Early, equivalent ERP masked priming effects for regular and irregular morphology

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ABSTRACT

Converging evidence from behavioral masked priming (Rastle & Davis, 2008), EEG masked priming (Morris, Frank, Grainger, & Holcomb, 2007) and single word MEG (Zweig & Pylkänen, 2008) experiments has provided robust support for a model of lexical processing which includes an early, automatic, visual word form based stage of morphological parsing that applies to all derivationally affixed words. The mechanisms by which regularly (walked, birds) and irregularly (gave, geese) inflected forms are processed are less well established. We combine the masked priming paradigm with EEG recording to directly compare the ERPs evoked by regularly and irregularly inflected forms. We find equivalent N250 priming effects for both types of morphological complexity, which argues for rapid, form based morphological parsing of all morphologically complex word forms.

1. Introduction

The question of how words like teacher and walked are parsed and recognized has been debated for more than 30 years (Rastle & Davis, 2008; Stockall & Marantz, 2006; Taft & Forster, 1975). On the one hand, these words can easily be parsed into a stem and affix, each of which makes a transparent, predictable contribution to the meaning and grammatical function of the whole word, and each of which is robustly attested in many other forms in the language. These facts motivate models such as that of Taft and Forster (1975); Taft (2004) or Stockall and Marantz (2006), that include an early, form based, affix-stripping mechanism that precedes and feeds into subsequent activation of stored lexical stems. On the other hand, words like teacher are familiar and frequently heard, read and produced, and many words that can be formally parsed into a stem and affix are not so obviously transparent semantically (a folder is not usually understood as ‘a person who folds’). These facts have motivated a range of models without early, form based decomposition, in which complex familiar words are stored whole in the lexicon (Albright & Hayes, 2003; Butterworth, 1983) or recognized via associative networks with no morphological units at all (Rumelhart & McClelland, 1986, chap. 18).

A second, related question is how words like sang or geese, that do not follow the regular morphological patterns of the language, are parsed and stored. Models that do not include decomposition for regular allomorphy also, obviously, do not assume decomposition for irregulars. The same form and meaning similarity based associations that link walk with its relatives walked, walking, and walkable link sing with its relatives sang, singing, singer in these models (Devlin, Jamison, Matthews, & Connerman, 2004; Rumelhart & McClelland, 1988, chap. 18; Seidenberg & McClelland, 1989).

By contrast, models that assume rule based decomposition for regulars are split between those, such as the extremely influential Words & Rules model (Pinker & Prince (1988, chap. II) inter alia) that adopt the whole word storage + similarity associations model for irregulars, and those that extend the rule based approach to generate irregulars as well (Chomsky & Halle, 1968; Halle & Marantz, 1994; Stockall & Marantz, 2006; Yang, 2002). These latter models posit ‘full, across the board, decomposition’ (Stockall & Marantz, 2006), with no categorical differences between regular and irregular allomorphy, or between concatenative (affixal) and non-concatenative morphology. The rules in (1) show how Distributed Morphology (Halle & Marantz, 1994) would account for ‘sold’, ‘sang’ and ‘slept’. In (1), we have the fragment of grammar that generates the three possible allomorphs of the English past tense morpheme. The abstract past tense morpheme \( T_{\text{past}} \) can be realized in any of three ways: \( \theta, /t/, \text{or } /d/ \). The first two options are restricted to a small set of roots, which are listed with the irregular allomorph, while the \( /d/ \) option is freely available and applies to any root that does not appear on one of the memorized lists.

\[
T_{\text{past}} \rightarrow \theta \text{[ifT. SING.SIT.BID...]} \\
\rightarrow /t/ \text{[IF LEAVE.BEND.BUY.TEACH...]} \\
\rightarrow /d/ 
\]

(1)

The rules in (1) are sufficient to account for all regular past tense forms and for all zero-change forms (hit, cut), which simply take...
the null allomorph of the past tense, rather than the default /d/. Forms like sang or sold require additional stem vowel adjustment rules such as the rule in (2-a), which maps the high front vowel /i/ to the low front vowel /æ/ in stems like sing and swim, when those stems occur together with the past tense morpheme.

a. /s/ → /æ/, \[ \text{sing, swim, ring...} \] 

b. /t/ → /æ/, \[ \text{keep, sweep, leap, sleep, dream...} \] 

c. . . .

Thus the irregular past tense form sold is hypothesized to be generated from the verb root sell + the regular /d/ allomorph of the past tense + a morpho-phonological adjustment rule that maps /s/ → /æ/. The irregular past tense song, is generated from /s/ + the null allomorph of the past tense + the rule /s/ → /æ/, and irregular slept from /s/ + the /t/ allomorph of the past tense + the rule /t/ → /æ/.

The models proposed by Yang (2002) and Stockall and Marantz (2006) use slightly different formalisms that account for the variation in the realization of the past tense morpheme and the stem allomorphy across the ~170 irregular roots in slightly different ways, but the critical core claim shared by all these theories is that processing the letter string ‘taught’ involves activating the root \[ \text{teach} \] and that this activation is the result of successfully recognizing the surface [taught] sound (or taught letter string) as the output of a rule that operates over underlying [it] sequences.

The prediction of these models, then, is that the early word form recognition processes must be sensitive not just to the patterns associated with regular allomorphy, but also to those associated with irregular allomorphy. The work of Albright (2002) and Albright and Hayes (2003) on ‘islands of reliability’ in the irregular allomorphy of English and Italian suggests that this claim is not as unlikely as it might otherwise seem. They show that speakers are sensitive to even subtle stochastic regularities in the morphological patterning of their language. For example, although the stem/past tense alternation found in bleed \~ bled, lead \~ led, feed \~ fed, read \~ read, and breed \~ bred is certainly irregular (only a small set of stems participate in the alternation), it is actually highly reliable (by Albright and Hayes’ counts, 6/7 stems ending in eed have past tense allomorphs that rhyme with bled). This high degree of consistency in even irregular allomorphy means the pattern recognition system responsible for initial form based decomposition (discussed in detail below) could plausibly detect possible irregular morphemes as well as regular. Given that ablaat and similar morphologically conditioned stem alternations are widely attested across the world’s languages, it would not be surprising for an early, word form based, morphological parsing mechanism to be capable of detecting this kind of pattern.

The experiment reported here addresses both the general issue of whether regular morphological inflection is rapidly detected by the same early, morpho-orthographic parsing mechanisms that have been argued to operate over derivational affixes, and the more specific question of whether irregular allomorphy is also parsed by these same mechanisms, by combining the behavioral masked priming + lexical decision paradigm with EEG recordings.

1.1. Behavioral masked morphological priming

In the masked priming paradigm, a prime is visually presented for only 30–50 ms and the prime is masked by the prior presentation of a masking stimulus, typically a series of hash marks (###) or random consonant strings (SDFHJJK). The prime is either immediately followed by another mask or by the target which serves as a backward mask. The short prime duration, as well as the presence of the forward (and backward) mask, prevents the subject from consciously perceiving the prime. Moreover, the close temporal proximity of the prime and target allows little time for the prime to be processed in isolation from the target, and thus any effects of the prime on responses to the target are presumed to reflect early automatic lexical processes rather than strategic and/or episodic memory effects (Forster & Davis, 1984). When primes are fully visible to the subject, it is unclear whether the priming effects observed are the result of automatic lexical processes, (e.g. activation of a lexical entry) or the result of an episodic memory of the prime influencing the decision process. Such priming studies are also vulnerable to the use of predictive strategies by subjects if the relationship between prime-target pairs becomes obvious (Feustel, Shiffrin, & Salasoo, 1983; Jacoby, 1983). These concerns can be mitigated with the use of a masked prime (Forster & Davis, 1984). The classic finding using this paradigm is faster responses for target words preceded by identical or similar prime words when compared to primes that are unrelated to the target.

Feldman, O’Connor, and Del Prado Martín (2009) and Rastle and Davis (2008) both provide an overview of the recent literature using this paradigm to investigate morphological complexity. The core finding is that when a masked prime word is related to the target by a possible morpho-orthographic relationship, lexical decision times to the target are significantly faster than when the same target is preceded by an unrelated prime. This result is nicely captured in the title of Rastle, Davis, and New (2004)’s paper: “The broth in my brother’s brothel: Morpho-orthographic segmentation in visual word recognition”. This title derives from the key comparison between a prime target pair like brother ~ broth, in which the prime can plausibly be decomposed into a stem ‘broth’ and a familiar suffix ‘-er’, and a prime target pair like brothel ~ broth, in which the prime cannot be decomposed, because ‘-el’ is not an attested suffix in English. Rastle et al. find that pseudo-complex primes such as brother and adder significantly facilitate lexical decision reaction times to their pseudo-stem targets (broth, add) whereas primes which contain the target as an orthographic substring, but do not contain an existing suffix (brothel, adder) are not associated with any such facilitation.

Starting with the work of Rastle, Davis, Marslen-Wilson, and Tyler (2000), at least 20 experiments using the masked priming paradigm to compare real and pseudo/opaque derivational morphology have been published. The consensus of this literature using masked priming and the behavioral lexical decision task to investigate morphological complexity is strong support for a model in which there is an early, automatic, obligatory, visual word form based stage of morpho-orthographic segmentation in which all possible affixes are stripped from their stems (Rastle & Davis, 2008).

There is debate within this literature about whether this earliest stage of morphological processing is purely word form based (Rastle & Davis, 2008) or may involve lexical-semantic factors (Feldman et al., 2009). Feldman et al. (2009)’s review of the literature finds that across the 18 experiments they survey, genuinely morphologically related primes are, on average, associated with greater facilitation effects than pseudo-related primes. They argue that this means that the semantic overlap between morphological relatives must be playing a role at the earliest stages of processing, and thus that the early segmentation is not purely form based. However, an explanation for differences in prime magnitude can also be found in stem: whole word transition probabilities (Hay, 2001), which are a purely word form based measure. Stem:whole word transition probabilities are calculated as the ratio of the stem frequency to the whole word frequency. For transparently complex words like taxable or teacher, the probability of the whole word given the stem (tax or teach) is fairly low: tax and teach occur as whole words on their own, and in combination with many other derivational and inflectional morphemes. Conversely, for pseudo-complex words like brother, the probability of the whole word given the stem is very high: broth is a low frequency word itself, and this stem occurs in...
no common derived or inflected words. Thus the transitional probability from the (putative) stem to the whole word is an excellent index of the probability that the whole word is morphologically complex. The higher the stem/whole word transition probability, the lower the likelihood that the whole word is inflected or derived from the stem, and vice versa. Lewis, Solomyak, and Marantz (2011); Lewis and Marantz (submitted for publication) (discussed in Section 1.3) show that these transition probabilities are, indeed, an excellent predictor of early neural sensitivity to morphological complexity, and that no appeal to semantic factors is required to account for differences in early processing responses between transparent and opaque morphologically complex word forms.

1.2. Masked morphological priming from irregularly inflected primes

Meunier and Marslen-Wilson (2000) use the masked priming paradigm to examine the representation of regular and irregular verb forms in French. They find that regular and irregular verb forms prime their infinitive forms equally, suggesting that they are both represented in a single system, but this experiment did not include an orthographic overlap condition, thus limiting the conclusions that can be drawn. Other research investigating irregular allomorph priming with the masked priming paradigm (Kieler, Joanisse, & Hare, 2008; Pastizzo & Feldman, 2002) provides additional evidence suggesting that at least some irregulars do prime their stem targets, but the two studies come to conflicting conclusions about exactly which irregulars these are. Pastizzo and Feldman find priming for high overlap irregulars like gave ~ give, but not for low overlap pairs like taught ~ teach, while Kieler et al. find essentially the opposite pattern.

In an effort to resolve these conflicts, Crepaldi, Rastle, Coltheart, and Nickels (2010) compared genuinely related irregular prime–target pairs like sold ~ sell and mice ~ mouse with pseudo-irregular pairs like bold ~ bell and spice ~ spouse. Using the masked priming design, Crepaldi et al. found that irregularly inflected primes significantly facilitated reaction times to their targets, but that there was no facilitation for prime-target pairs where the prime and target were similar to one another in the same way as an existing irregular prime and target, but had no plausible morphological relationship to one another (e.g. bold ~ bell). Crepaldi et al. did not directly compare regulars and irregurals. Their results, and the results of the other studies reporting significant masked priming effects for irregular allomorph primes, suggest that irregular allomorphs are very rapidly analyzed, leading to rapid activation of their stem correlates, and thus facilitation in the masked priming paradigm. However, the lack of a pseudo-irregular priming effect in the Crepaldi et al. experiments raises doubts about whether irregulars are analyzed by the same morpho-orthographic mechanisms as regular allomorphs with overt, segmentable affixes. Crepaldi et al. conclude that irregulars are not segmented morpho-orthographically, and thus that regulars should be associated with greater priming effects than irregurals.

By contrast, theories such as Albright and Hayes (2003), Halle and Marantz (1994) and Stockall and Marantz (2006), make no principled distinction between regular and irregular allomorphy, even at the orthographic form level of representation. As discussed above (Section 1), irregular verbs cluster into what Albright and Hayes (2003) term ‘islands of reliability’. Given that many of the past tense forms that exhibit these sub-regularities are themselves highly frequent, and thus regularly encountered, these patterns are predicted to be available to an early visual linguistic pattern recognition system.

1.3. Neural correlate of early, morpho-orthographic segmentation

Given the robust body of behavioral evidence for early, visual word form based, morphological segmentation for affixed forms, the question naturally arises as to whether the visual word form area/response identified by Cohen et al. (2000) as being the first processing response specifically sensitive to linguistic word form features in a number of languages (Lehtonen et al., 2007; McCandliss, Cohen, & Dehaene, 2003; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2005; Turkiainen, Corneliussen, & Salmelin, 2002) also shows sensitivity to morpho-orthographic features. Zweig and Pyllkänen (2008) addressed this question using a single word reading paradigm (no primes or masks) and a visual lexical decision task. Zweig and Pyllkänen (2008) experiment 1 compared three types of word stimuli: (a) transparently complex suffixed forms like teacher (b) unsegmentable monomorphs such as stretch and (c) forms with an –er ending, but that could not be plausibly segmented such as winter (there is no stem ‘wint’). Experiment 2 made the same comparisons with prefixes: complex: refill vs. unsegmentable: throng vs. no-stem: resume. Zweig and Pyllkänen (2008) used the Tailor coordinates of the Visual Word Form Area as reported in Cohen et al. (2000) to model the MEG activation. In both experiments, the forms that could be segmented into two discrete pieces differed from those that could not: they evoked greater amplitudes from the visual word form area response component peaking approximately 170 ms after the onset of the visually presented word. There were no differences between forms like winter or resume which contain a substring that could be an affix, but no plausible stem, and unsegmentable monomorphs like stretch or throng. Zweig and Pyllkänen (2008) argue that this increased activation for morphologically complex words indexes precisely the early stage of visual word form based morphological segmentation argued for from the behavioral masked morphological priming literature.

Solomyak and Marantz (2010); Lewis et al. (2011) and Lewis and Marantz (submitted for publication), in a series of experiments using distributed source modeling of the MEG signal evoked by single words, have confirmed this finding that activity originating in the fusiform gyrus is differentially sensitive to morphological complexity. In these studies, Marantz and his colleagues find that activity originating in the left fusiform gyrus and peaking between 140 and 190 ms after the onset of a visually presented word (the M170 component) increases as a function of the decomposability of that word, but is not modulated by semantic factors.

Lewis et al. (2011) and Lewis and Marantz (submitted for publication) show that the magnitude of the M170 response is, in fact, highly correlated with the stem:whole word transition probability of a potentially morphologically complex word. Words with low transition probabilities (and thus high probability of being complex) are associated with greater M170 amplitudes than words with higher TPs (lower probability of being complex). This purely word form based measure predicts precisely the difference between teacher and brother reported by Feldman et al. (2009), with no need to appeal to semantic factors.

The behavioral masked priming literature and MEG single word reading literature, then, provide convergent, consistent evidence supporting a model of visual lexical processing in which morphological constituents are very rapidly and automatically detected on the basis of their orthographic form.

Interestingly however, research directly combining the masked morphological priming paradigm with measurements of the evoked neural correlates from EEG recordings, has so far produced a less consistent picture.

Research combining masked repetition priming with EEG has resulted in a clear pattern of evoked ERP components that can be related to a well motivated functional architecture for word recognition (Grainger & Holcomb, 2009; Holcomb & Grainger, 2006, 2007). A series of ERP components, whose amplitudes are modulated by priming, appear to reflect processing that proceeds from visual features to orthographic representations and finally to meaning.
The earliest of these components, the N/P150, is also the most focal, producing priming effects that are visible only at the most anterior and posterior sites primarily in the right hemisphere; positive-going at occipital sites (especially over the right hemisphere) and negative-going at more anterior sites. This effect has been observed across several studies using words (Holcomb & Grainger, 2006), single letters (Petit, Midgley, Holcomb, & Grainger, 2006) and pictures of objects (Eddy, Schmid, & Holcomb, 2006). Evidence that the N/P150 is modulated by such a diverse range of stimuli, including non-linguistic stimuli, suggests that it reflects an early, low level process, possibly one that is involved in mapping visual features onto higher level representations (Holcomb & Grainger, 2006). This component is, then, unlikely to be the ERP analog of the MEG M170/Visual Word Form component, and thus is not expected to show the same sensitivity to morpho-orthographic patterns.

The second component found to be sensitive to linguistic processes operating in the masked priming paradigm is the N250 (Holcomb & Grainger, 2006). The N250 is a negative going wave with an onset around 175 ms, a duration of approximately 150 ms and a peak at around 250 ms. It has a broad scalp distribution with the largest effects over the more frontal sites. It is larger, and peaks earlier, to targets following primes with which they share no letters than to targets that are partial repetitions of their primes, while targets that are partial repetitions of their primes produce larger N250s than full repetitions. (Holcomb & Grainger, 2006, 2007) suggest that the N250 may reflect the processing of sub-letter visual feature representations and sub-word orthographic representations (i.e. letters and letter clusters). In particular, they propose that the amplitude of the N250 may reflect the degree of mismatch between letter and letter-cluster representations that are activated by the prime stimulus, and those representations receiving activation from the target. This component is the likeliest to reflect the early VWFA processing indexed by the MEG M170.

Finally the third component implicated in masked repetition priming is the N400 component (Brown & Hagoort, 1993; Kutas & Hillyard, 1984), starting around 350 ms and ending around 550 ms with a central-posterior scalp distribution that was most negative to targets that were completely unrelated to their primes, least negative to targets that were complete repetitions of their primes and intermediate to targets that partially overlapped their primes. Holcomb and Grainger (2006) suggest that in its early phase it reflects the mapping of lexical form onto meaning, with later N400 effects reflecting integration across semantic representations (see Lau, Phillips, & Poeppel (2008) for an extremely thorough review of the literature on the timing, anatomical generators and functional interpretations of the N400 response).

The masked priming paradigm combined with EEG recording has now been used in four studies investigating morphological priming, with results that are roughly consistent with this three component/three stage model. Lavric, Clapp, and Rastle (2007) (LCR); Morris et al. (2007) (MTGH) and Morris, Grainger, and Holcomb (2008) (MGH) all compared genuine, transparent derivation morphological complexity (Morph: teacher ~ teach) with pseudo complexity (Psuedo: corner ~ corn) and orthographic overlap (Ortho: brother ~ broth) in English. The two Morris et al. studies used the same materials, but while the 2007 study used the more common lexical decision task, the 2008 study used a go/no-go semantic categorization task. Royle, Drury, Bourguignon, and Steinhauer (2010) (RDDBS) compared French inflectional complexity (Morph: cassat ~ casse ‘broke’ ~ ‘broken’) with orthographic overlap (Ortho: cassat ~ casse ‘blackcurrant’ ~ ‘break’) and semantic similarity (Sem: brise ~ case ‘break’ ~ ‘break’) and used the lexical decision task.

These four studies used slightly different variations on the masked priming design (duration of masked prime, presence or absence of backwards mask, SOA between prime and target, number of items, etc.), and focused on slightly different analysis time windows and groupings of electrodes, which lead to inevitable differences in the results, summarized in (Table 1).

This pattern of results is roughly what we expect given the behavioral masked priming, MEG single word and ERP repetition priming studies: at the earliest latencies (100–200 ms) we see sensitivity to visual feature overlap between prime and target, but not to semantics or to whether the overlap is morphological or not; between 200 and 300 ms, we see differentiation between morpho-orthographic overlap and pure form overlap (in some studies); and between 300 and 500 ms there is further dissociation between genuine and pseudo morphological overlap.

But given the variability in each of these three time windows across very similar studies, it’s clear that more research is required to establish the reliability, and therefore interpretability, of this pattern.

Our research, then, was motivated by three goals: first, to directly compare regular and irregular morphological inflection processing in English using the masked priming + lexical decision paradigm, which is so well established as a tool for investigating the early stages of morphological processing; second, to use EEG to track the time course of this processing and determine when differences between inflection types emerge; and third, to help resolve the inconsistencies in the ERP masked morphological priming literature by adding data from English inflectional allomorphy.

If regular inflectional morphology is detected on the basis of the same morpho-orthographic segmentation processes as affixal derivational morphology, we should see robust facilitation effects for regular past tense priming in the N250 time window. If irregular inflectional allomorphy is also detected and parsed on the basis of morpho-orthographic features, then we should see similarly robust priming effects for irregular past tense to stem priming in the same early time window. And if the N250 response is genuinely sensitive to these processes of morpho-orthographic parsing, we should see significant differences between morphological and orthographic priming conditions (Lavric et al., 2007; Morris et al., 2008).

2. Materials and methods

2.1. Participants

Twenty participants from the Tufts University community (15 female, aged 18–25, mean = 21.3) were paid for their participation and gave informed consent to participate. The data from three subjects, one male and two females, were excluded from analysis, one because of failure to complete the study, one for reporting a diagnosis of dyslexia, and one for excessive eye movement artifacts. Participants were right-handed native English speakers with normal or corrected-to-normal vision, with no reported linguistic or neurological impairment.

2.2. Stimuli

The stimuli were 120 regular and 120 irregular past tense and stem verb forms, chosen from the CELEX English database. These 120 irregular verbs almost exhaust the set of English irregular verb roots (there are about 170 such roots in total, but 26 of these are zero-change (hit, cut), and a further 18 are sufficiently uncommon as to have lexical decision accuracy scores below 75% in the English Lexicon Project Database (shrive-shrove, rend-rent, clothe-clad, etc)). Thus unlike the studies by Crepaldi et al. (2010), Kieler et al. (2008) and Pastizzo and Feldman (2002), our experiment offers a compre-
hensive investigation of English past tense irregular allomorphy processing.

Each stem form appeared in four conditions: (a) primed by itself (ID), (b) primed by its past tense form (PT), (c) primed by an Orthographic Control (OC) that differed in only one letter, and (d) primed by an unrelated item with which it shared no letters (UN).

We matched regular and irregular verb stems on length and log surface frequency (CELEX database, Baayen, Piepenbrock, & Van Rijn (1993)) and past tense primes on log surface frequency as seen in Table 2. An ANOVA on log surface frequency, with verb type (regular, irregular) and Verb Tense (past, stem) as factors revealed no main effects of either verb type ($F(1,238) = 2.005, p = .158$) or verb tense ($F(1,238) = 1.086, p = .298$) and no significant interaction ($F(1,238) = 2.20, p = .139$). A similar ANOVA on length revealed a main effect of both Prime Type ($F(1,238) = 545.03, p < .001$) and verb tense ($F(1,238) = 52.512, p < .001$) as well as a significant interaction ($F(1,238) = 88.408, p < .001$), due to the fact that regular past tense primes were longer than all other conditions.

Across the two verb types we also matched the orthographic control and unrelated prime conditions on length (OC and UN: $F(1,238) = 3.497, p = .063$) and log surface frequency (OC: $F(1,238) = 427, p = .514$; UN: $F(1,238) = 52.8, p = .468$).

From these stimuli 4 lists were constructed, each containing 30 items per condition (240/list). No item appeared in more than one condition in any given list. In a testing session each participant was given 2 of the four lists, separated by a short break, and the order of presentation of the two lists was counterbalanced across participants. Thus, each participant saw each target verb in two of the four possible conditions. In total, each participant saw 480 experimental items, 60 in each of the 4 conditions. In addition to the experimental items, each list contained 480 pseudoword filler items created by changing one or two letters of an existing word (nonwords were phonotactically well formed). As with the experimental items, 60 nonword targets were preceded by identity primes, 60 by unrelated primes that shared no letters with the target, 60 by primes that differed in only one letter, 30 by primes consisting of the target followed by the suffix ‘-ed’ (analogous to regular past tense primes), and 30 by primes that differed from their targets due to a vowel change (analogous to irregular past tense primes).

2.3. Procedure

Participants were seated in a comfortable chair in a darkened room at a distance of 140 cm from the computer monitor. Each testing session began with a short practice block, followed by the experimental block. Participants were told that they would see a list of words and nonwords on the computer monitor and were instructed to respond as quickly and as accurately as possible indicating whether the stimulus was a word (dominant hand) or a nonword (non-dominant hand) by pressing one of two response keys. Visual stimuli were presented on a 19-inch monitor, with a diagonal viewable screen size of 18 inches, and a width of approximately 14.5 in; set to a refresh rate of 100 Hz (which allows 10 ms resolution of stimulus control). Stimuli were displayed at high contrast as white letters (Verdana font) on a black background. Each letter was 40 pixels tall by 20 pixels wide. The screen resolution was 800 by 600 pixels, and the visual angle subtended by stimuli ranged from 1.1° to 3.25°. Primes were presented in lower case letters for 50 ms, preceded by a 500 ms forward mask and a 20 ms backward mask composed of hash marks (#######). The target was then presented in upper case letters for 300 ms followed by a 1200 ms ITI.

2.3.1. Recording procedure

The electroencephalogram (EEG) was recorded from 29 active tin electrodes held in place on the scalp by an elastic cap (Electro-Cap International). In addition to the 29 scalp sites, additional electrodes were attached to below the left eye (to monitor for vertical eye movement/blinks), to the right of the right eye (to monitor for horizontal eye movements), over the left mastoid bone (reference) and over the right mastoid bone (recorded respectively to monitor for differential mastoid activity). All EEG electrode impedances were maintained below 5 kΩ. The EEG was amplified by an SA Bioamplifier with a bandpass of 0.01 and 40 Hz and the EEG was continuously sampled at a rate of 200 Hz throughout the experiment.

2.3.2. Data analysis

ERPs time locked to the onset of target words in each category were formed off-line from trials free of excessive artefact or response error. Trials characterized by EOG artefact in excess of 70 μV were rejected, resulting in 8.25% of trials being discarded. This percentage did not vary significantly across experimental conditions ($p > .09$). In addition, any trials with incorrect behavioral responses were also excluded from the averages. All trials were

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**Table 1**

Significant effects of masked priming manipulations on ERPs as reported in previous literature.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>MTCH2007</th>
<th>LCR2007</th>
<th>MGH2008</th>
<th>RDGS2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>100–200 (ms)</td>
<td>M.P.O</td>
<td>No analysis for this epoch</td>
<td>M.P.O</td>
<td>M.S.O</td>
</tr>
<tr>
<td>200–300 (ms)</td>
<td>Reduced negativities for M and P across all electrodes, significant effects for O only at frontal electrodes</td>
<td>M.P.O</td>
<td>Increased positivities, all conditions</td>
<td>Reduced negativities for M and P across all electrodes, for P at midline electrodes, no significant effects for O</td>
</tr>
<tr>
<td>300–500 (ms)</td>
<td>Decreased negativities for M, not P or O</td>
<td>M.P.O</td>
<td>Increased positivities at frontal sites and negativities at occipital sites, all conditions</td>
<td>Reduced negativities for M and O, not for S</td>
</tr>
</tbody>
</table>

M = Morphologically Related, P = Pseudo-morphologically Related, O = Orthographically Related, S = Semantically Related. Analyses do not include midline electrodes for any time window.

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**Table 2**

Mean (SE) length and log lexical frequencies for the three prime types for the two verb conditions.

<table>
<thead>
<tr>
<th>Prime Type</th>
<th>Length</th>
<th>Log frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>Irregular</td>
<td>Regular</td>
</tr>
<tr>
<td>Mean (SE)</td>
<td>Mean (SE)</td>
<td>Mean (SE)</td>
</tr>
<tr>
<td>Verb stem*</td>
<td>4.27 (0.06)</td>
<td>4.44 (0.07)</td>
</tr>
<tr>
<td>Past tense</td>
<td>6.08 (0.07)</td>
<td>5.43 (0.08)</td>
</tr>
<tr>
<td>Ortho control</td>
<td>4.27 (0.06)</td>
<td>4.44 (0.07)</td>
</tr>
<tr>
<td>Unrelated</td>
<td>4.27 (0.06)</td>
<td>4.44 (0.07)</td>
</tr>
</tbody>
</table>

*M = Morphologically Related, P = Pseudo-morphologically Related, O = Orthographically Related, S = Semantically Related.

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baselined to the average of activity in the 100 ms pre-target period and were low-pass filtered at 15 Hz. We calculated the mean voltage in the 100–200, 200–300 ms and 300–500 ms time windows relative to the 100 ms pre-target baseline. The calculations in the 100–200 ms epoch were based on a different set of electrodes than for the other epochs as explained below. These time epochs were chosen because they correspond to peaks in the waveforms elicited by the stimuli that were identified by visual inspection and also to the latency ranges that have been found for the N/P150, the N250 and the N400 (Holcomb and Grainger, 2009).

We calculated difference scores by subtracting the latency or mean amplitude for each of the three types of related trials (identity, past tense, and orthographic control) from those for the unrelated trials.

The univariate approach to repeated measures ANOVA requires the assumption of sphericity. One form of sphericity is compound symmetry, which requires that all variances of the repeated measures are equal, and that all correlations between the pairs of repeated measurements are equal (O’Brien & Kaiser, 1985). When this assumption is violated, as is frequently the case with ERP data sets, then various adjustments are introduced to compensate for the violations (e.g. Greenhouse & Geisser, 1959; Huynh & Feldt, 1970; techniques still widely used). However, the contrasts involved in testing repeated measures effects do not need to be independent of each other if we use multivariate criteria to simultaneously test the statistical significance of the two or more repeated measures contrasts, hence the MANOVA approach to repeated measures ANOVA has gained popularity in recent years (Groh-Bordin, Zimmer, & Ecker, 2006; Maurer, Blau, vonChova, & McCandliss, 2010; Pizzagalli, Regard, & Lehmann, 1999). In our analyses, we follow the recommendations of O’Brien and Kaiser (1985) and report multivariate test statistics.

All MANOVAs were run using the general linear model approach in SPSS, and subjects were a random factor in all analyses. Fixed factors were Verb Type, Prime Type, Anteriority and Laterality, and all factors were crossed in the model. The Verb Type factor contrasted mean ERP amplitude difference scores for the regular and irregular verbs, while the Prime Type factor contrasted mean ERP amplitude difference scores in the identity, past tense and orthographic control conditions. To analyze the scalp distribution of the ERP effects, we included two factors, Anteriority and Laterality. The Anteriority factor represented the anterior–posterior distribution of electrodes locations from the back to the front of the head, while the Laterality factor represented the left–right distribution and included three levels contrasting electrode locations at left hemisphere, midline and right hemisphere locations.

We report any significant main effects of the experimental factors verb type and prime type and any interaction of the topographical factors anteriority and laterality with the experimental factors. We analyzed the mean amplitude difference scores by selecting 9 representative sites distributed across the scalp (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) [see Fig. 2].

The N/P150 was analyzed with a specific set of six occipital and frontal electrodes (O1,Oz,O2, FP1, FpZ, Fp2), selected because previous masked priming ERP studies have indicated that N/P150 priming effects are largely restricted to frontal pole and occipital sites (Chauncey, Holcomb, & Grainger, 2008; Morris et al., 2008). For these data, we again used a repeated-measures MANOVA with four within-subjects factors (verb type, prime type, anteriority and laterality), but for this data set, the Anteriority factor comprised two, as opposed to three levels.

Voltage amplitudes vary considerably over the topography of the head, but in the absence of interactions with the experimentally manipulated variables, these differences mean little, so we report only results concerning the main effects of the experimentally manipulated factors, and the interaction of these factors with the topographic factors anteriority and laterality.

We analyzed reaction times and accuracy rates with a 2 × 3 repeated measures ANOVA with verb type (regular, irregular), and prime type (identity, past tense, orthographic control) as factors. As with the electrophysiological data, difference scores were computed by subtracting the reaction times or error rates for each of the three types of related trials (identity, past tense and orthographic control) from those for the unrelated trials. Any responses that were below 200 ms or above 1500 ms were excluded from the analysis.

The z level was set at 0.05. Planned comparisons for all analyses were computed to investigate any effects involving more than two conditions. Because we were interested primarily in the differences between prime types, to investigate the main effect of Prime Type or any interactions involving this factor, we compared identity to past tense primes, identity to orthographic control primes and past tense to orthographic control primes, producing three planned comparisons. To correct for multiple comparison, we performed Bonferroni corrections by multiplying each p-value by the number of comparisons made. For all comparisons, we report the mean difference, the standard error, and the corrected p-values. Corrected p-values that meet the z-threshold are marked with ∆.

3. Results

3.1. Behavioral results

Analyses of the reaction time data (see Table 3) yielded a significant effect of Prime Type (F(2,18) = 89.4, p < .001*) as well as a Prime Type by Verb Type interaction (F(2,18) = 15.9, p < .001*). There was no main effect of verb type. Inspection of the mean difference scores for the main effect of prime type showed that identity primes elicited significantly greater priming effects than past tense primes (MID = 13.6(2.1), t = 6.38, p < .001**). In turn, the priming effect for past tense primes was greater than for orthographic control primes (MPT = OC = 35.0(4.4), t = 7.95, p < .001**). The verb type by prime type interaction arose because for regular verbs, past tense primes produced greater priming effects than did orthographic control primes (MPT = OC = 49.8(6.3), t = 7.89, p < .001**) but did not differ from identity primes (MPT = ID = 1.0(3.2), t = 0.31, p = 1.0). In contrast, for irregular verbs, past tense primes were less effective than identity primes (MPT = ID = 26.2(4.1), t = 4.66, p < .001**), but produced greater effects than Orthographic Control primes (MPT = OC = 20.1(4.3), t = 9.11, p < .001**).

Analysis of the accuracy scores (Table 4) revealed a significant main effect of prime type (F(2,18) = 8.0, p < .003*) but no effect of verb type and no prime type by verb type interaction (all ps > .1). Planned comparisons indicated that responses to targets preceded by their stems and to those preceded by past tense forms did not differ (MID – PT = 1.04(0.6), t = 1.71, p = .3), but orthographic control primes were significantly less effective than both identity primes (MID – OC = 4.1(1.0), t = 3.99, p = .002*) and past tense primes (MPT – OC = 3.0(0.8), t = 3.76, p = .004*).

3.2. ERP results

Fig. 1 plots the mean sensor activation for regular and irregular verb targets preceded by identity, unrelated, and past tense primes over all sensors. In the epoch from 0–800 ms after the onset of the target we observed an initial small negative-going potential (N1) peaking between 40 and 70 ms immediately followed by a larger positivity peaking between 140 and 180 ms. These early potentials are likely to reflect sensory processing related to processing the mask, prime and target stimuli. Following these early potentials,
we observed a series of two negative deflections, the first peaking around 250 ms post-target (N250) and the second at around 400 ms post target (N400). Both were maximal at centro-parietal sites.

The two negativities (N250 and N400) were followed by a large positive deflection peaking around 500 ms (which we call the late positive component, or LPC). A number of studies suggest that this late positive component (LPC) of the event related potential can be viewed as an index of stimulus evaluation and comparison processes (Kutas, McCarthy, & Donchin, 1977; McCarthy, 1981). In a 'same/different' decision paradigm as well as a semantic categorization paradigm, Chabot, York, and Waugh (1984) found high correlations between mean response latency and the latency value where the LPC reached its maximum value at the electrode positions monitored (Pz, C2, C3) (midway between C3 and P3) and C4' (midway between C4 and P4). Thus we decided to conduct post hoc tests to investigate this component.

Fig. 2 plots the difference waves, computed by subtracting the mean voltage for each of the three types of related trials (past tense, identity and orthographic control) from those for the unrelated trials.

Table 3

<table>
<thead>
<tr>
<th>Prim/Type</th>
<th>Regular</th>
<th>Irregular</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SE)</td>
<td>Diff. (SE)</td>
</tr>
<tr>
<td>Unrelated</td>
<td>533.20 (12.23)</td>
<td>32.09 (3.74)</td>
</tr>
<tr>
<td>Past tense</td>
<td>501.11 (12.84)</td>
<td>33.09 (4.23)</td>
</tr>
<tr>
<td>Identity</td>
<td>500.11 (13.11)</td>
<td>17.76 (5.38)</td>
</tr>
<tr>
<td>Orthographic control</td>
<td>550.96 (15.47)</td>
<td>–17.76 (5.38)</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Prim/Type</th>
<th>Regular</th>
<th>Irregular</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SE)</td>
<td>Diff. (SE)</td>
</tr>
<tr>
<td>Unrelated</td>
<td>5.50 (1.90)</td>
<td>6.33 (1.35)</td>
</tr>
<tr>
<td>Past tense</td>
<td>3.92 (1.19)</td>
<td>1.58 (0.98)</td>
</tr>
<tr>
<td>Identity</td>
<td>3.58 (0.93)</td>
<td>1.92 (1.20)</td>
</tr>
<tr>
<td>Orthographic control</td>
<td>8.08 (1.66)</td>
<td>–2.58 (1.12)</td>
</tr>
</tbody>
</table>

3.2.2. 200–300 ms epoch

Analyses of the mean amplitude data in this time window yielded a significant effect of prime type (F(2,18) = 18.4, p < .001) as well as a significant prime type by laterality interaction (F(4,16) = 4.1, p = 0.17). There was no main effect of verb type, nor did verb type participate in any significant interactions (all ps > 0.1).

Inspection of the mean amplitude difference for the main effect of prime type (see Table 5) showed that while targets in both the past tense and identity conditions elicited N250 priming effects, those in the orthographic control condition showed no significant priming. Planned comparisons confirmed these findings; the mean amplitude difference for targets in the identity and past tense conditions did not differ (MPT – ID = 0.3 (0.3), t = 1.16, p = 0.25), but the mean amplitude difference for targets in the orthographic control condition was significantly more positive (a smaller N250 priming effect) than for those in the identity (MOC – ID = 1.1 (0.2), t = 4.77, p < .001) and past tense conditions (MOC – PT = 0.8 (0.2), t = 4.78, p = .001). Visual inspection of the voltage maps revealed that the Prime Type by Laterality interaction was probably due to the fact that the effect appeared greatest at midline sites.

3.2.3. 300–500 ms epoch

Analyses of the mean amplitude data in this time window yielded a significant effect of prime type (F(2,18) = 16.6, p < .001) as well as a significant prime type by anteriority interaction (F(4,16) = 3.9, p = .021). There was no main effect of Verb Type, nor did Verb Type participate in any significant interactions (all ps > 0.1).

Inspection of the mean amplitude differences (Table 6) for the main effect of prime type revealed that prime-target pairs in both the past tense and identity conditions elicited large N400 priming effects, i.e. more negative responses to unrelated than to related pairs. In contrast, there was no significant priming effect for prime-target pairs in the orthographic control condition.

Planned comparisons confirmed these findings, showing that mean amplitude differences for items in the identity and past tense conditions did not differ (MID – PT = 0.4 (0.3), t = 1.16, p = 1.0), but that the difference for items in the orthographic control condition was significantly more positive than for those in the identity (MOC – ID = 1.2 (0.3), t = 3.97, p = .002) and past tense conditions (MOC – PT = 1.25 (0.2), t = 5.84, p < .001).

Visual inspection of the voltage maps, and pairwise comparisons (Table 7), revealed that the prime type by anteriority interaction was due to the centro-parietal distribution of the effect, typical of the N400: at centro-parietal sites the N400 priming effect for prime-target pairs in the identity and past tense conditions was greater than for pairs in the orthographic control condition. However at frontal sites, these differences between conditions were not as great.

3.2.4. Late Positivity (LPC)

In the response time and accuracy measures, regular past tense and identity primes evoked equivalent priming effects but
Fig. 1. Grand average difference waveforms at 15 scalp electrode sites for regular and irregular verbs preceded by unrelated (black), past tense (red) and identity (blue) primes. Target onset is marked by the vertical calibrating bar, and each tick mark on the x-axis represents 100 ms. Negative voltages are plotted upward.
irregular past tense primes, although they produced greater effects than orthographic control primes, were less effective primes than identity primes.

In contrast, the electrophysiological data showed that for both regular and irregular verbs, past tense and identity primes were equally effective in reducing the amplitude of the N250 and N400 components. Visual inspection of our data suggested that the peak latency of the late positive component (LPC) might correlate with our behavioral data. Thus we decided to conduct a post hoc analysis of peak latency difference scores in the 300–700 ms interval post stimulus onset at electrode site Pz where the amplitude of the LPC was maximal, to see if this hypothesis was supported. As with the amplitude data, difference scores, i.e. priming effects, were computed by subtracting the peak latency for each of the three types of related trials (identity, past tense and orthographic control) from that for the unrelated trials.

We conducted a 2 × 3 repeated measures MANOVA with verb type (regular, irregular), and prime type (identity, past tense, orthographic control) as factors. We found a significant effect of prime type \( F(2,18) = 48.6, p < .001 \) as well as a significant prime type by verb type interaction \( F(2,18) = 4.13, p = .03 \).

Planned comparisons conducted to examine the main effect of prime type showed that orthographic control primes elicited smaller priming effects (longer latencies) than both past tense

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**Fig. 2.** Grand average difference waveforms at 9 scalp electrode sites for regular (Panel A) and irregular (Panel B) verbs. The difference waveforms were computed by subtracting the amplitude for each of the three types of related trials (past tense (dashed line), identity (dotted/dashed line) and orthographic control (solid line)) from those for the unrelated trials, thus larger amplitude difference waves reflect a larger difference between Related and unrelated trials. Negative voltages are plotted upward. Where amplitudes for both the Related and unrelated trials have the same sign (+) and priming is associated with a decrease in amplitude, the resulting difference waves share this sign. Target onset is marked by the vertical calibrating bar, and each tick mark on the x-axis represents 100 ms. To the right of each panel is shown an enlarged view of electrode site CZ to illustrate in greater detail the N250, N400 and LPC. At the center of the figure we show the electrode montage. The nine sites used for the MANOVA are highlighted.
Fig. 3. Voltage maps reflecting the subtraction of the related (identity, past tense, orthographic control) conditions from the unrelated conditions at 150 ms, 250 ms and 400 ms post-target for regular (Panel A) and irregular (Panel B) verbs.

**Table 5**
Mean amplitude differences (μV) for Past tense, identity and orthographic control primes in the N250 time window (200–300 ms). Amplitude differences were calculated by subtracting the mean voltage for each of the three types of related trials (past tense, identity and orthographic control) from those for the unrelated trials. A negative score reflects a decrease in negativity for the related compared to unrelated trials.

<table>
<thead>
<tr>
<th>Verb type</th>
<th>Prime type</th>
<th>Mean (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>Past tense</td>
<td>-0.45 (0.30)</td>
</tr>
<tr>
<td></td>
<td>Identity</td>
<td>-0.90 (0.43)</td>
</tr>
<tr>
<td></td>
<td>Orthographic control</td>
<td>0.28 (0.35)</td>
</tr>
<tr>
<td>Irregular</td>
<td>Past tense</td>
<td>-0.74 (0.22)</td>
</tr>
<tr>
<td></td>
<td>Identity</td>
<td>-0.90 (0.28)</td>
</tr>
<tr>
<td></td>
<td>Orthographic control</td>
<td>0.14 (0.26)</td>
</tr>
</tbody>
</table>

**Table 6**
Mean amplitude differences (μV) for past tense, identity & orthographic control primes in the N400 time window (300–500 ms). Amplitude differences were calculated as for Table 5. A negative score reflects a decrease in negativity for the related compared to unrelated trials.

<table>
<thead>
<tr>
<th>Verb type</th>
<th>Prime type</th>
<th>Mean (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular</td>
<td>Past tense</td>
<td>-0.35 (0.27)</td>
</tr>
<tr>
<td></td>
<td>Identity</td>
<td>-0.52 (0.34)</td>
</tr>
<tr>
<td></td>
<td>Orthographic control</td>
<td>0.86 (0.25)</td>
</tr>
<tr>
<td>Irregular</td>
<td>Past tense</td>
<td>-0.73 (0.30)</td>
</tr>
<tr>
<td></td>
<td>Identity</td>
<td>-0.47 (0.31)</td>
</tr>
<tr>
<td></td>
<td>Orthographic control</td>
<td>0.55 (0.24)</td>
</tr>
</tbody>
</table>

**Table 7**
Mean amplitude differences for all pairwise comparisons of Past Tense (PT), Identity (ID) & Orthographic Control (OC) primes in the N400 time window. A negative score reflects a decrease in negativity for the related compared to unrelated trials.

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>Comparison</th>
<th>Mean diff. (SE)</th>
<th>t-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>PT – ID</td>
<td>-0.080 (0.32)</td>
<td>0.25</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>PT – OC</td>
<td>-0.903 (0.23)</td>
<td>3.98</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>ID – OC</td>
<td>-0.820 (0.34)</td>
<td>2.42</td>
<td>0.08</td>
</tr>
<tr>
<td>Central</td>
<td>PT – ID</td>
<td>-0.100 (0.27)</td>
<td>0.36</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>PT – OC</td>
<td>-1.306 (0.24)</td>
<td>5.53</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>ID – OC</td>
<td>-1.211 (0.32)</td>
<td>3.81</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Parietal</td>
<td>PT – ID</td>
<td>0.050 (0.25)</td>
<td>0.18</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>PT – OC</td>
<td>-1.533 (0.22)</td>
<td>7.04</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>ID – OC</td>
<td>-1.577 (0.30)</td>
<td>5.24</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

(MPT – OC = 53.1 (8.9), t = 5.95, p < .001) and identity primes (MID – OC = 68.9 (6.8), t = 10.13, p < .001), but that past tense and identity primed conditions did not differ from each other in latency (MID – PT = 15.75 (7.3), t = 2.16, p = .13) (see Table 8).

The verb type by prime type interaction arose because, for regular verbs, past tense primes produced greater effects (shorter latencies) than did orthographic control primes (MPT – OC = 61.25 (13.5), t = 4.54, p = .001) but did not differ from identity primes (MPT – ID = 1.25 (8.8), t = 0.14, p = 1.0). In contrast, for irregular verbs, past tense primes were less effective than identity primes (MPT – ID = -32.75 (9.8), t = 3.35, p = .01). But produced greater effects (shorter latencies) than orthographic control primes (MPT – OC = 45.0 (16.6), t = 2.71, p = .04). This pattern was similar to that found in the reaction time data.

**4. Discussion**

Our behavioral data were similar to those of previous overt priming studies that have found full priming for regular verbs and reduced priming for irregulars (Marslen-Wilson, Hare, & Older, 1993; Stanners, Neiser, Hermon, & Hall, 1979; Sonnenstuhl, Eisenbeiss, & Clahsen, 1999; Stockall & Marantz, 2006), and fit the pattern predicted by Crepaldi et al. (2010). Both regular and irregular past tense primes significantly facilitated lexical decision times to their stem targets as compared both to unrelated and to orthographically similar primes, but the magnitude of the effect was greater by 18 ms for the regular than the irregular past tense primes. Moreover, the priming effect for the regular verbs was equivalent to the priming effect for identity primes, while irregular past tense forms evoked less facilitation than identity primes did.

The ERP data revealed a different pattern. In the earliest measure, the N1/P150, we found evidence of a main effect of priming for all related vs. unrelated conditions. There was a reduction in

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The fact that we get this body of results really reflects general morpho-orthographic analysis mechanisms sensitive to sub-regularities (Albright & Hayes, 2003). However, it is worth noting that although irregular past tense priming is not associated with significantly different effects than regular Past Tense priming or identity priming in these early epochs, numerically the impact of the related prime is different for these three conditions, and different in the two early time windows. The magnitude of the N250 priming effect is greatest for the identity priming condition, and weakest for the regular verb priming condition, with the irregular verb priming effect lying almost exactly between the two. For the N400 response, however, irregular past tense priming is associated with the largest effect, regular past tense priming with the smallest effect, and identity priming in the middle. Given that these are mere numerical trends, and not predicted by either the Crepaldi et al. (2010) model or by the Stockall and Marantz (2006) model, we resist the temptation to speculate about their possible interpretation. Further research, perhaps using techniques like the correlational analyses of Solomyak and Marantz (2010) is clearly required.

What we can conclude from our results is that a mere 50 ms of exposure to ‘sold’ is sufficient to affect the early, visual word form based processing of ‘sell’ just as strongly as 50 ms of exposure to ‘walked’ facilitates processing of ‘walk’ (or even as strongly as 50 ms of exposure to a word affects reactivation of that same word in the identity priming condition), despite the lack of an orthographically transparent morphological relationship between the two forms in the sold – self cases. For this to be possible, the morphological relationship between ‘sold’ and ‘sell’ must be accessible to early stages of form based, pre-semantic processing — with only 50 ms of prime exposure and 20 ms SOA between prime and target, there is no time for ‘sold’ to activate ‘sell’ on the basis of the kinds of lexical semantic similarity associations posited in the Word and Rules (Pinker & Prince, 1988, chap. II) model.

This result has clear consequences for our models of the mental lexicon. The combined results of Crepaldi et al. (2010), Kielar et al. (2008), Pastizzo and Feldman (2002), and Meunier and Marslen-Wilson (2000) and the data reported above (together with the substantial masked priming and MEG single word reading evidence for regular decomposition) clearly favor a model in which all potentially morphologically complex letter strings are very rapidly parsed into their constituent morphemes, even when that process of parsing does not involve simply stripping off linearly adjacent affixes.

Given Crepaldi et al. (2010)’s failure to find pseudo-irregular priming effects (‘bold’ did not prime ‘bell’), but our finding of robust irregular allomorph priming effects in the N250 time window associated with visual word form processing (Holcomb & Grainger, 2006), it is clear that further research is required to pin down the exact mechanisms involved in word form based parsing of irregular allomorph. Kielar et al. (2008) found that irregulars ending in ‘-t’ or ‘-d’ evoked greater reaction time priming responses than irregulars without any overt exponent of the regular past tense morpheme—exactly what we would expect given morpho-orthographic analysis mechanisms sensitive to sub-regularities (Albright & Hayes, 2003).

If we have now established that such a highly irregular set of forms as the English irregular past tense verbs are rapidly and reliably parsed as morphologically complex, then this early form based parsing mechanism is hypothesized to be very general indeed. Other ‘irregular’ morphological phenomena, including Semantic templatic morphology (McCarthy, 1981), process morphology such as reduplication (Marantz, 1982), productive ablaut (Anderson, 1985), and polysynthesis (Baker, 1996) are all predicted to be processed by similar mechanisms (modulo variations in orthographic systems). To the extent that the processing of these phenomena have been investigated using paradigms that allow

Table 9
Summary of differences between related and unrelated trials. ID and OC means are averaged across regular and irregular verb target conditions.

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>ID (µV)</th>
<th>Reg (µV)</th>
<th>Irreg (µV)</th>
<th>OC (µV)</th>
<th>LPC (ms)</th>
<th>N250 (ms)</th>
<th>N400 (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.90</td>
<td>-0.45</td>
<td>-0.74</td>
<td>0.21</td>
<td>+63.5</td>
<td>+36.3</td>
<td>+0.71</td>
</tr>
<tr>
<td>N250</td>
<td>-0.49</td>
<td>-0.35</td>
<td>-0.73</td>
<td>-0.71</td>
<td>-32.1</td>
<td>-13.3</td>
<td>-5.4</td>
</tr>
<tr>
<td>N400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 The fact that the single word reading MEG studies which use cortical source-space models to determine regions of interest find effects 50–100 ms earlier than the EEG, masked priming studies reporting averaged sensor data is not cause for alarm. In fact Mohanan, Fiorentino, and Poeppel (2008) investigate masked repetition priming using MEG. Employing averaged sensor data analysis techniques, they find significant priming effects peaking around 225 ms post stimulus onset.
us to distinguish early from late stages of processing, the evidence is consistent with this prediction (Boudela & Marslen-Wilson, 2001; Boudela & Marslen-Wilson, 2004; Badecker & Allen, 2002; Frost, Deutsch, & Forster, 2000; Kazanina, Dukova-zheleva, Geber, Kharlamov, & Tonciulescu, 2008), but further confirmatory research is of course required. The research reported here, which combines the brief stimulus presentation of masked priming with the detailed temporal resolution of EEG provides a clear starting point for this research.

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