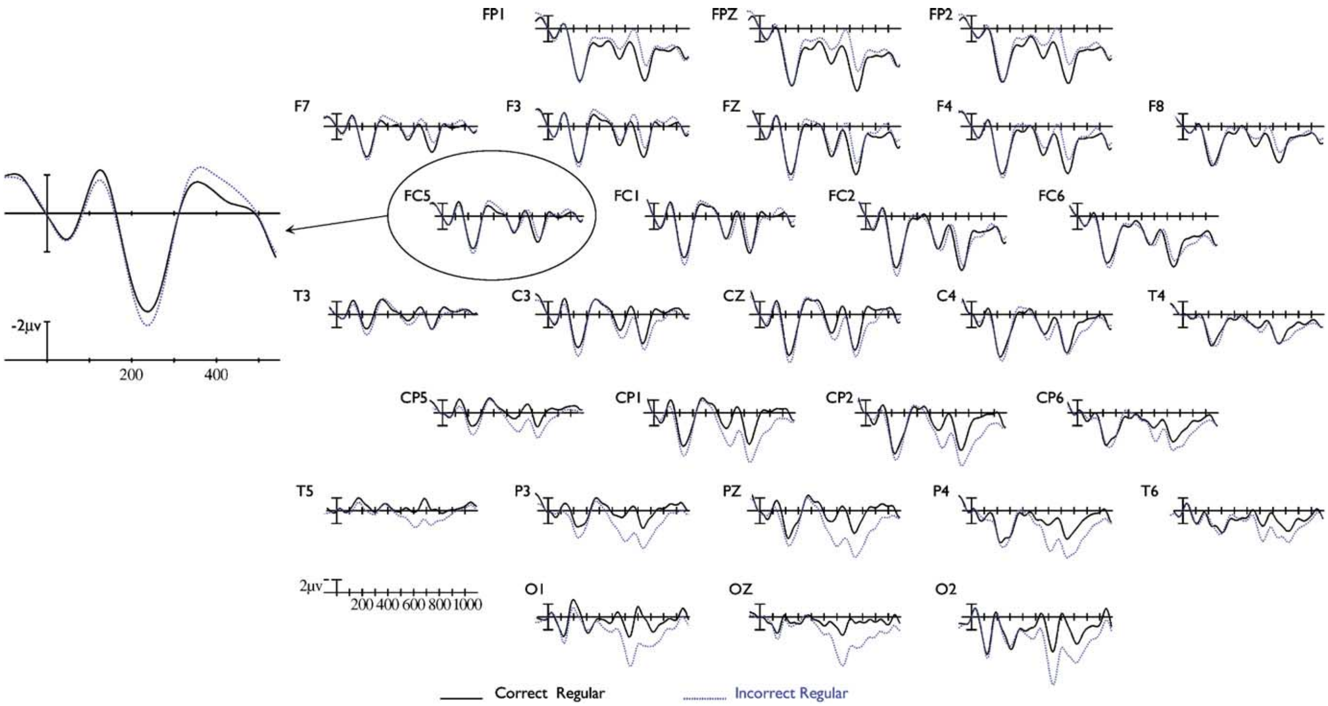


Fig. 2. Grand average ERP waveforms for correct (solid lines) and incorrect (dotted lines) regular past tense verb forms at 29 scalp electrode sites. On the right side of the figure the left fronto-central site FC5 is depicted on a larger scale illustrating the LAN found for incorrect regular forms in the 300–500 ms time window. There is also a large posterior positivity and an anterior negativity in the 600–1000 ms time window for incorrect forms.

($F(1,20)$ = 5.2, $P$ = 0.03) and a marginally significant interaction at Mid-lateral sites ($F(1,20)$ = 4.3, $P$ = 0.05). Although analyses of simple effects failed to clarify the source of this interaction, visual inspection of the waveforms (see Figs. 2 and 3) suggested that this interaction may have been due to a greater asymmetry between left and right hemispheres in the response to the incorrect irregulars than for any other condition, suggesting that this condition generated the most robust left anterior negativity (LAN) (Fig. 4).

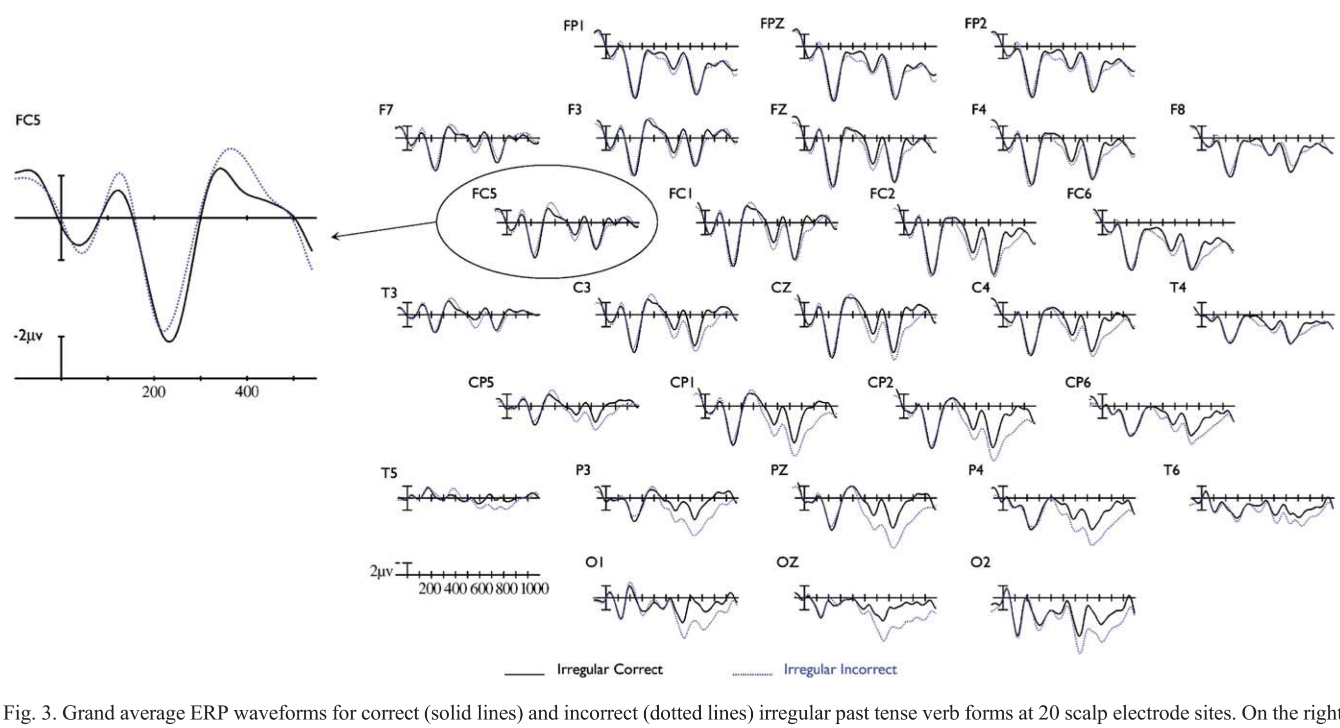


Fig. 3. Grand average ERP waveforms for correct (solid lines) and incorrect (dotted lines) irregular past tense verb forms at 20 scalp electrode sites. On the right side of the figure the left fronto-central site FC5 is depicted on a larger scale illustrating the LAN found for incorrect regular forms in the 300–500 ms time window. There is also a large posterior positivity for incorrect forms in the 600–1000 ms time window.

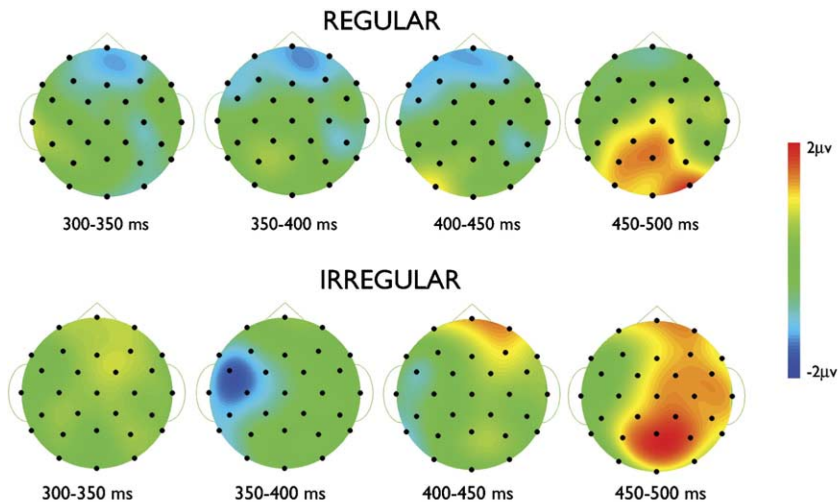


Fig. 4. The spatial distribution of the anterior negativity at the scalp surface (Incorrect-Correct) in 300–500 ms time window for regular (top) and irregular (bottom) verbs.

### 2.2.3. 600–1000 ms epoch

Analyses of data in this time window yielded a significant main effect of CORRECTNESS and a significant CORRECTNESS by ELECTRODE interaction in all four analyses (see Table 1). ERPs to incorrect verb forms were generally more positive than to correct forms, and tests of simple effects showed that this difference was significant at central and posterior electrode sites but not significant at anterior sites (see Table 2).

There was also a significant REGULARITY by CORRECTNESS by ELECTRODE interaction at the Inner and Mid-lateral sites (see Table 1). The interaction was marginal at midline and outer lateral sites. Separate ANOVAs conducted at bilateral pairs of electrode sites at the inner and mid-lateral columns showed that at anterior sites the REGULARITY × CORRECTNESS interaction was either significant (F3 and F4: $F(1,20) = 6.1$, $P = 0.02$) or marginally so (FC1 and FC2: $F(1,20) = 3.2$, $P = 0.09$) but not significant at central and posterior sites($P > 0.2$). Tests of simple effects for regular and irregular verbs at anterior sites failed to clarify the source of the three way interaction effect as responses to neither verb type showed a significant effect of CORRECTNESS. However, visual inspection of the waveforms (see Figs. 2 and 3) suggested that this interaction may have been driven by an anterior positivity for incorrect regular verbs that was not observed for incorrect irregulars.

In summary, these data suggest that both the incorrect regular forms and the incorrect irregular forms elicited a P600-like effect (Fig. 5).

## 2.3. Discussion

We predicted that only the incorrect irregular verbs, which contained violations of morphological structure in the form of incorrect combinations of separable bound morphemes, would elicit brain responses indicative of combinatorial processing such as the LAN and/or P600 but not brain responses indicative of lexical processing such as the N400.

In contrast to our predictions, we found that all incorrect verb forms elicited a left anterior negativity (LAN) at around 400 ms. However, it was particularly pronounced for the incorrect irregulars[1].

In the 600–1000 ms time window, again in contrast to our predictions, we also found that ERPs to all incorrect verb forms were generally more positive than to correct forms; this positivity was greatest at posterior electrode sites.

The fact that LAN and P600 effects were (a) found in response to both the morphological violations, i.e., the regularized irregular verbs, as well as to the incorrect regular verbs which were morphologically simple, may have been due to the fact that, in this study, we used verbs embedded in sentence contexts. If the LAN and P600 effects that we observed reflect processing difficulties related to violations of combinatorial structure at both the morphological and syntactic levels, in a sentence context, there may well be two potential sources of these effects. Structural violations at the morphological level may generate a LAN and a P600, but non-words in a sentence context may also lead to (a) difficulty with the extraction of syntactic information from a

[1] The negativity for the incorrect regulars appeared to be more centro-frontal in its distribution than the negativity for the incorrect irregulars, hence, it is unclear whether it should be characterized as an N400 or as a left anterior negativity. Although the negativity for the incorrect regulars showed hemispheric differences, particularly visible at electrode sites FC5 and FC6, a comparison of the voltage maps for the incorrect regulars and incorrect irregulars shows a clear difference in the topographic distribution of the two components (see Fig. 4), a difference that is supported by the presence of a of a REGULARITY by CORRECTNESS × HEMISPHERE interaction. It is possible that the component elicited by the incorrect regulars may be an N400 whose distribution is modified by the presence of an overlapping posterior positivity and thus appears more frontal. It would not be unexpected to see an N400 effect for the incorrect irregulars as these are similar to non-words and therefore would be expected to produce a large N400 effect.

Table 1
ERP analyses of parasagittal columns of scalp electrodes: main effect of CORRECTNESS, CORRECTNESS by ELECTRODE interaction, and REGULARITY by CORRECTNESS by ELECTRODE interaction for 600–1000 ms time window

| CORRECTNESS | | | | CORRECTNESS by ELECTRODE | | | REGULARITY by CORRECTNESS by ELECTRODE | | |
|---|---|---|---|---|---|---|---|---|---|
| Analysis | *df* | *F* | *P* | *df* | *F* | *P* | *df* | *F* | *P* |
| Midline | 1,20 | 12.3 | 0.002 | 4,80 | 31.2 | <0.001 | 4,80 | 3.0 | 0.08 |
| Inner lateral | 1,20 | 11.3 | 0.003 | 2,40 | 41.06 | <0.001 | 2,40 | 6.7 | 0.013 |
| Mid-lateral | 1,20 | 8.5 | 0.008 | 3,60 | 39.8 | <0.001 | 3,60 | 4.4 | 0.037 |
| Outer lateral | 1,20 | 6.2 | 0.022 | 4,80 | 28.5 | <0.001 | 4,80 | 3.3 | 0.059 |

non-existent lexical entry, triggering a LAN, and (b) difficulty integrating the ill-formed item into a sentence context, thereby triggering a reanalysis reflected in a P600. If this explanation is valid, we would expect to see a difference between morphological violations and lexical anomalies in the processing of single words in the absence of a sentence context. Experiment 2 was designed to evaluate this hypothesis.

## 3. Experiment 2: word acceptability judgment task

The goal of Experiment 2 was to test the hypothesis that the LAN and P600 effects that we observed in Experiment 1 could be attributed to sentence-level processes. If so, we would expect these effects to be eliminated or attenuated with the use of a single word paradigm. In Experiment 2, we presented critical words in list form, without a sentence context. If these effects were eliminated or attenuated for both regular and irregular verbs, this would be evidence in support of the hypothesis that the effects observed in Experiment 1 were due to sentence-level processing difficulties. If, however, the incorrect irregular verbs, which contained violations of morphological structure in the form of incorrect combinations of separable bound morphemes, were to elicit a LAN and/or a P600 effect, while the morphologically simple incorrect regulars did not, this would be evidence in favor of the hypothesis that the LAN and P600 effects found in Experiment 1 reflected more than one underlying cognitive process, i.e., processing difficulties at both the syntactic and morphological levels.

Table 2
ERP analyses of parasagittal columns of scalp electrodes: simple effects tests of CORRECTNESS, for 600–1000 ms time window

| Anterior sites | | | | Central and posterior sites | | | |
|---|---|---|---|---|---|---|---|
| Analysis | *df* | *F* | *P* | Analysis | *df* | *F* | *P* |
| $F_{Pz}$ | 1,20 | 2.7 | 0.1 | Cz | 1.20 | 11.1 | 0.003 |
| $F_z$ | 1,20 | 1.8 | 0.6 | Pz | 1,20 | 48.3 | <0.001 |
| | 1,20 | | | Oz | 1,20 | 37.5 | <0.001 |
| FC1 and FC2 | 1,20 | 1.0 | 0.3 | C3 and C4 | 1,20 | 10.2 | 0.005 |
| | | | | CP1 and CP2 | 1.20 | | |
| F3 and F4 | 1.20 | 0.5 | 0.5 | CP5 and CP6 | 1,20 | 18.3 | <0.001 |
| FC5 and FC6 | 1.20 | 0.4 | 0.5 | P3 and P4 | 1.20 | 38.8 | <0.001 |
| FP1 and FP2 | 1,20 | 0.3 | 0.6 | T5 and T6 | 1,20 | 22.7 | <0.001 |
| F7 and F8 | 1,20 | 1.8 | 0.2 | O1 and O2 | 1,20 | 45.4 | <0.001 |
| T3 and T4 | 1,20 | 2.5 | 0.1 | | | | |

### 3.1. Method

#### 3.1.1. Subjects

Subjects were 20 adults (5 men and 15 women), ranging in age from 19 to 28 years (mean 21.7 years). The data from four subjects, one male and three females, were excluded from analysis, one because he reported a diagnosis of dyslexia and three for excessive eye movement artifact. Of the remaining 16 subjects, all were right-handed native English speakers with normal or corrected-to-normal vision, and none reported any linguistic or neurological impairment. All were members of the Tufts University community and were paid for their participation.

#### 3.1.2. Stimuli

The stimuli were the same as in Experiment 1, but in this experiment, each verb was presented in isolation, without a sentence context.

#### 3.1.3. Procedure

On each trial, a word appeared for 300 ms. After a 900-ms blank interval, a "blink" stimulus consisting of a pair of dashes surrounded by a pair of parentheses (a schematic representation of closed eyes) appeared on the screen for 2 s. Subjects were encouraged to blink while the blink stimulus remained on the screen and to refrain from blinking at other times. Subjects were instructed to press one of two buttons of a game controller immediately after the appearance of a word if the word was ungrammatical or wrong, i.e., it was not a normal English word, and another if the word was correct. The hand that subjects used to press the buttons was counter-balanced across subjects.

#### 3.1.4. Data analysis

As in Experiment 1, we calculated the mean voltage in each of three time windows (150–250 ms, 300–500 ms and 600–1000), and the data were analyzed with four separate repeated measures ANOVAs with REGULARITY, CORRECTNESS, HEMISPHERE and ELECTRODE as factors. Trials characterized by excessive EOG artifact were rejected, resulting in the 6.8% of trials being discarded. This percentage did not vary significantly across experimental conditions ($P > 0.19$). The Geisser–Greenhouse correction was applied when evaluating effects with more than one degree of freedom. Finally, as suggested by McCarthy and Wood [19], analyses with significant interactions of stimulus

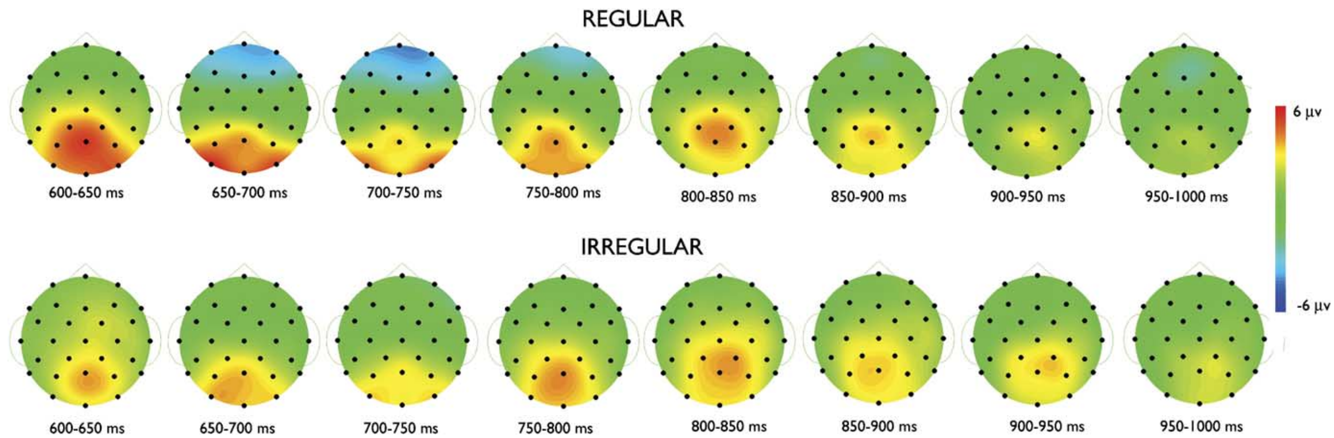


Fig. 5. The spatial distribution of the posterior at the scalp surface (incorrect-correct) in 600–1000 ms time window for regular (top) and irregular (bottom) verbs.

variables with a topographic factor (e.g., Electrode Site or Hemisphere) were repeated after amplitude values were normalized (using *z* scores) separately within each level of the Word- or Sentence-type factor. Only interactions significant after normalization are reported.

### 3.2. Results

#### 3.2.1. Grammaticality judgments

Participants judged the correct regular and irregular past tenses to be grammatical on 91.6% and 95.3% or the trials respectively. Incorrect irregular verb forms were judged to be grammatical on 25.5% of all trials, and the "irregularized" regular verb forms were judged grammatical on 22% of trials. There was no significant REGULARITY × CORRECTNESS interaction ($F(1,15) = 0.4$, $P = 0.97$).

#### 3.2.2. 300–500 ms epoch

In the 300–500 ms time window, there was a significant effect of REGULARITY in all four analyses (see Table 3) due to a widespread negativity for all irregular verbs, both correct and incorrect (see Fig. 6). There was also a significant CORRECTNESS by ELECTRODE interaction (see Table 3) in all four analyses. Separate analyses performed at each electrode site along the midline axis and pairs of sites along the lateral axes showed that this interaction was driven primarily by an anterior negativity for correct forms (see Table 4). At midline sites, there was a significant REGULARITY by CORRECTNESS interaction, and at the outer lateral sites, there was a significant REGULARITY by CORRECTNESS by ELECTRODE interaction (see Table 3). At midlines sites, separate analyses of regular and irregular verbs showed that there was a significant CORRECTNESS effect for irregular verbs ($F(1,15) = 7.6$, $P = 0.014$) but not for regulars ($P > 0.9$).

Separate ANOVAs conducted at bilateral pairs of outer lateral electrode sites revealed that at anterior sites, the REGULARITY × CORRECTNESS interaction was significant (FP1 and FP2: $F(1,15) = 10.2$, $P = 0.006$; F7 and F8: $F(1,15) = 6.5$, $P = 0.02$). However, at central, temporal and posterior sites, the interaction did not reach significance ($P > 0.1$ at all sites). At anterior sites, responses to incorrect irregular past tenses were more positive than those to correct irregulars (FP1 and FP2: $F(1,15) = 14.6$, $P = 0.002$; F7 and F8: $F(1,15) = 4.4$, $P = 0.05$). Responses to correct and incorrect regular verbs on the other hand did not differ; the *P* values for comparisons between correct and incorrect forms were greater than .1 at all sites.

#### 3.2.3. 600–1000 ms epoch

In the 600–1000 ms time window, there was a significant main effect of CORRECTNESS ($F_1(1,15) = 15.7$, $P = 0.001$; $F_2(1,15) = 27.5$, $P < 0.001$; $F_3(1,15) = 29.5$, $P < 0.001$; $F_4 = 28.5$, $P < 0.001$), with incorrect verbs eliciting more positive responses than correct verbs and a significant REGULARITY by CORRECTNESS interaction in all four analyses ($F_1(1,15) = 28.5$, $P < 0.001$; $F_2(1,15) = 26.9$ $P < 0.001$; $F_3(1,15) = 18.9$ $P = 0.001$; $F_4(1,15) = 19.4$ $P <$

Table 3
ERP analyses of parasagittal columns of scalp electrodes: main effect of REGULARITY, REGULARITY by CORRECTNESS, CORRECTNESS by ELECTRODE, and REGULARITY by CORRECTNESS by ELECTRODE interactions for the 300–500 ms time window

| Analysis | REGULARITY | | | REGULARITY by CORRECTNESS | | | CORRRECTNESS by ELECTRODE | | | REGULARITY by CORRECTNESS by ELECTRODE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *df* | *F* | *P* | *df* | *F* | *P* | *df* | *F* | *P* | *df* | *F* | *P* |
| Midline | 1,15 | 6.5 | 0.023 | 1,15 | 4.7 | 0.047 | 4,60 | 6.8 | 0.007 | 4,60 | 2.8 | 0.092 |
| Inner lateral | 1,15 | 7.0 | 0.018 | 1,15 | 4.2 | 0.059 | 2,30 | 13.7 | 0.001 | 2,30 | 2.0 | 0.174 |
| Mid-lateral | 1,15 | 9.5 | 0.008 | 1,15 | 2.7 | 0.122 | 3,45 | 11.0 | 0.002 | 3,45 | 3.2 | 0.084 |
| Outer lateral | 1,15 | 6.7 | 0.020 | 1,15 | 2.7 | 0.118 | 4,60 | 7.1 | 0.009 | 4,60 | 6.7 | 0.007 |

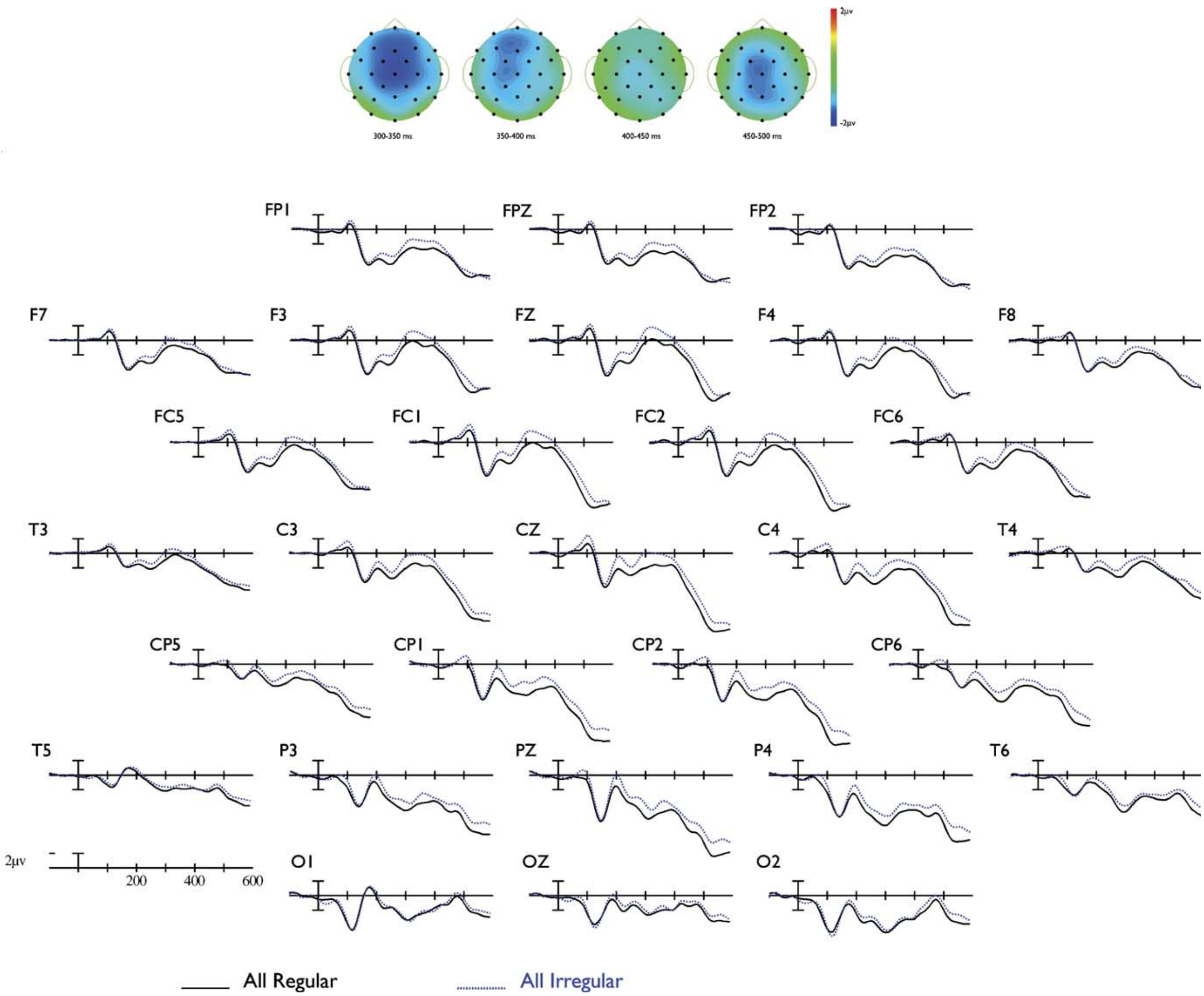


Fig. 6. Grand average ERP waveforms for regular (solid lines) and irregular (dotted lines) past tense verb forms at 29 scalp electrode sites showing an anterior negativity for irregular verbs in the 150–250 and 300–500 ms time window. Shown at the top of the figure is the spatial distribution of the negativity (irregular–regular) at the scalp surface in the 300–500 ms time window.

0.006). Separate analyses of responses to regular and irregular verbs revealed that for irregular verbs, incorrect forms generated more positive ERPs than correct forms ($F_1$(1,15) = 25.1, $P$ < 0.001); $F_2$(1,15) = 38.2, $P$ < 0.001; $F_3$(1,15) = 34.7, $P$ < 0.001; $F_4$(1,15) = 30.5, $P$ < 0.001). However, for regular verbs, responses to correct and incorrect forms did not differ except marginally at outer lateral sites ($F_1$(1,15) = 0.18, $P$ = 0.7; $F_2$(1,15) = 4.4, $P$ = 0.4; $F_3$(1,15) = 2.3, $P$ = 0.2; $F_4$(1,15) = 4.4, $P$ = 0.05) (see Figs. 7 and 8).

Table 4
Tests of simple effects for the factor CORRECTNESS in 300–500 ms time window

| Anterior sites | | | | Central and posterior sites | | | |
|---|---|---|---|---|---|---|---|
| Analysis | *df* | *F* | *P* | Analysis | *df* | *F* | *P* |
| $F_{Pz}$ | 1,15 | 6.8 | 0.02 | Cz | 1,15 | 2.7 | 0.1 |
| $F_z$ | 1,15 | 5.9 | 0.03 | Pz | 1,15 | 0.39 | 0.5 |
| | | | | Oz | 1,15 | 1.4 | 0.2 |
| FC1 and FC2 | 1,15 | 4.3 | 0.06 | C3 and C4 | 1,15 | 0.8 | 0.4 |
| | | | | CP1 and CP2 | 1,15 | 0.7 | 0.4 |
| F3 and F4 | 1,15 | 3.6 | 0.08 | CP5 and CP6 | 1,15 | 2.2 | 0.2 |
| FC5 and FC6 | 1,15 | 0.5 | 0.5 | P3 and P4 | 1,15 | 0.85 | 0.4 |
| FP1 and FP2 | 1,15 | 5.0 | 0.04 | T5 and T6 | 1,15 | 7.2 | 0.02 |
| F7 and F8 | 1,15 | 0.45 | 0.5 | O1 and O2 | 1,15 | 4.5 | 0.05 |
| T3 and T4 | 1,15 | 1.3 | 0.3 | | | | |

Although the difference between correct and incorrect regular verbs was not significant, visual inspection of the waveforms revealed a small, temporally restricted positivity for the irregularized regular verbs (‘sept’). In order to further investigate this phenomenon, we analyzed the mean voltage amplitude in two separate, narrower time windows, 500–700 ms and 700–1000 ms.

### 3.2.4. 500–700 ms epoch

In the 500–700 ms time window, there was a significant main effect of CORRECTNESS in all four analyses, with incorrect forms more positive than correct forms. There was also a significant REGULARITY by CORRECTNESS interaction at midline and inner lateral sites (see Table 5). Separate analyses of regular and irregular verbs at the midline and inner lateral sites showed a significant CORRECTNESS effect for both regular and irregular verbs in all four analyses, however, the effect was greater for irregular verbs (partial $\eta^2 > 0.5$ in all four analyses) than for regular verbs (partial $\eta^2 = 0.3$ in all four analyses).

### 3.2.5. 700–1000 ms epoch

This analysis showed a significant main effect of CORRECTNESS with incorrect forms more positive than correct forms, a significant REGULARITY by CORRECTNESS interaction in all four analyses(see Table 6) and a significant REGULARITY × CORRECTNESS × ELECTRODE interaction at midlines sites ($F(4,60) = 3.3$, $P = 0.045$). Separate analyses of regular and irregular verbs showed that there was a significant effect of CORRECTNESS for irregular verbs ($F_1(1,15) = 13.4$, $P = 0.002$, $F_2(1,15) = 32.2$, $P < 0.001$, $F_3(1,15) = 29.8$, $P < 0.001$, $F_4(1,15) = 29.1$, $P < 0.001$) but not for regular verbs ($P > 0.1$ in all analyses). Separate analyses at each electrode site along the midline showed that there was a significant CORRECTNESS × REGULARITY interaction at posterior sites ($F_{Cz}(1,15) = 11.2$, $P = 0.004$; $F_{Pz}(1,15) = 23.8$, $P < 0.001$; $F_{Oz}(1,15) = 11.2$, $P = 0.004$) but not at anterior sites ($P > 0.1$). Tests of simple effects at each of the posterior sites showed that there was a significant difference between correct and incorrect forms for the irregular verbs ($F_{Cz}(1,15) = 12.6$, $P = 0.003$; $F_{Pz}(1,15) = 16.1$, $P = 0.001$; $F_{Oz}(1,15) = 5.9$, $P = 0.03$) but not for the regulars ($P > 0.01$).

These analyses indicate that although incorrect forms of both regular and irregular verbs elicited late positivities, these were quite different in terms of their amplitude and time course suggesting that these components may reflect more than one underlying cognitive process or alternatively a single process taking place at multiple levels of linguistic structure (e.g., morphological and syntactic) (Figs. 7 and 8).

## 3.3. Discussion

We predicted that the regularized irregular verbs (e.g., 'runned'), which contained violations of morphological structure in the form of incorrect combinations of separable bound morphemes, would again elicit a LAN effect as well as a P600 effect. We also predicted that, given the single word context, there would be a greater P600 effect for the morphological violations, than for the morphologically simple incorrect forms (e.g., 'sept').

Table 5
ERP analyses of parasagittal columns of scalp electrodes: main effect of REGULARITY, AND REGULARITY by CORRECTNESS interaction in the 500–700 ms time window

| Analysis | CORRECTNESS main effect | | | REGULARITY by CORRECTNESS interaction | | |
|---|---|---|---|---|---|---|
| | *df* | *F* | *P* | *df* | *F* | *P* |
| Midline | 1,15 | 16.6 | 0.001 | 1,15 | 14.1 | 0.002 |
| Inner lateral | 1,15 | 15.2 | 0.001 | 1,15 | 5.9 | 0.028 |
| Mid-lateral | 1,15 | 18.2 | 0.001 | 1,15 | 2.3 | 0.15 |
| Outer lateral | 1,15 | 15.4 | 0.001 | 1,15 | 1.2 | 0.29 |

Table 6
ERP analyses of parasagittal columns of scalp electrodes: main effect of REGULARITY, AND REGULARITY by CORRECTNESS, interaction for the 700–1000 ms time window

| Analysis | CORRECTNESS | | | REGULARITY by CORRECTNESS | | |
|---|---|---|---|---|---|---|
| | *df* | *F* | *P* | *df* | *F* | *P* |
| Midline | 1,15 | 7.3 | 0.02 | 1,15 | 15.0 | 0.002 |
| Inner lateral | 1,15 | 23.3 | <0.001 | 1,15 | 27.7 | <0.001 |
| Mid-lateral | 1,15 | 23.5 | <0.001 | 1,15 | 21.9 | <0.001 |
| Outer lateral | 1,15 | 23.2 | <0.001 | 1,15 | 12.9 | 0.003 |

In the 300–500 ms time window, we found a widespread negativity for all irregular verbs and an anterior negativity for correct irregular past tenses. Neither of these negativities was left lateralized suggesting that they should not be characterized as typical LANs but rather as N400 effects. Incorrect regulars, which are similar to non-words and therefore would be expected to produce a large N400 effect, did not appear to do so.

In the 600–1000 ms time window, although incorrect forms of both regular and irregular verbs elicited late positivities, these effects were quite distinct in terms of their amplitude and time course. For regular verbs, responses to incorrect forms (e.g., 'sept') produced very small, temporally restricted effects while for the irregular verbs the effects were larger and more temporally extended. Although because of the nature of English irregular past tense formation we could not directly match the incorrect and correct regulars, as we did for the irregular items, it seems unlikely that this confound underlay the differences we found between regulars and irregulars. The fact that the correct and incorrect forms of regular verbs were different items that were unmatched on factors such as frequency predicts that we should see a greater difference between correct and incorrect regulars than irregulars. However, this is the opposite of what we found. Hence, it appears likely that the differences we found reflect true effects of regularity.

Because the late positive effects seen for the irregulars and for the regulars differed in both their amplitude and time course, it seems likely that they are distinct components. The positivity seen for the irregularized regular verbs is similar in its time course and morphology to the P3 "oddball" component, while the positivity to the regularized irregulars, with a greater duration and more widespread distribution, is similar to the classic P600 effect. Although we equalized the number of correct and incorrect verb forms over the course of the session so as to avoid P3 effects, the incorrect regular verbs were more similar to non-words than the incorrect irregulars, and it may be that this difference led

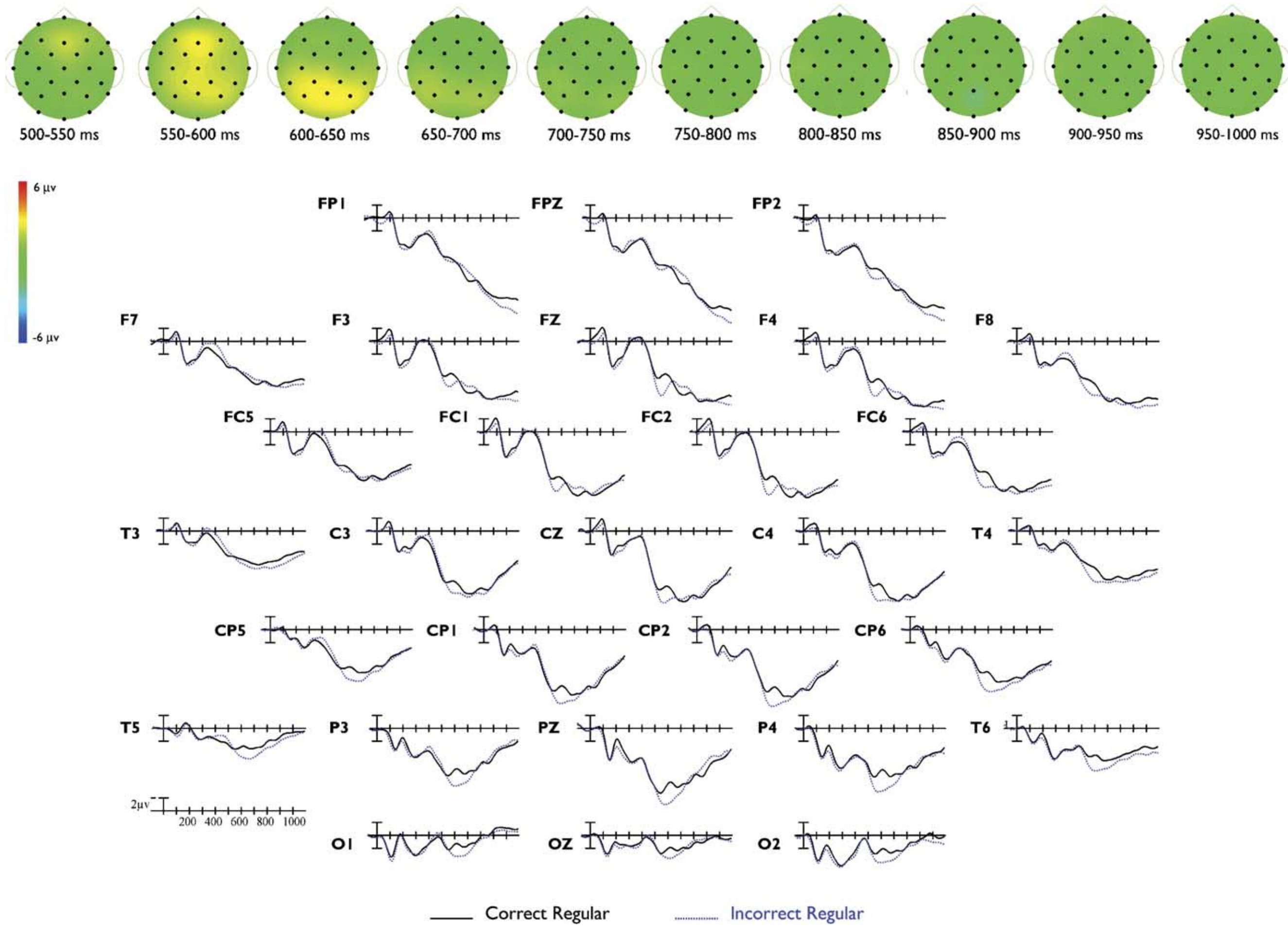


Fig. 7. Grand average ERP waveforms elicited by correct (solid lines) and incorrect (dotted lines) regular past tense verb forms at 29 scalp electrode sites. Shown at the top of the figure is the spatial distribution of the late positivity (incorrect–correct) at the scalp surface in the 600–1000 ms time window.

to subjects categorizing them separately resulting in an “oddball” type effect.

The absence of a robust P600 effect for the incorrect regular verb forms in this single-word study suggests that the P600 effect that we observed for incorrect regulars in Experiment 1 may have been partially due to integration difficulties or reanalysis effects at the sentence level. In contrast to the incorrect regulars, the regularized irregulars that contained morphological violations generated a large and sustained late positivity in the absence of a sentence context, suggesting that the P600 may reflect structural processing difficulties at the morphological as well as the sentential level.

## 4. General discussion

The purpose of these two studies was to investigate brain responses to morphologically correct and incorrect English verb forms in both single-word and sentence contexts, with the goal of clarifying whether combinatorial processes at the word and sentence level share common brain mechanisms. We reasoned that if they do, we should expect to find that morphological violations elicit ERP components similar to those that are elicited by syntactic violations. The findings thus far in the literature have been inconsistent; some researchers have found a LAN for incorrect regularizations but not for irregularizations, others have found a bilateral broadly distributed, albeit somewhat anterior component reminiscent of the N400 to past tense inflectional over-regularization errors, while still others have found both a LAN and a P600 to verb stem formation and past tense inflectional over-regularization errors. It has been suggested that these discrepancies may stem from differences in the nature of the task, single-word versus sentence processing, or the nature morphological systems of the languages under investigation, stem-based versus affix-based inflection. Thus, our goals for this pair of studies were two-fold, to see if there were differences to brainwave responses to morphological violations in single-word versus sentence contexts and to compare the results of this study in English, an affix-based inflectional language, with those that have previously been found for German, Italian and Catalan.

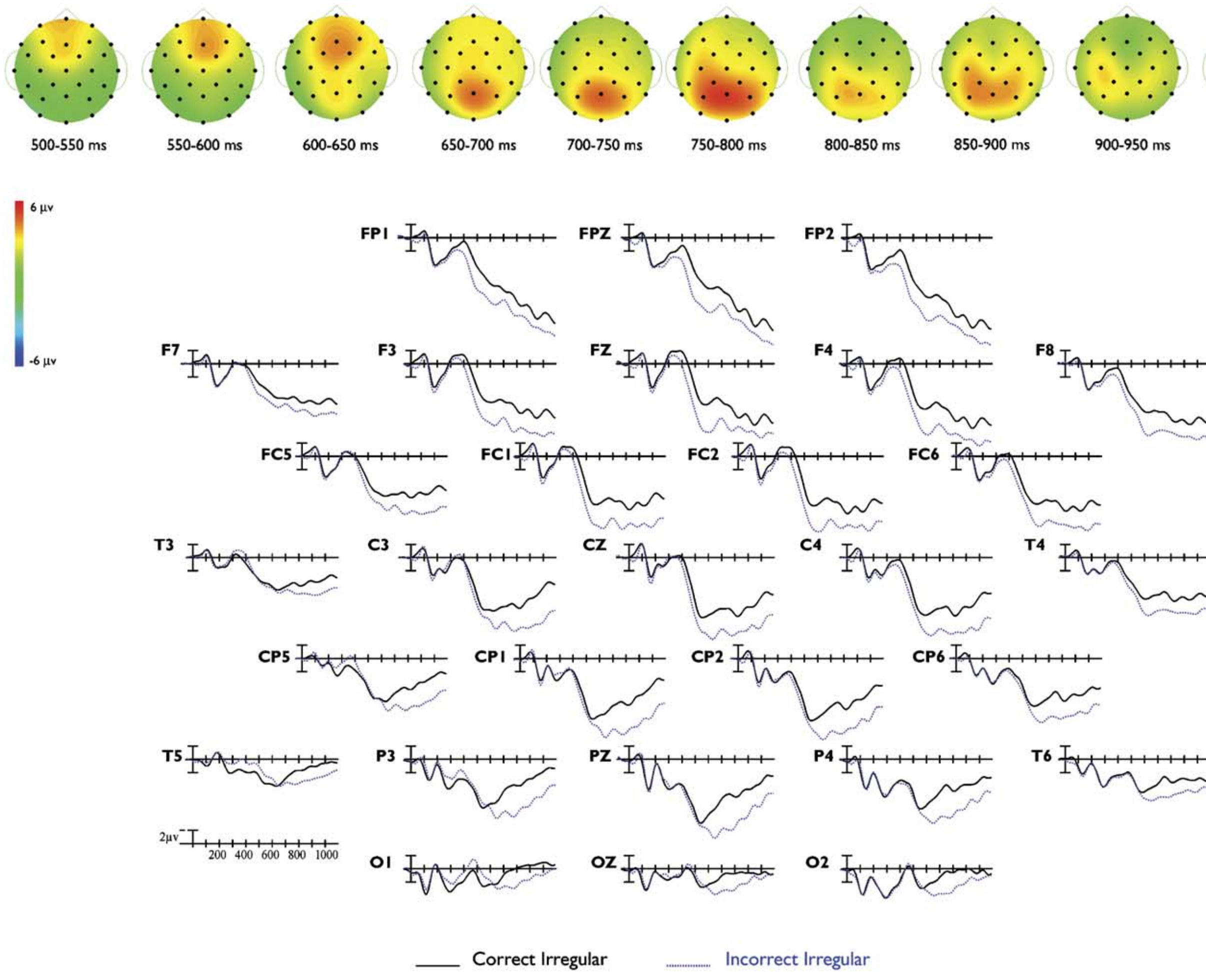


Fig. 8. Grand average ERP waveforms elicited by correct (solid lines) and incorrect (dotted lines) irregular past tense verb forms at 29 scalp electrode sites. Shown at the top of the figure is the spatial distribution of the late positivity (incorrect–correct) at the scalp surface in the 600–1000 ms time window.

### *4.1. Late posterior positivities*

In Experiment 1, we found that both morphological violations and lexical anomalies, presented in a sentence context, elicited a broadly distributed yet predominantly posterior positivity in the 600–1000 ms time window, an effect we argued is similar to the syntactic P600. The fact that the P600 effect was also found in response to the lexical anomalies which were morphologically simple and hence did not contain violations of morphological combinatorial rules suggests that this component reflected more than one underlying cognitive process. In a sentence context, there may well be two potential sources of these effects. Structural violations at the morphological level may generate a LAN and a P600, but non-words in a sentence context may also lead to (a) difficulty with the extraction of syntactic information from a non-existent lexical entry, triggering a LAN, and (b) difficulty integrating the ill-formed item into a sentence context, thereby triggering a reanalysis reflected in a P600.

Given this explanation, we predicted that we would find a difference between morphological violations and lexical anomalies in the processing of single words in the absence of a sentence context. This is in fact what we found. In a single-word paradigm, in the 600–1000 ms time window, only the morphological violations elicited robust late positivities. For regular verbs, responses to incorrect forms produced much smaller more time restricted effects that are reminiscent of the P3 “oddball” effect. These data suggest that the P600 effect that we observed for lexical anomalies in Experiment 1 may have been partially due to integration difficulties or reanalysis effects at the sentence level.

Our data differ from those of Penke and colleagues [29] who failed to find P600 effects for incorrect irregular verbs. However, their stimuli differed from ours in that they presented their critical verbs as the final word of a simple declarative sentence. Prior studies [25] have shown that sentence final words from semantically difficult to interpret sentences (e.g., with a syntactic anomaly earlier in the sentence) often have somewhat larger N400s. This effect has been interpreted as reflecting, in part, a sentence-level closure or wrap-up process whereby the degree of coherence of the entire sentence is evaluated [26]. A large N400 to the incorrect irregulars in the Penke study, especially if temporally extended, may have obscured any potential P600 effect.

The presence of a P600 effect in response to morphological violations but not to lexical anomalies in the single word paradigm suggests that the P600 may in fact reflect difficulties with general combinatorial processes, at both the morphological and the syntactic level. The P600 may reflect the detection of a combinatorial mismatch between grammatical units, or it may signal the reanalysis of such a mismatch. In the case of "regularized" irregular verbs such as 'bringed', once the lemma-level lexical entry for the stem 'bring' has been accessed, the syntactic features of the lemma should indicate its status as an irregular verb. However, if this information conflicts with the presence of the regular past tense inflectional morpheme '-ed', the existence of two conflicting pieces of syntactic information should lead to reanalysis. Our data are consistent with this interpretation.

### *4.2. Negativities in the 300–500 ms time window*

In both experiments, all subjects showed a robust P600 effect for the morphological violations. However, responses in the 300–500 ms time window were less uniform across the two studies. In Experiment 1, all incorrect verb forms elicited a left anterior negativity (LAN) at around 400 ms, but it was particularly pronounced for the incorrect irregulars. The negativity for the incorrect regulars appeared to be more fronto-central in its distribution than the negativity for the incorrect irregulars.

In Experiment 2, we did not find a LAN for any of the incorrect verb forms. Rather, we found an N400-like effect for all irregular verbs. The presence of a LAN for both lexical anomalies and morphological violations in Experiment 1, and its absence in Experiment 2, suggests that the LAN may reflect difficulties in processing at the syntactic rather than morphological level and hence is unsurprisingly absent in a single word paradigm.

Our data differ from those of Penke and colleagues [29] who found LAN effects for incorrect irregular verbs in both sentence and list conditions. However, their stimuli differed from ours in that they used German particle verbs such as 'aufladen', rather than simplex verbs as their stimuli. It can be argued that particle verbs are more similar to syntactic constructions such as phrases, than they are to individual words [22]. This difference in stimuli may explain the discrepancies between our data and those of Penke and colleagues [29] and seem to support our speculation that the LAN may reflect difficulty at the syntactic rather than morphological level of linguistic structure.

In contrast, the N400 for irregular past tenses in Experiment 1 is consistent with a view of the lexicon in which the past tense forms of regular verbs are generated by rule while irregular forms are stored in memory [18,30–33]. If irregular past tenses are retrieved as whole forms from the lexicon, during processing of these words, we would expect to see components that are indicative of lexical access and integration such as the N400.

However, all words (or stems) must be retrieved from the lexicon and integrated into the current semantic context, so why are N400 responses so much greater for irregulars forms in general and irregular past tenses in particular? Allen, Badecker and Osterhout [1] suggest that comprehension of regularly inflected complex words recruits two distinct processes, one that processes the lexical content of stems and another that extracts the syntactic features of affixes. This theory implies that it may be more difficult and effortful to extract the information required for successful semantic integration from irregular past tense forms.

Given this hypothesis, if presented with an irregular past tense such as 'brought', the processor would be unable to use the "stem feature extractor" to access the syntactic features normally marked by the stem. It would be forced to access the entire lexical entry before being able to process any aspect of the word. In contrast, for a regularly inflected form like 'walked', the processor could identify part of the meaning of the word, +PAST, simply by invoking the process that extracts features from affixes. If irregulars have to be processed by a single system, while regulars can engage two, the processing of regularly inflected words, even incorrectly inflected ones like 'bringed', should be in some sense "easier" than the processing of correct irregular past tenses, like 'brought'.

This idea is supported by the finding that the N400 is larger to words with more associations than words with few [13,16]. It can be argued that because irregular past tenses (e.g., 'brought') incorporate both the meaning of the verb and of the past tense affix, they are associated with more semantic associations than the uninflected stem (e.g., 'bring' or 'walk') which is the only part of regularly inflected verbs that undergoes lexical lookup.

The negativities associated with irregular verbs in the 150–250 ms time window of Experiment 2 may have been an early manifestation of the processing difficulty associated with irregular verbs. However, given how early these differences appear, they may also reflect orthographic differences between regulars and irregulars. Although we tried to control for as many lexical variables as possible, there are some that were not controlled (e.g., bigram frequency); and since the regular and irregular verb classes comprise different lexical items, it is possible that orthographic differences may be driving these early effects.

One lingering issue is whether differences between the incorrect irregulars (e.g., 'bringed') and incorrect regulars (e.g., 'sept') are due to our experimental hypotheses of difference between these conditions or is attributable to the presence/absence of a segmentable affix for the incorrect irregulars and/or to the presence/absence of a stem change for the incorrect regulars. In addition, it might be the case that forms such as 'sept' do not elicit the more pronounced LAN and more robust and widespread P600 effects found for incorrect irregulars, not because irregulars do not involve combinatorial processes, but because the stem cannot be identified as an existing one in English. However, we believe that our original interpretation of the data is still valid. Because the irregularized past tenses that we used, like the real irregular past tense verb forms on which they were based, do not have readily identifiable stems, they cannot be identified as instances of morpho-syntactic combinatorial violations, i.e., the incorrect combination of an affix and stem. In addition, the differences that we found between correct and incorrect forms were all in the direction of greater effects for irregulars than for regulars. If stem changes between the correct and incorrect regular past tense were driving these effects, we would expect to see greater effects (i.e., greater differences between correct and incorrect forms) for regular verbs than for irregulars. Hence, our data do not appear to support this hypothesis.

Another concern is that there may be a larger repetition effect for the irregular forms in each list than for the regular ones, given that the irregulars appear in three different forms (correct past tense, incorrect past tense, infinitive) whereas the regulars appear in only two (correct past tense, infinitive). However, if there was a larger repetition effect for irregulars, we would expect to see a main effect of REGULARITY, but we would not expect to see a REGULARITY by CORRECTNESS interaction. Our predictions focus on the difference between correct and incorrect regular forms and between correct and incorrect irregular forms. These differences should be unaffected by main effects of REGULARITY. In the one instance where we do find a regularity effect, a greater N400 effect for irregular verbs in Experiment 2, this effect is the opposite of what one would expect to find (an attenuation of the N400) if there was a larger repetition effect for the irregular forms. Hence, we believe that our interpretation of the data is still valid.

### *4.3. Stem-based versus affix-based inflection*

In these two studies, we found all three types of effects that have been found in previous studies, the LAN, the N400 and the P600. Some of our results for English inflection are similar to those found by Rodriguez-Fornells et al. [34] for stem formation processes in Catalan[2]. In Catalan, according to Rodriguez-Fornells et al., "the 1st conjugation is the only one that shows unrestricted generalizability [suggesting that] the first conjugation is the only default class. Thus, from a dual-mechanism perspective, one might hypothesize that 1st conjugation stem formation is rule-based, whereas 2nd and 3rd conjugation stems are lexically stored, paralleling the differences between regular and irregular inflection."[34] Rodriguez-Fornells et al. state that LAN effects were seen for over-applications of the default 1st conjugation theme vowel – *a* – to a verb form that requires a 2nd or 3rd conjugation form, a process that is akin to the regularization of an irregular. In Experiment 1, we also found more robust LAN effects for regularizations of irregular verbs than for the irregularization of regulars.

On the other hand, Rodriguez-Fornells et al. found that incorrect 1st conjugation forms in which the correct theme vowel was replaced with the 3rd conjugation form, a process akin to the irregularization of a regular, did not yield a LAN effect. We failed to find LAN effects for irregularizations that were as great as those for the regularizations.

Although there are some differences between our data and those of Rodriguez-Fornells et al. (we failed to find LAN effects for irregularizations that were as great as those for the regularizations, we did find a small LAN effect for the incorrect irregulars in Experiment 1 which Rodriguez-Fornells et al. did not find), the similarities between our the English and Catalan data suggest an underlying similarity in the morphological processes of Romance and Germanic languages.

## 5. Conclusion

The presence of a P600 effect in response to morphological violations suggests that the P600 may reflect difficulties with combinatorial processes at multiple levels of linguistic analysis, i.e., morphological and syntactic, and does not depend on the existence of sentence context. In particular, the P600 may reflect the detection of a combinatorial mismatch between grammatical units, or it may signal the reanalysis of such a mismatch. It is interesting to note that the P600 is elicited to morphological violations in both single word tasks and in a sentence context, while the LAN only appeared as a response to violations in sentence contexts. This suggests that the LAN is sensitive to processes involved in integrating a word into its syntactic context, while the P600 is sensitive to morpho-syntactic processes that can be, although they are not necessarily, independent of a sentential context (e.g., reanalysis of the morpho-syntactic structure of a word or phrase).

Our data also provide limited support for a model of verb inflection in which regular verbs can be formed by rule, while irregular verbs must be accessed via the mental lexicon. Correct irregular past tenses, which cannot be decomposed into a stem and affix, and hence are presumed to undergo lexical look-up, generated N400-like responses

[2] Our findings do not parallel those of Rodriguez-Fornells in every respect. Rodriguez-Fornells et al. obtained LAN effects for regularizations, but not for irregularizations. In Experiment 1 of the present study, LAN effects were found for both regularizations and irregularizations, although it must be noted that the irregularization effects were quite weak and their interpretation is unclear. In experiment 2, there were no LAN effects for any incorrect verb form, but as we argue, the LAN may reflect difficulties in processing at the syntactic rather than morphological level and hence would unsurprisingly be absent in a single word paradigm.

indicative of lexical processing. Incorrect stem–affix combinations, i.e., the regularized irregular past tenses, produced components – the LAN and P600 – commonly found in response to violations of syntactic rules. However, incorrect regular forms, which like the correct regular past tenses, contained no separable bound affixes and, hence, which might also be expected to elicit N400-like responses did not do so. Although these data are inconclusive with respect to the mechanism used for processing the incorrect regular, i.e., irregularized, forms they seem to be best explained by a dual-mechanism account of lexical processing.

## Appendix A

| Past tense | Log frequency per million of past tense | Length past tense | Stem | Log frequency per million of stem | Length past tense | Verb type |
|---|---|---|---|---|---|---|
| Added | 1.34 | 5 | Add | 1.32 | 3 | Regular |
| Agreed | 1.30 | 6 | Agree | 1.30 | 5 | Regular |
| Armed | 1.52 | 5 | Arm | 0.00 | 3 | Regular |
| Called | 1.92 | 6 | Call | 1.70 | 4 | Regular |
| Changed | 1.66 | 7 | Change | 1.60 | 6 | Regular |
| Checked | 0.78 | 7 | Check | 0.95 | 5 | Regular |
| Danced | 0.48 | 6 | Dance | 0.60 | 5 | Regular |
| Faded | 0.60 | 5 | Fade | 0.30 | 4 | Regular |
| Helped | 1.18 | 6 | Help | 1.78 | 4 | Regular |
| Kicked | 0.60 | 6 | Kick | 0.48 | 4 | Regular |
| Liked | 1.30 | 5 | Like | 1.69 | 4 | Regular |
| Lived | 1.45 | 5 | Live | 1.75 | 4 | Regular |
| Loaded | 0.60 | 6 | Load | 0.00 | 4 | Regular |
| Locked | 0.95 | 6 | Lock | 0.48 | 4 | Regular |
| Looked | 2.01 | 6 | Look | 2.04 | 4 | Regular |
| Needed | 1.49 | 6 | Need | 1.87 | 4 | Regular |
| Noted | 0.85 | 5 | Note | 0.60 | 4 | Regular |
| Opened | 1.43 | 6 | Open | 1.08 | 4 | Regular |
| Packed | 0.60 | 6 | Pack | 0.48 | 4 | Regular |
| Parked | 0.60 | 6 | Park | 0.00 | 4 | Regular |
| Paused | 0.78 | 6 | Pause | 0.00 | 5 | Regular |
| Played | 1.36 | 6 | Play | 1.61 | 4 | Regular |
| Poured | 0.85 | 6 | Pour | 0.78 | 4 | Regular |
| Printed | 0.70 | 7 | Print | 0.30 | 5 | Regular |
| Quoted | 0.60 | 6 | Quote | 0.48 | 5 | Regular |
| Raised | 1.26 | 6 | Raise | 1.04 | 5 | Regular |
| Reached | 1.45 | 7 | Reach | 1.28 | 5 | Regular |
| Served | 1.04 | 6 | Serve | 1.20 | 5 | Regular |
| Showed | 1.32 | 6 | Show | 1.63 | 4 | Regular |
| Sighed | 0.70 | 6 | Sigh | 0.00 | 4 | Regular |
| Smiled | 1.26 | 6 | Smile | 0.70 | 5 | Regular |
| Snapped | 0.48 | 7 | Snap | 0.00 | 4 | Regular |
| Started | 1.60 | 7 | Start | 1.62 | 5 | Regular |
| Stretched | 0.78 | 9 | Stretch | 0.60 | 7 | Regular |
| Talked | 1.28 | 6 | Talk | 1.74 | 4 | Regular |
| Tended | 0.78 | 6 | Tend | 1.20 | 4 | Regular |
| Turned | 1.81 | 6 | Turn | 1.54 | 4 | Regular |
| Voted | 0.48 | 5 | Vote | 0.85 | 4 | Regular |
| Walked | 1.49 | 6 | Walk | 1.28 | 4 | Regular |
| Washed | 0.78 | 6 | Wash | 0.90 | 4 | Regular |
| Aged | 1.60 | 4 | Age | 0.00 | 3 | Regular |
| Asked | 1.97 | 5 | Ask | 1.75 | 3 | Regular |
| Caused | 1.18 | 6 | Cause | 1.11 | 5 | Regular |
| Claimed | 0.90 | 7 | Claim | 0.95 | 5 | Regular |
| Closed | 1.78 | 6 | Close | 0.90 | 5 | Regular |
| Colored | 1.52 | 7 | Color | 0.00 | 5 | Regular |
| Cried | 1.00 | 5 | Cry | 0.90 | 3 | Regular |
| Dressed | 1.08 | 7 | Dress | 0.48 | 5 | Regular |
| Dropped | 1.18 | 7 | Drop | 1.00 | 4 | Regular |
| Earned | 0.60 | 6 | Earn | 0.70 | 4 | Regular |
| Filled | 1.18 | 6 | Fill | 1.00 | 4 | Regular |
| Forced | 1.23 | 6 | Force | 0.95 | 5 | Regular |
| Glanced | 0.78 | 7 | Glance | 0.00 | 6 | Regular |

**Appendix A (*continued*)**

| Past tense | Log frequency per million of past tense | Length past tense | Stem | Log frequency per million of stem | Length past tense | Verb type |
|---|---|---|---|---|---|---|
| Grabbed | 0.60 | 7 | Grab | 0.30 | 4 | Regular |
| Grinned | 0.48 | 7 | Grin | 0.00 | 4 | Regular |
| Guessed | 0.60 | 7 | Guess | 1.11 | 5 | Regular |
| Hated | 0.85 | 5 | Hate | 1.00 | 4 | Regular |
| Judged | 0.48 | 6 | Judge | 0.60 | 5 | Regular |
| Jumped | 0.70 | 6 | Jump | 0.70 | 4 | Regular |
| Killed | 1.28 | 6 | Kill | 1.28 | 4 | Regular |
| Knocked | 0.70 | 7 | Knock | 0.48 | 5 | Regular |
| Loved | 1.20 | 5 | Love | 1.51 | 4 | Regular |
| Marked | 0.70 | 6 | Mark | 0.60 | 4 | Regular |
| Moved | 1.54 | 5 | Move | 1.51 | 4 | Regular |
| Paid | 1.40 | 4 | Pay | 1.62 | 3 | Regular |
| Passed | 1.45 | 6 | Pass | 1.30 | 4 | Regular |
| Picked | 1.26 | 6 | Pick | 1.20 | 4 | Regular |
| Planned | 0.95 | 7 | Plan | 0.78 | 4 | Regular |
| Rushed | 0.70 | 6 | Rush | 0.48 | 4 | Regular |
| Seemed | 1.92 | 6 | Seem | 1.74 | 4 | Regular |
| Shifted | 0.48 | 7 | Shift | 0.48 | 5 | Regular |
| Shocked | 0.78 | 7 | Shock | 0.00 | 5 | Regular |
| Slipped | 0.78 | 7 | Slip | 0.60 | 4 | Regular |
| Solved | 0.60 | 6 | Solve | 0.78 | 5 | Regular |
| Stopped | 1.46 | 7 | Stop | 1.58 | 4 | Regular |
| Tied | 0.90 | 4 | Tie | 0.60 | 3 | Regular |
| Used | 2.10 | 4 | Use | 1.83 | 3 | Regular |
| Waited | 1.11 | 6 | Wait | 1.45 | 4 | Regular |
| Wanted | 1.83 | 6 | Want | 2.21 | 4 | Regular |
| Warned | 0.78 | 6 | Warn | 0.48 | 4 | Regular |
| Broke | 1.20 | 5 | Break | 1.30 | 5 | Irregular |
| Bred | 0.30 | 5 | Breed | 0.30 | 4 | Irregular |
| Brought | 1.70 | 5 | Bring | 1.65 | 7 | Irregular |
| Built | 1.40 | 5 | Build | 1.23 | 5 | Irregular |
| Clung | 0.30 | 5 | Cling | 0.30 | 5 | Irregular |
| Dealt | 0.70 | 4 | Deal | 1.04 | 5 | Irregular |
| Dug | 0.48 | 3 | Dig | 0.60 | 3 | Irregular |
| Fell | 1.43 | 4 | Fall | 1.20 | 4 | Irregular |
| Fed | 0.90 | 4 | Feed | 0.95 | 3 | Irregular |
| Felt | 1.91 | 4 | Feel | 1.94 | 4 | Irregular |
| Fought | 0.85 | 5 | Fight | 1.20 | 6 | Irregular |
| Fled | 0.48 | 4 | Flee | 0.00 | 4 | Irregular |
| Flew | 0.78 | 3 | Fly | 0.90 | 4 | Irregular |
| Froze | 0.00 | 6 | Freeze | 0.00 | 5 | Irregular |
| Gave | 1.86 | 4 | Give | 2.08 | 4 | Irregular |
| Grew | 1.26 | 4 | Grow | 1.36 | 4 | Irregular |
| Left | 1.92 | 5 | Leave | 1.76 | 4 | Irregular |
| Meant | 1.46 | 4 | Mean | 1.99 | 5 | Irregular |
| Rode | 0.60 | 4 | Ride | 0.60 | 4 | Irregular |
| Rose | 1.20 | 4 | Rise | 1.00 | 4 | Irregular |
| Ran | 1.45 | 3 | Run | 1.54 | 3 | Irregular |
| Said | 2.74 | 3 | Say | 2.34 | 4 | Irregular |
| Sought | 0.85 | 4 | Seek | 1.04 | 6 | Irregular |
| Shook | 1.23 | 5 | Shake | 0.70 | 5 | Irregular |
| Shot | 0.95 | 5 | Shoot | 0.70 | 4 | Irregular |
| Sank | 0.48 | 4 | Sink | 0.48 | 4 | Irregular |
| Sat | 1.66 | 3 | Sit | 1.48 | 3 | Irregular |
| Slid | 0.48 | 5 | Slide | 0.30 | 4 | Irregular |
| Spun | 0.30 | 4 | Spin | 0.00 | 4 | Irregular |
| Sprang | 0.48 | 6 | Spring | 0.00 | 6 | Irregular |
| Stood | 1.62 | 5 | Stand | 1.46 | 5 | Irregular |
| Stole | 0.30 | 5 | Steal | 0.48 | 5 | Irregular |
| Stuck | 0.95 | 5 | Stick | 0.85 | 5 | Irregular |
| Stung | 0.00 | 5 | Sting | 0.00 | 5 | Irregular |
| Swam | 0.30 | 4 | Swim | 0.60 | 4 | Irregular |

*(continued on next page)*

**Appendix A (*continued*)**

| Past tense | Log frequency per million of past tense | Length past tense | Stem | Log frequency per million of stem | Length past tense | Verb type |
|---|---|---|---|---|---|---|
| Swung | 0.60 | 5 | Swing | 0.60 | 5 | Irregular |
| Told | 1.99 | 4 | Tell | 2.05 | 4 | Irregular |
| Thought | 2.07 | 5 | Think | 2.48 | 7 | Irregular |
| Won | 1.15 | 3 | Win | 1.11 | 3 | Irregular |
| Wrote | 1.51 | 5 | Write | 1.51 | 5 | Irregular |
| Bore | 0.60 | 4 | Bear | 1.11 | 4 | Irregular |
| Began | 1.95 | 5 | Begin | 1.48 | 5 | Irregular |
| Bound | 0.30 | 4 | Bind | 0.00 | 5 | Irregular |
| Bit | 0.30 | 4 | Bite | 0.30 | 3 | Irregular |
| Bled | 0.00 | 5 | Bleed | 0.00 | 4 | Irregular |
| Blew | 0.70 | 4 | Blow | 0.70 | 4 | Irregular |
| Bought | 1.26 | 3 | Buy | 1.49 | 6 | Irregular |
| Caught | 1.34 | 5 | Catch | 1.20 | 6 | Irregular |
| Chose | 0.90 | 6 | Choose | 1.20 | 5 | Irregular |
| Crept | 0.30 | 5 | Creep | 0.00 | 5 | Irregular |
| Drew | 1.18 | 4 | Draw | 1.15 | 4 | Irregular |
| Drank | 0.95 | 5 | Drink | 1.00 | 5 | Irregular |
| Drove | 1.20 | 5 | Drive | 1.18 | 5 | Irregular |
| Ate | 1.00 | 3 | Eat | 1.53 | 3 | Irregular |
| Found | 1.98 | 4 | Find | 2.11 | 5 | Irregular |
| Flung | 0.60 | 5 | Fling | 0.00 | 5 | Irregular |
| Got | 2.24 | 3 | Get | 2.47 | 3 | Irregular |
| Heard | 1.76 | 4 | Hear | 1.67 | 5 | Irregular |
| Held | 1.63 | 4 | Hold | 1.51 | 4 | Irregular |
| Kept | 1.62 | 4 | Keep | 1.94 | 4 | Irregular |
| Knelt | 0.30 | 5 | Kneel | 0.00 | 5 | Irregular |
| Knew | 2.06 | 4 | Know | 2.53 | 4 | Irregular |
| Lent | 0.00 | 4 | Lend | 0.48 | 4 | Irregular |
| Lost | 1.62 | 4 | Lose | 1.30 | 4 | Irregular |
| Made | 2.30 | 4 | Make | 2.34 | 4 | Irregular |
| Met | 1.48 | 4 | Meet | 1.11 | 3 | Irregular |
| Sold | 1.04 | 4 | Sell | 1.11 | 4 | Irregular |
| Sent | 1.49 | 4 | Send | 1.32 | 4 | Irregular |
| Slept | 0.85 | 5 | Sleep | 1.04 | 5 | Irregular |
| Slung | 0.00 | 5 | Sling | 0.00 | 5 | Irregular |
| Spoke | 1.46 | 5 | Speak | 1.51 | 5 | Irregular |
| Spent | 1.45 | 5 | Spend | 1.34 | 5 | Irregular |
| Spread | 0.85 | 6 | Spread | 0.85 | 6 | Irregular |
| Swore | 0.30 | 5 | Swear | 0.60 | 5 | Irregular |
| Swept | 0.78 | 5 | Sweep | 0.30 | 5 | Irregular |
| Took | 2.08 | 4 | Take | 2.28 | 4 | Irregular |
| Taught | 1.11 | 5 | Teach | 1.11 | 6 | Irregular |
| Tore | 0.60 | 4 | Tear | 0.48 | 4 | Irregular |
| Threw | 1.08 | 5 | Throw | 1.00 | 5 | Irregular |
| Wore | 1.18 | 4 | Wear | 1.18 | 4 | Irregular |

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