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AN ERP STUDY OF REGULAR AND IRREGULAR ENGLISH PAST TENSE INFLECTION

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Abstract

Compositionality is a critical and universal characteristic of human language. It is found at numerous levels, including the combination of morphemes into words and of words into phrases and sentences. These compositional patterns can generally be characterized by rules. For example, the past tense of most English verbs ("regulars") is formed by adding an -ed suffix. However, many complex linguistic forms have rather idiosyncratic mappings. For example, "irregular" English verbs have past tense forms that cannot be derived from their stems in a consistent manner. Whether regular and irregular forms depend on fundamentally distinct neurocognitive processes (rule-governed combination vs. lexical memorization), or whether a single processing system is sufficient to explain the phenomena, has engendered considerable investigation and debate. We recorded event-related potentials while participants read English sentences that were either correct or had violations of regular past tense inflection, irregular past tense inflection, syntactic phrase structure, or lexical semantics. Violations of regular past tense and phrase structure, but not of irregular past tense or lexical semantics, elicited left-lateralized anterior negativities (LANs). These seem to reflect neurocognitive substrates that underlie compositional processes across linguistic domains, including morphology and syntax. Regular, irregular, and phrase structure violations all elicited later positivities that were maximal over right parietal sites (P600s), and which seem to index aspects of controlled syntactic processing of both phrase structure and morphosyntax. The results suggest distinct neurocognitive substrates for processing regular and irregular past tense forms: regulars depending on compositional processing, and irregulars stored in lexical memory.

Introduction

A curious feature of natural human languages is that, in spite of their many regular patterns, "all grammars leak" (Sapir 1921). That is, there are typically exceptions to the predictable patterns that can be characterized by grammatical rules. For example, although most English verbs are inflected in the past tense with the suffix *–ed*, a regular pattern that can be explained in a straightforward way by the combination of verb stem and suffix, a few hundred verbs are

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irregular: they do not seem to take the *-ed* suffix, and instead undergo a variety of a priori unpredictable changes to the stem.

This distinction between regular and irregular patterns has been explained in different ways. “Dual-system” theories posit that regular past tense forms are computed compositionally by a rule-governed mental grammar, whereas representations of irregular past tense forms are stored in and retrieved from lexical memory (Clahsen 1999;Pinker 1991,1999;Schreuder & Baayen 1995). On a dual-system view, these distinct cognitive components also have distinct neural underpinnings (Marslen-Wilson & Tyler 1998;Pinker 1991,1999;Ullman 2001a;Ullman et al. 1997). On one neurocognitive dual-system view (Ullman 2001a,2004;Ullman et al. 1997), rule-governed composition across linguistic domains, including regular inflection and syntax, relies on the frontal/basal-ganglia-based procedural memory system that also underlies non-linguistic motor and cognitive skills, especially those involving sequences. In contrast, irregulars and other lexical forms are learned and represented in an associative mental lexicon that relies on the temporal-lobe-based declarative memory, which also subserves knowledge of facts and events.

Another perspective hypothesizes compositional processing for irregular as well as regular forms. According to Distributed Morphology, irregular verbs are linked by rote memory to specific affixes, thereby allowing the combination of the verb stem and the particular affix (e.g., *keep* + *-t* ⇒ *kept*, *dig* + *-0* ⇒ *dug*), as well as the application of word-specific “stem readjustment” rules (e.g., i-a in spring-sprang; Halle & Marantz 1993). Thus one would expect neurocognitive commonalities (reflecting combination) as well as dissociations (reflecting the greater dependence of irregulars on memory) between regular and irregular inflection, although to our knowledge the posited mechanisms have not been explicitly linked to specific neural substrates.

“Single-mechanism” accounts of morphological processing posit that regulars and irregulars are both processed by the same memory-based mechanisms. The ability to generalize inflectional patterns to new items arises from the associative nature of the lexicon rather than from a separate rule-governed process (Bybee 1995;Joanisse & Seidenberg 1999;McClelland & Patterson 2002;Rumelhart & McClelland 1986). According to one single-mechanism model, irregulars depend more than regulars on (temporal lobe-based) semantic representations, whereas regulars depend to the same degree as irregulars on (frontal lobe-based) phonological representations as long as the two verb types have equivalent phonological complexity (Bird et al. 2003;Joanisse & Seidenberg 1999,2005;McClelland & Patterson 2002). On this view, any greater reliance of regulars than irregulars on frontal structures is due to the general tendency for regular past tense forms to be more phonologically complex than irregular past tense forms (e.g., regulars generally have more phonemes; compare *walked* and *dug*).

The neurocognitive bases of regular and irregular inflection have been investigated in several languages, and using a variety of methodological approaches, including in developmental, psycholinguistic, and neurological studies. We and others have argued that the evidence largely supports a dual-system view (Clahsen 1999;Pinker 1991,1999;Pinker & Ullman 2002), and in particular one in which regulars are generally composed by the frontal/basal-ganglia procedural memory system, while representations of irregulars are stored in an associative lexical memory that depends on the temporal-lobe-based declarative memory system (Pinker & Ullman 2002;Ullman 2001a,2004;Ullman et al. 1997). However, this interpretation of the evidence is by no means uncontroversial, and others have argued that the evidence is rather more consistent with single-mechanism models (Bird et al. 2003;Joanisse & Seidenberg 1999;McClelland & Patterson 2002). Thus the issue is still open, and further evidence is necessary to help constrain the range of possible theoretical interpretations.

Hemodynamic neuroimaging studies concerning this issue have produced somewhat equivocal results. Numerous studies have shown differences in the brain areas activated by regular and irregular morphology, both in comprehension (Jaeger et al. 1996;Laine et al. 1999;Vannest, Newman et al. 2005;Vannest, Polk et al. 2005) and in production (Beretta et al. 2003;Dhond et al. 2003;Joanisse & Seidenberg 2005;Sahin et al. 2006). A number of studies have shown particular activation in frontal and/or basal ganglia structures for regulars (Dhond et al. 2003;Jaeger et al. 1996;Joanisse & Seidenberg 2005;Laine et al. 1999;Sahin et al. 2006;Vannest, Newman et al. 2005;Vannest, Polk et al. 2005). However, frontal activation is often seen for irregulars as well, with some studies reporting no differences between regulars and irregulars (Beretta et al. 2003;Sach et al. 2004) and others reporting greater frontal activation for irregulars (Jaeger et al. 1996;Sahin et al. 2006). Further, one study that found greater inferior frontal activation for regulars than irregulars attributed this difference to phonological factors rather than morphological status (Joanisse & Seidenberg 2005).

The study reported here examines the regular/irregular distinction by recording event-related brain potentials (ERPs), which can reveal both temporal and spatial characteristics of the neurocognitive processes underlying language processing. ERPs elicited by syntactic and lexical semantic processing have been shown to be associated with different spatiotemporal patterns of neural activity, suggesting non-identical neural correlates. Lexical-semantic violations (e.g., **He shaved off his moustache and city*) elicit an N400, a negative potential peaking that peaks about 400 ms following the stimulus, and is maximal over central-parietal electrode sites (Kutas & Federmeier 2000;Kutas & Hillyard 1984). The N400 may reflect the difficulty of integrating sensory input with the “current context” in an individual’s working memory and with established semantic knowledge (Kutas & Federmeier 2000;Rugg & Doyle 1994). N400s are also elicited by stimuli such as pseudowords, possibly because they possess enough similarity to meaningful items that the system attempts to integrate these into some meaningful context (Kounios & Holcomb 1994;Rugg & Nagy 1987).

Syntactic violations typically elicit one or more ERP components that are distinct from the N400. The most widely-reported such components are left anterior negativities LANs[i] - 150–500 msec) and later positivities (500–1000 msec), frequently labeled P600s[ii]. A “biphasic’ LAN-late positivity pattern has been observed for phrase structure violations (e.g., *The scientist criticized Max’s of proof the theorem`; Friederici et al. 1993;Hagoort et al. 2003;Münte et al. 1993;Neville et al. 1991), syntactic agreement violations (e.g., *The elected officials hopes to succeed`; Barber & Carreiras 2005;Demestre et al. 1999;Hagoort & Brown 2000;Osterhout 1997;Osterhout & Mobley 1995), and violations of morphological structure (see below).

According to one view, early (100–200 msec) LANs, which are frequently observed in response to phrase structure violations, reflect early word category identification and syntactic structure building, while LANs in the 300–500 msec range reflect morphological processing, as well as syntactic and lexical integration (Friederici 2002). Alternatively, it has been suggested that

[i]The LAN has a somewhat variable scalp distribution, sometimes being maximal over anterior midline rather than left hemisphere electrodes (Hagoort & Brown 2000) and other times over left fronto-temporal rather than very anterior sites (Rodriguez-Fornells et al. 2001). That these waveforms are all classified as LANs seems to be justified on several grounds, both functional (they are observed in consistent contexts, e.g., in response to syntactic violations), and descriptive (they have similar temporal and spatial characteristics). It is important to point out that while many studies have reported LANs, others have not, even for syntactic violations where a LAN has been found in other studies (Hagoort et al. 1993;Osterhout 1997;Osterhout et al. 2002;Osterhout & Mobley 1995). Such negative findings may be due to lower signal-to-noise ratios or greater inter-subject and/or inter-item variability in some studies, which may affect a comparatively small and transient ERP component such as the LAN more than higher-amplitude and more sustained component like the late positivity. Additionally, in some studies that failed to observe a LAN, the sentence materials did not contain outright sentence violations, but rather correct but unusual structures (Friederici 2002). See the main text for further discussion.

[ii]Here we will avoid the use of the term P600 and instead refer to this pattern simply as a “late positivity”, since the latency of the effect can vary between different types of eliciting conditions.

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LANs may reflect morphological structure building (Gross et al. 1998;Penke, Weyerts et al. 1997;Rodriguez-Fornells et al. 2001;Weyerts et al. 1997), or a failure to "bind" syntactic constituents (be they morphemes or words) (Hagoort 2005;Hagoort et al. 2003). Along similar lines, Ullman (2001a;2004) has posited that LANs reflect procedural memory processes related to grammatical structure building in both morphology and syntax. Hoen & Dominey (2000) have proposed a somewhat different domain-general interpretation of the LAN, suggesting that it relates to the rule-governed processing of symbols.

The late positivity, which is elicited both by violations and under conditions of increased syntactic complexity or ambiguity, appears to be the sum of a number of different but complementary neurocognitive processes. These may include the diagnosis of parsing difficulties or syntactic violations, and the "second-pass" resolution of syntactic complexity, ambiguity, and violations (Friederici 1995;Friederici 2002;Friederici et al. 2001;Hagoort et al. 1993;Kaan et al. 2000;Kaan & Swaab 2003;Osterhout & Holcomb 1992,1993).

A number of ERP studies have examined the regular/irregular distinction in inflectional morphology, in a variety of languages. In priming paradigms, the bases of regular inflected forms have been found to show a similar reduction in N400 amplitude when preceded by the inflected form (*walked-walk*) as when preceded by themselves (*walk-walk*). In contrast, irregular bases do not show such an N400 reduction when preceded by their inflected forms (e.g., *kept-keep*). This effect, which has been demonstrated in English (Münte et al. 1999), German (Weyerts et al. 1996), and Spanish (Rodriguez-Fornells et al. 2002), has been taken to suggest that regularly but not irregularly inflected forms are processed compositionally - specifically that the base is activated when the regular inflected form is decomposed into base and affix (Münte et al. 1999).

Another line of investigation has examined violations of inflectional morphology. Weyerts et al. (1997) investigated violations of German noun plurals by combining stems of regular nouns with irregular affixes (e.g., **Korsett-en*), and irregular stems with regular affixes (e.g., **Parasit-s*). Although both regulars and irregulars in German involve affixation, several lines of behavioral evidence suggest that regulars are subject to morphological decomposition, while irregulars are generally stored as whole forms (see, e.g., Clahsen 1999 for a review). Only the over-application of the regular plural affix to irregular stems (*Parasit-s*) elicited a LAN. In contrast, regular stems paired with the irregular suffix elicited an N400, interpreted as reflecting these items' being processed as non-words, since the irregular affixes were not thought to have independent status as morphemes. Penke et al. (1997) used a similar paradigm with German verbal participles. Again a LAN was found only for the mis-application of the regular suffix to irregular stems, though in this study no consistent effect was obtained for the combination of regular stems with the irregular suffix. A third study examined violations of Italian past participles (Gross et al. 1998). As in Penke et al., the incorrect application of regular morphemes to irregular bases (i.e., over-regularizations) elicited a negativity from 300–500 msec, while no reliable ERP effect was found for "irregularized" regulars. The negativity for over-regularizations, however, had a widespread scalp distribution rather than a left anterior focus. This may be explained by the fact that there was a greater degree of phonological dissimilarity between the correct and incorrect forms in the Italian study (e.g., *preso*/**prendato*) than in the German study (e.g., *aufgeladen*/**aufgeladet*), which may have led to a more N400-like effect if the Italian violations were treated as non-words rather than decomposed.

Another ERP violation study investigated Catalan, in which stem formation rules generally require the insertion of a conjugation class-dependent theme vowel between the verb root and the inflectional affix (Rodriguez-Fornells et al. 2001). Stems of the first conjugation class are hypothesized to involve rule-governed composition, while those of the other classes are thought to be stored as whole words (Rodriguez-Fornells et al. 2001). Analogous to the German studies, the mis-application of the first conjugation Catalan theme vowel to bases of other conjugation classes (i.e., over-regularizations) resulted in a LAN, although with a scalp distribution that was slightly less anteriorly focused, while the incorrect combination of an (irregular) third conjugation class theme vowel with a first conjugation verb did not elicit any reliable negativity. Unlike the German and Italian studies, the Catalan study also reported late positivities for all violation conditions. The authors suggest that the comprehension task in this study may have encouraged late positivity-related processes such as reanalysis and repair to a greater degree than did the recognition memory or word list paradigms used in the other studies.

Morris et al. (2005) also reported a LAN for over-regularizations in English (e.g., **bringed* vs. *brought*), but a negativity maximal over the most anterior midline electrodes for regular verbs that had undergone stem-internal changes similar to those occurring in English irregulars (e.g., **sept* vs. *seeped*). Both types of violations elicited later positivities. These findings are consistent with those from the previous studies insofar as the LAN was elicited by over-regularizations. The authors suggest that the anterior midline negativity for over-extensions or irregular patterns may have been an N400 coincident with the posterior late positivity, which “pushed” the N400 more anteriorly. This would be consistent with the N400 reported by Weyerts et al. (1997) for over-extensions of irregular patterns to regular stems in German.

Finally, Allen et al. (2003) employed a somewhat different paradigm, in which correctly-inflected regular and irregular past tense English verbs were presented in syntactically incorrect sentence contexts (e.g., **The man will <u>worked</u> on the platform*). Both regular and irregular violations elicited late positivities, but only for irregulars did the latency of the positivity correlate with the verb’s surface frequency. This pattern was interpreted as supporting dual-systems models in which irregularly inflected forms depend on (frequency-sensitive) lexical access, while regularly inflected forms are parsed into stem and affix. Somewhat surprisingly in light of the other studies, Allen et al. (2003) did not report a LAN effect. However, we note that no analyses were reported that could have in principle revealed the presence of a left anterior negativity, since statistics were provided only for midline electrodes[iii]. If indeed no LAN was present in this study, the discrepancy between this study and those discussed above may be explained by basic differences in the types of violations. Whereas the violations in Allen et al. were syntactically anomalous while being morphologically correct, in all of the other studies subjects were presented with non-existent morphological forms that were constructed using morphological transformations that were appropriate for the syntactic context (e.g., Y*esterday I bringed*). Although morphologically appropriate forms in syntactically inappropriate contexts have elicited LANs in some studies (e.g., agreement violations `; Barber & Carreiras 2005;De Vincenzi et al. 2003;Demestre et al. 1999;Gunter et al. 2000;Osterhout 1997;Osterhout & Mobley 1995), they have not been entirely reliable (Hagoort et al. 1993;Osterhout et al. 2002;Osterhout et al. 1996;Osterhout & Nicol 1999). Thus one possibility is that while LANs may be highly reliable for violations of syntactic or morphological constituents (i.e., phrase structure violations and violations involving irregular stems combined with regular affixes), they may be less consistent for the presentation of morphologically acceptable forms in syntactically inappropriate contexts.

The present study was designed to generate empirical data to help constrain the range of possible theories regarding morphological processing. Subjects were presented with stem (unmarked) forms in sentence contexts in which the past tense inflected form was expected (e.g., *Yesterday I *<u>whip</u>/<u>whipped</u> an egg.; Yesterday I *<u>weep</u>/<u>wept</u> for joy*.). If morphologically-related LANs are elicited reliably only by the illegal application of regular morphemes, such

[iii]The authors justify such restricted analyses on the basis of their focused interest in N400 and P600 effects (which are most robust at midline electrodes), and “because effects at lateral sites did not appear to depart from midline trends in any theoretically interesting manner” (page 411).

as to the base of an irregular verb, then one would not expect LANs to be elicited by our violations, for either regular or irregular verbs. If however the LAN is sensitive more generally to violations of regular morphology, then the absence of regular morphemes where they are expected should also elicit LANs. In this case a LAN should be elicited by the violations of regular verbs according to dual-system accounts, by the violations of irregular as well as regular verbs according to accounts that posit affixation for both types of verbs (Halle & Marantz 1993), and by neither verb-type on single-mechanism accounts. If LANs are reliably elicited by morphologically appropriate forms (in this case an unmarked form) in syntactically inappropriate contexts, then LANs should be found for both verb types. If however LANs are not reliably elicited in these circumstances (see above), we would not expect such effects for either regulars or irregulars.

If the presentation of unmarked forms in contexts requiring a past tense constitutes a semantic violation (of “pastness”), then N400s might be found for violations on both types of verbs. The single-mechanism view in which irregulars depend especially on semantics (Joanisse & Seidenberg 1999;Patterson et al. 2001) might predict that only irregulars would elicit an N400, or at least greater N400 amplitudes than for regulars. In contrast, an N400 might not be expected for irregulars on a dual-system view.

Given that late positivities have been reliably observed in response to morphosyntactic violations, such effects were predicted for violations of both regular and irregular morphology. The presence of late positivities for both verb types does not clearly distinguish the competing theories discussed above, since all accept some type of past tense commonality between the two conditions.

We also included two other conditions in this experiment: phrase-structure violations (which reliably elicit a LAN and P600) and lexical semantic violations (which reliably elicit an N400). These served as “reference” conditions. That is, obtaining the expected ERPs for these conditions would show that the absence of any such effects in response to the violations of regular and irregular morphology cannot easily be attributable to factors such as subject or session variability.

Methods

Participants

We tested 26 native English-speaking American males with normal or corrected-to-normal vision. All subjects were right-handed (Oldfield 1971) with no left-handed relatives in their immediate families. None had been exposed to any languages other than English in childhood, nor had any achieved a significant level of fluency in any second language. Subjects had no history of developmental, neurological, or psychiatric disorders, and were not taking any medications at the time of testing. They were paid $7/hour for their participation, gave voluntary consent to participate in accordance with University of Oregon guidelines, and were informed that they were free to withdraw from the study without prejudice at any time.

Stimuli

The stimuli for this experiment consisted of 256 simple declarative English sentences, 64 in each of 4 conditions: regular past tense, irregular past tense, phrase structure and lexical semantics. For each sentence, an anomalous version was created to correspond to its correct “control” version. Stimuli were counterbalanced across subjects such that each subject saw only the control *or* the anomalous version of a given sentence. Thus each subject saw 32 correct and 32 anomalous sentences from each of the four conditions. The complete set of stimulus sentences is available from http://neuroimaging.psychology.dal.ca/documents/Reg-

Irg_ERP_stimuli.pdf, or can be requested from either of the corresponding authors. Four practice sentences (2 correct, 2 anomalous) were also created for each condition, using words that did not appear as target items in the experimental sentences.

In the regular past tense condition, sentences contained verbs that take a regular past tense (e.g., *Yesterday I frowned at Billy.*), while in the irregular past tense condition sentences contained verbs that take an irregular past tense (e.g., *Yesterday I ground up coffee.*). All sentences had similar structures, beginning with *Yesterday*, followed by a pronoun (*I*, *he*, or, *she*), the verb, and then the post-verbal argument. For each sentence, a corresponding anomalous sentence was created by replacing the past tense inflected form of the verb with its stem (unmarked) form (e.g., *Yesterday I frown at Billy.* and *Yesterday I grind up coffee.*)

All verbs were monosyllabic in both their stem and past tense forms. The irregular verbs were drawn from Pinker and Prince (1988). Any irregular verb whose regularized past tense form had an average acceptability rating of greater than 3.5 in Ullman (1993) was considered a doublet verb (e.g. *dive-dove/dived*), and was excluded. Also excluded were no-change verbs, whose past tense forms do not differ from their stems (e.g., *hit-hit*). Any regular verb whose stem was phonologically similar to any irregular verb (having an identical rime in the stem; e.g., *glide*, cf. *ride*, *hide*) was considered to be an "inconsistent regular", and was also excluded from the stimuli, since the past tense forms of such regulars are expected to be memorized (for discussion, see Ullman 1999,2001b).

The regular and irregular verbs were selected so as to be matched in a one-to-one manner on both past tense surface frequency and stem (unmarked form) frequency. Two relative frequency counts were used for this matching: (1) the Francis and Kucera (FK) counts (Francis & Kucera 1982), derived from 1 million words of text, drawn from a variety of sources; and (2) a frequency count extracted by a stochastic part-of-speech analyzer from 44 million words of unedited Associated Press (AP) news wires between February and December 1988 (Church 1988;Ullman 1999). Frequencies from each source were calculated as the natural logarithm of the raw frequency count, first augmented by 1 to avoid the undefined ln(0). Frequency did not differ significantly between regulars and irregulars for either past tense or stem forms on either frequency count (past tense -- FK: regulars, mean = 3.07, range = 0.00 – 5.79; irregulars, mean 3.09, range 0.00 – 6.06; $t(126) = 0.078$ p = 0.938. AP: regulars, mean = 3.07, range = 1.10 – 9.41; irregulars, mean = 5.93, range = 0.00 – 10.18; $t(126) = 0.106$ p = 0.916. stem form -- FK: regulars, mean = 2.97, range = 0.00–5.71; irregulars, mean = 3.20, range = 0.00 – 6.41; $t(126) = 0.885$ p = 0.378; AP: regulars, mean = 5.90. range = 0.69 – 9.25;, irregulars, mean = 6.07, range = 1.39 – 9.84; $t(126) = 0.466$ p = 0.642.

The regular and irregular verbs were also matched as closely as possible on phonological complexity. The mean number of phonemes (with diphthongs counted as a single phoneme) among the regular past tense forms was 4.2, as compared to 3.8 for the irregular past tenses. Although this difference was significant ($t(126) = 3.59$, $p < .001$), it was not large: on average, the irregular past tense forms were 89.2% as long as the regular past tense forms. Thus it would seem unlikely that the slightly longer regular forms would elicit a qualitatively different ERP pattern than the irregulars.

Correctly-formed control sentences for the phrase structure and lexical semantic conditions were quite similar to each other. Roughly half of each of these had similar structures to those of the past tense conditions, beginning with a past tense frame such as *Yesterday I…* or *Last week she…*, so that subjects could not predict what condition the sentence belonged to. The other half had more varied structures and length, and some were not in the past tense, in order to keep participants interested in the stimuli. For each sentence in the phrase structure condition, an anomalous version was created, modeled on Neville (1991), by placing a closed-class word immediately after the possessive *'s*, where a noun was required (e.g., **Yesterday I drank Lisa's* <u>*by*</u> *brandy the fire*, as compared to the control version, *Yesterday I drank Lisa's brandy* <u>*by*</u> *the fire.*[iv]. In the lexical semantic condition, anomalous sentences contained nouns which were conceptually incompatible with the preceding verbs, e.g., **Yesterday Daniel sipped his* <u>*sarcasm*</u> *for hours.* None of the violations in any of the four conditions were sentence-final, thus avoiding sentence "wrap-up" ERP effects (Hagoort 2003;Osterhout et al. 1994;Osterhout & Nicol 1999).

Procedure

After giving informed consent and having the ERP cap applied, participants were seated in a dimly lit sound-attenuating booth. The sentences were presented visually, one word at a time in the center of a computer screen, at a rate found to be comfortable for participants in pilot testing (duration 300 msec; SOA 500 msec). Participants were seated 53 inches from the 23 inch monitor, at which distance the words subtended 1–3 degrees of visual angle horizontally and 0.5 degrees vertically. The presentation of each sentence was initiated by the subject's pressing either of the response box's two response buttons, which caused the outline of a box (7 x 3 degrees of visual angle) to appear in the center of the screen, followed by the first word after a variable (random) delay of 300 – 1100 msec, to attenuate ERP effects associated with the expectation of forthcoming stimuli. To forestall subjects' responding, and possibly generating ERP artifacts, too soon after the critical words in the sentences, the box outline remained on the screen during the presentation of the sentence and for 1500 msec following the onset of the final word of each sentence. Participants were instructed to refrain from blinking or making eye movements during this period. After the box disappeared from the screen, the question, "GOOD OR BAD?" appeared on the screen and remained until participants responded. At that point a fixation cross appeared on the screen and remained until another button press was made to initiate the next trial.

Subjects were instructed to silently read each sentence as it was presented on the video monitor, and at the end of each sentence, to press one of two buttons to indicate whether in their opinion the preceding sentence was well-formed English. The hands used to indicate the "good" and "bad" responses were counterbalanced across participants and across the four sets of stimuli as described above. Practice items were presented to participants prior to any of the experimental items. Procedural details for the practice session were identical to the experimental session, except that participants received visual feedback as to the accuracy of their response after each trial, and ERPs were not recorded. Participants were given 3 evenly-spaced breaks during the experiment, and were advised that they were free to rest for as long as they wished between sentences. On average, the experiment took about 2 hours, including informed consent and ERP cap application and removal.

[iv]Preliminary inspection of the data after approximately half the subjects were run revealed differences between the waveforms for the control and violation target words for the phrase structure condition, beginning at word onset. Examination of the stimuli revealed a likely cause: in approximately two thirds of these sentences, the words immediately preceding the target words differed in their word class (open vs. closed) between the control and violation conditions (e.g., "her" vs. "brandy" in **Yesterday I drank her* <u>*by*</u> *brandy the fire.* vs. *Yesterday I drank her brandy* <u>*by*</u> *the fire.*), thus affecting the baselines for the control vs. anomalous conditions (since open and closed class words tend to elicit different ERPs, e.g., Neville et al. 1992). We therefore changed all of the possessive pronouns that preceded critical words in the violation conditions with proper names with the possessive clitic *'s* (e.g., **Yesterday I drank Lisa's* <u>*by*</u> *brandy the fire*). It is these corrected stimuli that appear in the supplemental material. The ERPs elicited by phrase structure violations from subjects run before and after this change was made were examined to ensure that the results were comparable. The LANs in both cases were highly similar in their timing and scalp distribution, although the amplitude of this effect was greater in subjects run prior to the changes to the stimuli. This can be attributed to a more negative baseline in the violation condition in the original stimuli, which was precisely the reason the stimuli were changed.

ERP Recording and Data Analysis

Scalp electrical activity was recorded from 32 tin electrodes mounted in an elastic cap (Electro-Cap, OH, USA) according to positions specified by the International 10–20 system (Fz; FP1/2; F3/4; F7/8; FT7/8; FC5/6; T3/4; Cz; C3/4; C5/6; CT5/6; T5/6; Pz; P3/4; TO1/2; O1/02). Electrodes were also placed under the left eye and on the outer canthi of both eyes to monitor vertical and horizontal eye movements and blinks. Data from all scalp electrodes and the vertical eye channel were recorded relative to a reference electrode placed over the right mastoid bone. Activity from the left mastoid was also recorded, referenced to the right mastoid, and the data were re-referenced to the linked (bilateral) mastoids off-line prior to averaging and analysis. The two horizontal eye channels were referenced to each other.

The EEG was amplified by Grass 7P511 amplifiers (3dB cutoff, bandpass of 0.01–100 Hz) and digitized on-line at 256 Hz. Trials with eye movements, blinks, or excessive noise were identified offline (using a maximum peak-to-peak amplitude cutoff, with thresholds tailored to each subject’s data) and were not included in further averaging and analyses, nor were trials containing blocking (defined as 10 or more time points having the same value). Data from each subject were normalized relative to 200 msec, 10 microvolt calibration pulses that were delivered to each amplifier and were recorded in the same manner as the ERP data on the same day as that subject was run. Prior to group averaging, all channels from each subject were filtered using a 60 Hz digital notch filter to remove artifacts due to electrical line noise. Trials that participants responded correctly to were averaged together within each condition of interest over an epoch of 1200 msec, including a 200 msec prestimulus baseline.

Statistical analyses were aimed at capturing the early negative (LAN and N400) and late positive potentials that we predicted we would observe based on previous studies. For the early negativities, visual inspection of the waveforms confirmed that the 300–500 msec epoch used in numerous prior studies was appropriate to capture these effects in the current dataset. In order to test ther scalp distributions of the early negative violation effects statistically, electrodes were organized into 4 regions of interest (ROIs) for the ANOVAs involving the early temporal epoch – left anterior (electrodes F3, F7, FC5, FT7), left posterior (CT5, T5, P3, TO1, O1), right anterior (F4, F8, FC6, FT8), and right posterior (CT6, T6, P4, TO2, O2) – resulting in two 2-level electrode factors for the ANOVAs, Hemisphere and Anterior-Posterior. To assess the early negative effects for regular vs. irregular inflectional violations, a 2 x 2 x 2 x 2 ANOVA with factors Regularity (regular/irregular), Violation (good/bad), Hemisphere (left/right) and Anterior-Posterior was performed. Separately, 2 x 2 x 2 ANOVAs with factors Violation (good/bad), Hemisphere (left/right) and Anterior-Posterior were performed for each of the two reference conditions, phrase structure and lexical semantic. In cases where significant interactions were observed between Violation and electrode factors, follow-up analyses were performed to isolate the nature of these interactions, collapsing over factors with which an interaction was not found.

For the late positivity, visual inspection of the ERP waveforms indicated that while this effect peaked between 700 and 800 msec for the phrase structure violations(similar to previous studies), it occurred somewhat later in the two inflectional conditions, around 900–1000 msec. Thus to properly capture the peak of the late positive violation effect in each condition, we used a 600–800 msec epoch for the phrase structure condition and 800–1000 msec for the regular and irregular inflectional ANOVA. Since the late positivity is typically maximal over midline electrodes, only the 3 midline electrodes were used in the late epoch ANOVAs. Again regular and irregular conditions were included in one ANOVA, a 2 x 2 x 3 design with factors Regularity (regular/irregular), Violation (good/bad), and Anterior-Posterior (anterior/middle/posterior), while the late positivity for phrase structure violations was tested in a separate 2 x 3 (Violation x Anterior-Posterior) ANOVA.

Alpha was set at $p < 0.05$ for all statistical tests.

Results

Behavioral Data

Participants accurately detected the violations in all sentence conditions (< 10% errors in every condition), with no differences in accuracy between conditions (all F values < 1).

ERP Data

The results from the two "reference conditions" in this experiment bore out the findings of previous studies using these stimuli. Lexical semantic violations elicited a robust N400, maximal at the vertex of the scalp as seen in the ERP waveforms (see electrode Cz, Figure 1a) and scalp topographic maps (Figure 2a). Statistically, this was manifest as a significant main effect of Violation from 300–500 msec, $F(1,25) = 14.14$, $p = 0.001$. Phrase structure violations elicited a typical biphasic LAN-late positivity response. As seen in Figure 1b, the LAN was maximal at approximately 400 msec, and as Figure 2a shows the effect was greatest over the left hemisphere over central and temporal electrodes. From 300–500 msec, the ANOVA across all 4 quadrant ROIs revealed both a significant main effect of Violation, $F(1,25) = 10.46$, $p = 0.003$, and a Violation × Hemisphere interaction, $F(1,25) = 18.94$, $p < 0.001$. A follow-up analysis of this Violation × Hemisphere interaction revealed a significant effect of Violation over the left hemisphere (collapsed across anterior and posterior ROIs), $F(1,25)$ 20.6, $p < 0.001$, but not the right hemisphere, $F(1,25) = 1.66$, $p = 0.210$. The late positivity in response to phrase structure violations peaked at approximately 750 msec, as seen in Figure 1b, and was maximal over posterior midline electrode sites. From 600–800 msec over midline electrode sites there was a significant main effect of Violation, $F(1,25) = 25.69$, $p < 0.001$, as well as a Violation × Electrode (anterior-posterior) interaction, $F(2,50) = 6.14$, $p = 0.019$, reflecting the posterior distribution of the violation effect.

Examination of the ERP waveforms for the regular and irregular conditions (Figure 1c/d) showed an enhanced negativity over left anterior electrodes for regular but not irregular violations from approximately 300–500 msec. In this time window irregular violations elicited a smaller negativity with a very focal distribution over left posterior electrode sites. Both regular and irregular violations elicited later positivities, with similar latencies (from roughly 700–1100 msec – see Figure 1c/d) and scalp distributions (midline posterior – see Figure 2b). In the early time window (300–500 msec), the ANOVA across both conditions and all 4 quadrant ROIs revealed main effects of both Regularity, $F(1,25) = 5.86$, $p = 0.023$, and Violation, $F(1,25) = 7.71$, $p = 0.010$, as well as a four-way Regularity × Violation × Hemisphere × Anterior-Posterior interaction, $F(1,25) = 5.29$, $p = 0.030$. To understand this interaction, we performed additional *post hoc* ANOVAs for each ROI separately, with factors Regularity and Violation. This revealed a main effect of Violation only over the left anterior ROI, $F(1,25) = 17.70$, $p < 0.001$; none of the other ROIs showed any significant effects of Violation, nor was the Regularity × Violation interaction significant in any of the 4 ROIs. However, given our *a priori* hypothesis that regular but not irregular inflectional violations would elicit a LAN, we performed ANOVAs within the left anterior ROI separately for regulars and irregulars, with a single Violation factor. These revealed a robust effect of Violation for regulars, $F(1,25) = 10.95$, $p = 0.003$, but not for irregulars, $F(1,25) = 2.19$, $p = 0.151$. In the late temporal epoch (800–1000 msec), a significant main effect of Violation was obtained across regular and irregular conditions, $F(1,25) = 8.18$, $p = 0.008$, as well as a Violation × Anterior-Posterior interaction, $F(1,25) = 5.59$, $p = 0.025$, again reflecting the posterior distribution of the late positivity. No interactions between Regularity and Violation were found, indicating that the late positivities elicited by regular and irregular inflectional violations did not differ significantly.

Discussion

We conducted an event-related brain potential study to investigate whether the processing of regularly and irregularly inflected English past tense forms are associated with distinguishable electrophysiological signals. Subjects were presented with unmarked forms of both regular and irregular verbs in sentence contexts in which past tense forms were expected (e.g., *Yesterday I frown at Billy* or *Yesterday I grind up coffee*). In comparison to correct control sentences, regular past tense violations elicited a left anterior negativity (LAN) followed by a late positivity, whereas irregular past tense violations elicited only the later positivity. Phrase structure violations also yielded a LAN followed by a positivity, whereas lexical semantic violations elicited an N400.

The presence of a LAN for violations of regular but not irregular past tense suggests the existence of at least partially distinct neurocognitive processes in the processing of the two verb types from about 300 to 500 ms after reading a verb form, at least in the present task. In contrast, the fact that late positivities were elicited by both verb types suggests that regulars' and irregulars' later processing depends on shared neurocognitive processes. The presence of a LAN and subsequent positivity for the phrase structure violations, within the same subjects as elicited this biphasic pattern for the regular past tense violations, suggests that these violations of regular past tense and phrase-structure are processed by at least partially overlapping neural substrates in both early and later periods. Finally, the presence of an N400 only for lexical semantic violations suggests that none of the other violations depend on the same processes as this condition.

Two criticisms could be raised regarding the claims that regulars but not irregulars elicited a LAN, and that both regular and phrase structure violations elicited the same early negative LAN effect. Regarding the first, we found a four-way Regularity × Violation × Hemisphere × Anterior-Posterior interaction when all 4 scalp quadrants were considered, but no Regularity x Violation interaction within the left anterior ROI when considered on its own. However, the fact that a significant Violation effect was obtained for regulars but not irregulars within the left anterior ROI when each condition was considered separately, while no Violation effects were significant in any other ROI, strongly suggests the presence of a LAN for regulars but not irregulars. With regard to whether regular inflectional and phrase structure violations showed the same early effect, the Violation effect for regulars was limited to the left anterior ROI, while for the phrase structure condition it was significant over the left hemisphere with no Anterior-Posterior interaction. Examination of the scalp topographic maps in Figure 2a demonstrates the high degree of similarity in the distribution of the LAN for regular inflectional and phrase structure violations, with foci in both cases over anterior temporal electrode sites. However, the magnitude of the LAN was somewhat greater for phrase structure violations, and so it is evident over a more distributed set of electrodes, extending to electrodes in the left posterior ROI. This distribution is consistent with LANs found in response to both phrase structure (Neville et al. 1991) and morphological (Rodriguez-Fornells et al. 2001) violations previously. Thus the fact that an effect isolated to the left anterior ROI was not obtained in the phrase structure condition seems to reflect its overall magnitude rather than a true distributional difference[v], since the foci of the two effects are so similar.

What implications do these data have for specific theoretical frameworks? First, the different ERP patterns observed for regulars and irregulars in the 300–500 msec epoch, and in particular

[v]Historically, amplitude normalization has been used to test for distributional differences in the presence of amplitude differences {McCarthy, 1985 #2932}. However, Urbach & Kutas {, 2002 #2933} have identified several fundamental problems with this approach. Further, the study was not designed to allow a direct comparison between regular and phrase structure violation conditions - for example, items in the two conditions were not matched on critical factors such as frequency of occurrence or word class.

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the presence of a LAN for regulars and not irregulars, does not seem to be consistent with theories such as Distributed Morphology that propose compositional processing for both verb types (Halle & Marantz 1993). Note that although it might be argued that the shared late positivity reflects such compositional processes, the very lateness of this effect, combined with previous evidence suggesting that it is functionally related to processes of reanalysis and/or repair of morphological and syntactic parsing problems, seems to preclude such an account.

The data obtained in the present study are also problematic for the single-mechanism view that regular/irregular differences stem from a differential reliance on phonology and semantics (Bird et al. 2003;Bybee 1995;Joanisse & Seidenberg 1999;McClelland & Patterson 2002). First, if irregulars were particularly reliant on semantic processing, one might expect an N400 for irregular violations, which was not observed. Moreover, it does not appear to be the case that the LAN found for regulars is due to a greater phonological complexity among regular than irregular past tense items (Bird et al. 2003;Joanisse & Seidenberg 1999;McClelland & Patterson 2002). As discussed above, the regular and irregular past tense items had similar phonological lengths, with the irregulars 89% as long as the regulars – or, to put it differently, the irregulars were only 11% shorter than the regulars. It seems unlikely that this small percentage difference would result in qualitatively different effects: a LAN for regulars and not for irregulars. Additionally, there is no evidence to suggest that the LAN indexes the processing of phonological complexity. While to our knowledge no ERP studies of "phonological complexity" have been conducted, phonological processing has been the focus of numerous studies that have identified several ERP components, all of which seem distinct from the LAN. These include the mismatch negativity (Connolly & Phillips 1994;Connolly et al. 2001;Dehaene-Lambertz et al. 2000;Kujala et al. 2004;Rinne et al. 1999), the N320/350 (Bentin et al. 1999), and the N400-like "Rhyming Effect" elicited by stimuli that do not match phonological expectations (Barrett & Rugg 1990;Coch et al. 2005;Grossi et al. 2001;Rugg 1984). Furthermore, an explanation based on phonological complexity does not seem to be compatible with the occurrence of a LAN for phrase structure violations, especially since this effect is found when comparing ERPs elicited by the identical word when it is compatible vs. incompatible with the preceding phrase structure.

In contrast, the data do seem to be consistent with the dual-system view that regular but not irregular morphology is handled by a compositional process, describable by a symbolic rule. Most importantly, regulars but not irregulars elicited LANs, which, as we reviewed above, have been linked to compositional processes in both morphology and syntax. The fact that we did not observe a LAN for both types of inflectional violation suggests that this ERP effect was not due to the syntactic tense violation, as tense was incorrectly marked for both regulars and irregulars. The fact that LANs are elicited both by the pairing of a regular morpheme with an unacceptable stem, as shown in prior studies (see below for examples`; Bartke et al. 2005;Gross et al. 1998;Morris & Holcomb 2005;Penke, Weyerts et al. 1997;Rodriguez-Fornells et al. 2001;Weyerts et al. 1997), and by the stem of a regular verb lacking the regular affix, as in the present study, suggests that the two cases may be processed similarly. The presence of a LAN for phrase structure violations, in the same subjects that yielded a LAN for regulars, suggests the existence of shared neurocognitive substrates for aspects of processing regular morphology and syntactic phrase structure (Ullman 2001a,2004).

We suggest that LANs reflect a neurocognitive process that is subserved at least in part by procedural memory, and is involved in the rule-governed compositional (sequential and hierarchical) parsing of complex forms, across linguistic domains, including morphology and syntax. On this view, the temporal differences between LANs (i.e., the ELAN vs. the LAN) indicate when these processes apply, which in turn likely depends at least in part on which linguistic domain is engaged (e.g., syntactic, morphological) and the rapidity with which the violation becomes evident (e.g., on prefixes vs. suffixes). In contrast, differences in scalp distributions between LANs may reflect additive effects with other processes that are involved at the same time, but have somewhat different distributions.

Specifically, LANs may reflect increased activity of this system when a violation of compositionality is encountered. Such a violation could be manifested both by the *absence* of words or morphemes expected by the preceding context, and by the *presence* of words or morphemes that cannot be combined according to the morphological or syntactic rules of the language. For example, phrase structure violations are realized by the appearance of a word that is not of the category required for a particular position in a sentence, i.e., the absence of a word of the required category. Similarly, in the present study the preceding context (e.g., a sentence beginning with *Yesterday*) leads the parser to expect a past tense-inflected verb, with a compositional morphological structure (i.e., verb + *-ed*) predicted by default. When a regular verb lacking such an inflection is encountered, the expectation is violated, leading to a LAN. Since the parser cannot predict in advance whether the verb will be regular or irregular, the finding that the LAN was elicited only by the regular violations suggests that the expectation of an affix is blocked when an irregular verb (which would have associative linkages to its lexically-stored inflected form) is encountered. In studies in which the regular affix is inappropriately combined with the stem of an irregular, a LAN may be elicited because such a combination is illegal, perhaps because the already-parsed stem leads to the retrieval of the (correct) irregular past-tense form, resulting in the realization of the inappropriateness of the combination. Future studies are needed to test this hypothesis.

The finding that an N400 was elicited only by the lexical semantic condition, but not by irregulars, is also consistent with a dual-system view, at least under the commonly-held assumption that the N400 indexes integration of meaningful (i.e., semantic) information rather than purely lexical processes. The lack of an N400 in response to irregular violations in this study is also consistent with the interpretation that N400s elicited by violations of irregular morphology in previous studies were due to the fact that these stimuli were nonwords created by the addition of an irregular suffix to a regular stem (see above).

In contrast to the differences that were seen in the early time window between irregular inflection on the one hand, and regular inflectional and phrase structure violations on the other, all three conditions elicited later positivities. This finding was expected on the basis of the previous literature, in which late positivity (P600) effects have been reliably found for both morphosyntactic and phrase structure violations. The finding that the late positivities had similar midline-posterior scalp distributions in the regular, irregular, and phrase structure violation conditions here suggests shared neural generators reflecting similar neurocognitive processes, presumably related to “second-pass” controlled aspects of processing these syntactic (inflectional or phrase structure) violations. We suggest that a late positivity was elicited by both regular and irregular inflectional violations in the present study due to the fact that both constituted violations of syntactic tense, which may have led to attempts to reanalyze and repair the tense structure of the sentence. That the timing of the maximum amplitude of the positivity was similar for the two past tense violations, but was somewhat earlier for the phrase structure violation, suggests that the two past tense violations were processed similarly in this time window while phrase structure violations may have been more readily detected and/or repaired.

In sum, consistent with and extending upon previous results, the present data suggest that the early processing of regular past tense forms depends on neurocognitive mechanisms that may more generally underlie rule-governed composition in both morphology and syntax, whereas irregulars seem to be stored in and retrieved from lexical memory. The results also suggest that violations of both types of past tense forms involve a later process which seems to underlie aspects of controlled syntactic processing of both morphosyntax and phrase structure. Thus the ERP data support a dual-system model, in particular one in which regular and irregular past tense forms are subserved by at least partially distinct early neurocognitive processes, while both past tense types depend on a later processes that underlies aspects of morphosyntax.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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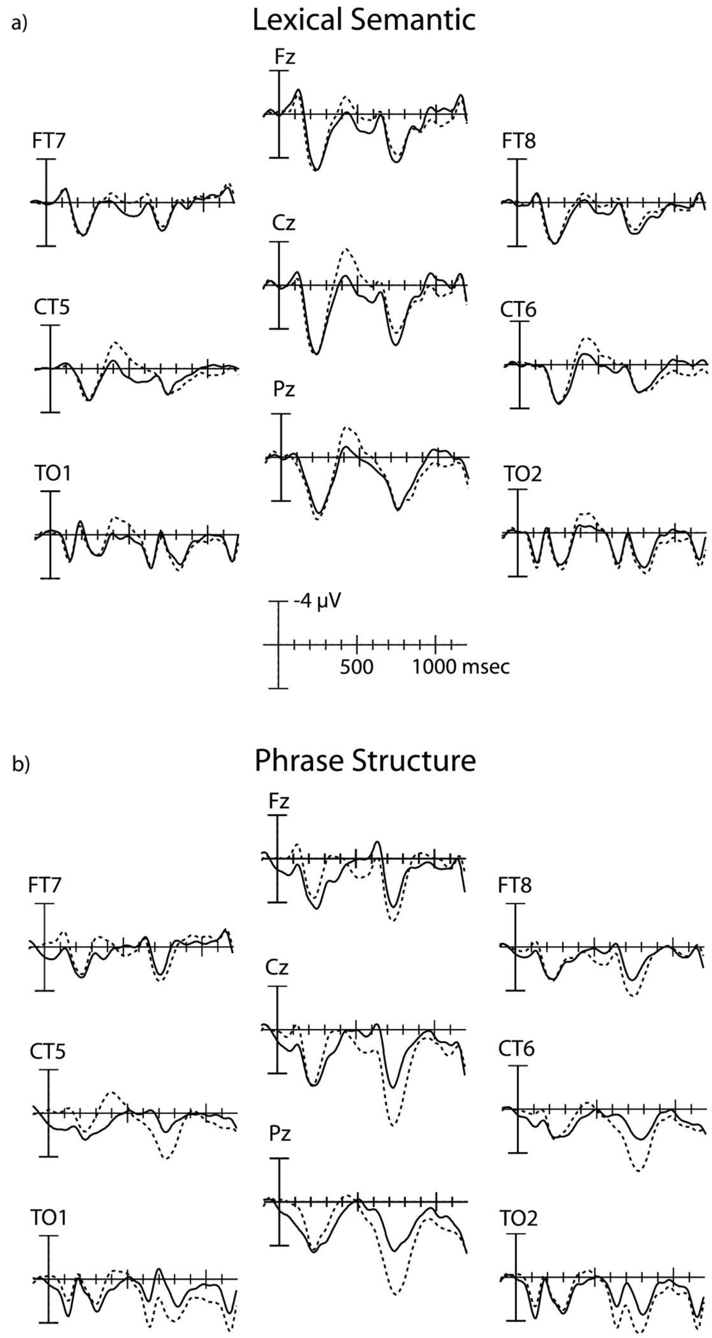
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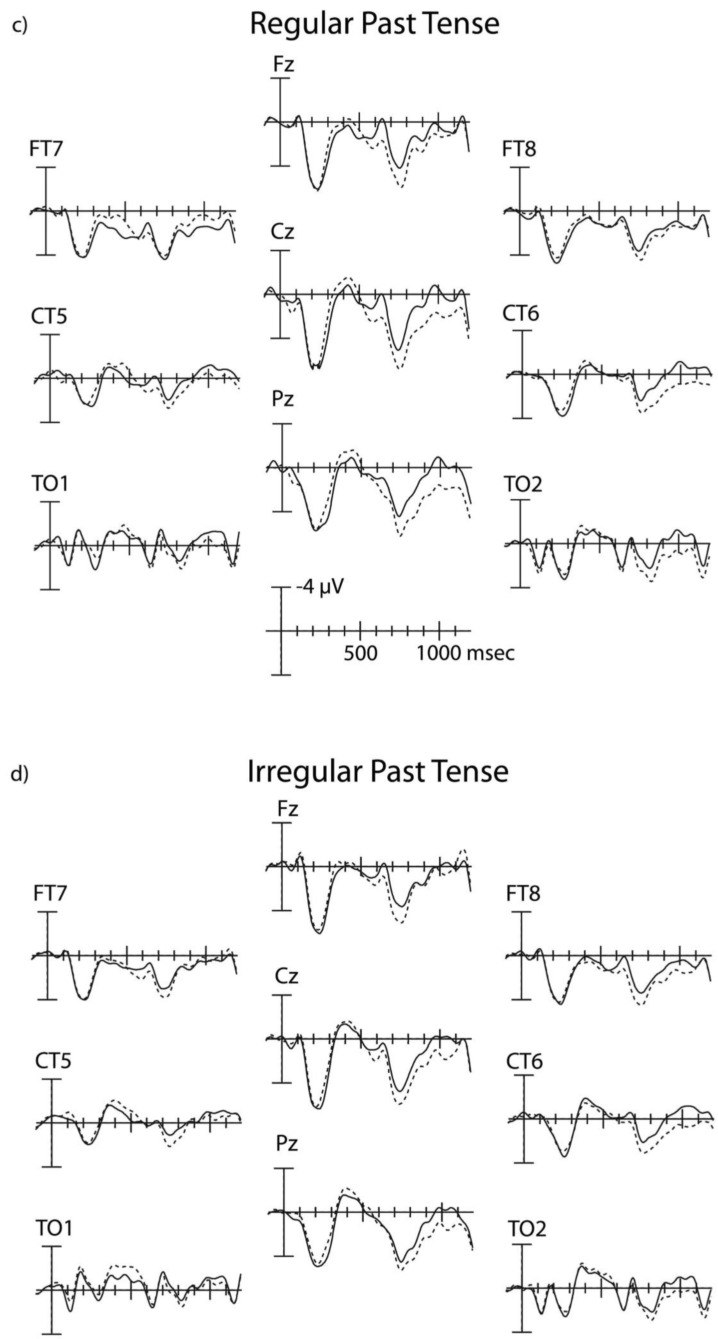

Figure 1.

Grand average ERPs for violation (dashed lines) and control (solid lines) target words in each condition. Waveforms for correct and incorrect target words are superimposed. The ordinate indicates the onset of the target word. Timing is given in milliseconds. Negative voltage is plotted upwards.

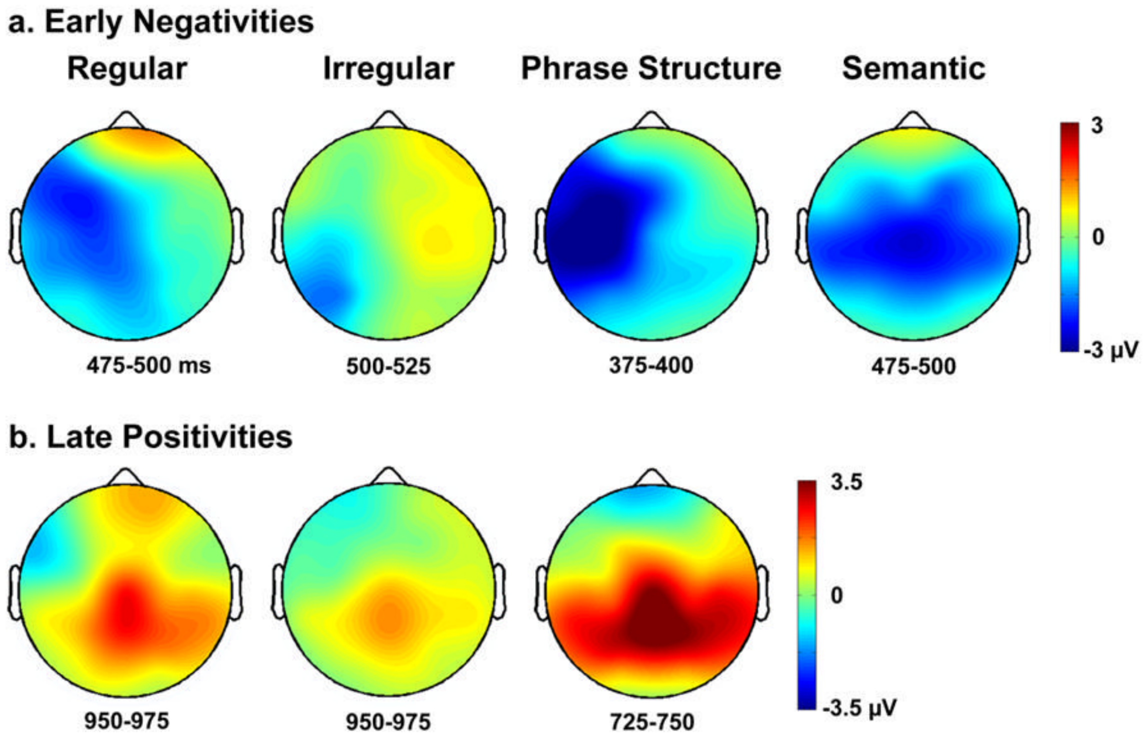

Figure 2.
Scalp topographic maps showing the distribution of the ERP components of interest in the early (a) and late (b) epochs. To capture the peak difference between violation and control words, 50 msec time widows were chosen for each condition centered around the peaks identified on the basis of examination of the waveforms (Figure 1).