A single route, full decomposition model of morphological complexity: MEG evidence

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ABSTRACT

Against longstanding assumptions in the psycholinguistics literature, we argue for a model of morphological complexity that has all complex words assembled by the grammar from lexical roots and functional morphemes. This assembly occurs even for irregular forms like *gave*. Morphological relatedness is argued to be an identity relation between repetitions of a single root, distinguishable from semantic and phonological relatedness. Evidence for the model is provided in two MEG priming experiments that measure root activation prior to lexical decision. Both regular and irregular allomorphs of a root are shown to access the root equally. These results are incompatible both with connectionist models that treat all morphological relatedness as similarity, and with dual mechanism models where only regular forms involve composition.

1. Introduction

The psychological status of the knowledge that the past tense of the English verb *blink* is *blinked*, while the past tense of *drink* is *drank* has been the subject of considerable debate over the past 25 years in the psycholinguistics and computational literature. For the most part, researchers have fallen into two main camps: those arguing a single mechanism can account for both regular and irregular allomorphy, and those claiming that two distinct mechanisms are required.

The single mechanism, full listing model (Rumelhart and Mclelland, 1986; Smolensky, 1995; Seidenberg and Gonnerman, 2000; Daugherty and Seidenberg, 2001, Mclelland and Patterson, 2002a, 2002b, 2003) is a claim that an association based network of similarity relations is the right way to model the relationship between forms like *taught* and *teach*, and between forms like *walked* and *walk*. Whether that relationship is regular or not is not a fundamental feature of the system, but instead a question of degree (irregular past tense forms are usually less phonologically similar to their present tense correlates than regular past tenses are, but the degree of semantic similarity is not affected by allomorphy).

In the model argued for by McClelland and colleagues, word forms are represented by units designating each phoneme, together with its predecessor and its successor. For irregulars, the connections from units coding *specific* input features to units coding for exceptional aspects of the inflection are strengthened, which allows specific properties of the input (such as ‘ee’ followed by final /p/) to modify specific properties of the output, so that items like *creep*, *keep* and *sleep* are correctly mapped to the past tenses *crept*, *kept* and *slept*[1].

Although the model is often described in terms of generating a past tense form from a stem input, McClelland and colleagues are clear to point out that this is not generativity in the Chomskian sense (Chomsky, 1968). The past tense output is 'generated' if its probability of being the past tense correlate of a particular stem is sufficiently high. This kind of generation only happens when the system encounters a novel stem form. Once a stem/past tense pair has been learned by the system, the notion of generation is no longer relevant. The connections between the two forms, mediated by the phonological associations, have stable, quantifiable strengths, just as other connections in the system do.

The Dual-Mechanism model (Pinker and Prince, 1988; Pinker, 1999; Freiderici et al, 1993; Ullman, et al, 1997; Baayen et al, 1997; Marslen-Wilson and Tyler, 1997, 1998, 2003, Clahsen, 1999, Ulman, 2001, Pinker and Ulman, 2002,) by contrast, is one in which morphologically irregular forms are accounted for by a fundamentally different system than regular forms are. The regulars are generated by rule. The word *walked*, for example, is created by a rule concatenating the two constituent pieces *walk* and [PAST]. Irregulars, on the other hand, are stored whole in the lexicon. The meaning of a word like *taught* is something like 'teach in the past', but the word doesn't decompose into two pieces, and is merely semantically and phonologically similar to *teach,* rather than composed from it.

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[1] Albright and Hayes (2003) also propose a model in which the specific phonological properties of stems are the crucial determinants of what form allomorphic variants will have, and subregularities (such as *creep~crept, sleep~slept, leap~leapt*) play an important role in the grammar. However Albright and Hayes differ from McLelland and colleagues in proposing a system of stochastic rules to derive allomorphs, rather than weighted associations. See McLelland and Patterson (2002) for further discussion of these two approaches.

The experimental results reported here provide evidence that neither of these two competing hypotheses is adequate to characterize both regular and irregular morphology. We argue that the correct model of allomorphy relies, like the model advanced by Mclelland and colleagues, on a single mechanism for generating both regular and irregular allomorphs. However, we also argue that morphological relatedness is not mere similarity, but is in fact an identity relation, and that morphologically complex words are actually derived by the rule goverened concatenation of stems and affixes.

1.1 Full, Across the Board Decomposition

There is no shortage of evidence for the psychological reality of regular morphology. Rastle et al (2000), for example, show that functional morphemes like *–ed,* or *–er* are recognized very early on in lexical processing on the basis of their low level form properties and are stripped from their stems.

Järvikivi and Niemi (2002) provide complementary evidence that stems are also treated as distinct units, even when they never surface as such. They prime monomorphemic nominative singular nouns like *sormi* “finger” with three different primes: identitical (*sormi*), bound stem allomorphs (*sorme* from *sormesta* “from finger”), and phonologically matched pseudo-words like *sorma*. Although the bound stem is a nonword in Finnish when it is presented in isolation, Järvikivi and Niemi find significant facilitation effects associated with the bound allomorph prime and none with the phonologically matched pseudo-word prime. In a followup expeirment, Järvikivi and Niemi (2002) show that whether the stem allomorph prime is bound or free is irrelevant. Both cases are associated with significantly decreased decision latencies to their targets.

Boudelaa and Marslen-Wilson (2003) also provide evidence in favour of a model in which words are decomposed into constituent morphemes, which variously contribute either idiosyncratic, encyclopaedic information (roots) or systematic and predictable information like grammatical category, tense, aspect, number etc (functional affixes). They provide this evidence in a series of experiments on Arabic.

Priming effects are well established for discontinuous triconsonantal roots in Semitic languages (see: Boudelaa and Marslen-Wilson, 2000 and Frost et al, 1997). Boudelaa and Marslen-Wilson (2003) find evidence that the skeletal tier morpheme itself can prime a target that shares that skeletal tier morpheme, but not its root or its vocalic melody. They find significant priming effects for this abstract morphological relatedness in masked, cross-modal & auditory-auditory priming experiments. The priming effect manifesting itself even in the masked priming paradigm is strong evidence for the effect being specifically morphological in nature, as semantic relatedness is not correlated with a processing advantage when the prime is not available to conscious recognition (Rastle et al, 2000; Rastle and Davis, 2003; Dehane et al, 2001).

Most importantly for our present purposes, however, the results of these experiments provide support for a model in which even the most abstract morphemes are manifest in psycholinguistic computation. There is, then, strong evidence from a range of unrelated languages and priming methodologies that full decomposition is both real and automatic. Recognition of a morphologically complex word involves decomposing it into its constituent morphemes.

The effects of regular morphological relatedness can be dissociated both from the effects of orthographic or phonological similarity and the effects of semantic similarity.

Feldman (2000) and Rastle et al (2000) both offer evidence that the behavioral effect produced by morphological priming can not be accounted for by a model in which morphological relatedness reduces to a combination of phonological and semantic relatedness.

Yet morphological relationships that involve some kind of irregularity often fail to pattern in these ways. Irregular allomorphs are associated with diminished and even entirely non-existent priming effects relative to regulars (Stanners et al, 1979; Marslen-Wilson et al, 1993; Gross et al, 1998; Sonnenstuhl et al, 1999, etc). Likewise neuropsychological investigations of impaired populations reliably find dissociations between regular allomorphy and regular allomorphy (Tyler, deMornay-Davies et al, 2002; Tyler, Randall et al, 2002; Miozzo, 2003). If decomposition really is *the* mechanism which permits lexical activation and recognition, why do the irregulars not seem to show the expected pattern?

Allen and Badecker (2002) and the variations on their experiments reported here provide the answer: we need a more articulated and nuanced model of how allomorphy is represented in the mental lexicon. Allen and Badecker show that the lack of priming from irregular past tense to stem found in, for example, Marslen-Wilson (1993) does not obtain for all irregular past tense-stem pairs. As long as the past tense form and the stem do not share a high degree of orthographic overlap, irregular past tense forms *do* prime their stems just as reliably as regulars do.

The two experiments reported here show that in fact all irregular past tense forms prime their stems and that the magnitude of the priming effect is the same for regulars and irregulars. In the earliest stages of lexical activation, irregular allomorphy appears to be irrelevant – all morphologically complex forms activate their root equally regardless of the phonological form of the various allomorphs. Only subsequent to this initial period of activation do we find effects of irregular allomorphy. These effects appear to depend crucially on the modality of the prime and on whether the directionality of the priming is from the past tense to the present tense form or from the present tense to the past tense form.

Understanding these complications requires a model in which we carefully distinguish roots from allomorphs and similarity from identity. The basic properties of this model are sketched in figure 1.

[Figure 1 about here]

A root in this model is a Saussurian sign – an arbitrary association between form and meaning (Saussure, 1916). Roots have to be learned and memorized, there is no principle or generalization that predicts that the meaning "*to impart or convey the knowledge of; to give instruction or lessons in (a subject); to make known, deliver (a message).*", is expressed by the phonological form /τιτ♣/. Likewise, there is no principle or generalization that predicts that the sound meaning pair "*to make another the recipient of (something that is in the possession, or at the disposal, of the subject)* " _ /γ□ϖ / represented by the root GIVE is sometimes realized as /γεϖ/, while the sound meaning pair "*to be alive, to have life*" _ /λ□ϖ / has no /λεϖ/ allomorph. That a specific root participates in an irregular morphological alternation is also idiosyncratic knowledge that must be learned and memorized.

This model contends that in the earliest stages of lexical processing, whether a root sometimes surfaces displaying a non-default inflectional pattern is irrelevant. Root activation is root activation. Figure 1 above depicts the processing of the letter string ‘taught’, as a process which involves the activation of the root TEACH and the functional morpheme that denotes the grammatical meaning ‘past tense’.

In order for the letter string ‘taught’ to activate the root TEACH, the surface [↲t] sound (or *aught* letter string) must be successfully recognized as the output of a rule that operates over underlying [ιτ♣] sequences. The exact mechanism by which root lexical activation is effected is beyond the scope of the current research.

Morphological priming, viewed in this model, is priming via reactivation. A prime, such as *taught* activates the root TEACH. The root remains active throughout the processing of *taught*, and is therefore well above its resting level of activation when the target *teach* is encountered. Since lexical activation of *teach* is precisely activation of the same root TEACH, activation is predicted to be facilitated in the primed case relative to an unrelated baseline.

This model of lexical storage and activation predicts that the precise form the root takes in its prime and target instantiations should be irrelevant at the earliest stages of lexical activation. If initial lexical activation is sensitive to the process of root activation, the prior presentation of any allomorph of the root will be reflected in a facilitation effect in the neural response associated with the lexical activation of the target.

Any effects of competition or interference between various allomorphs of a root are predicted to only affect later stages of processing. Experiment 2 reverses the usual past tense prime/stem target pattern in part to test this hypothesis and to begin attempting to understand just what those competition or interferences effects might be.

If Figure 1 represents initial activation, what does recognition look like in this model?

[Figure 2 about here]

Figure 2 is a simplified model of the processes involved in recognizing an allomorph such as *taught* that is irregularly derived from its constituent morphemes. The rules that derive the past tense allomorph must be engaged in order for the output of the rules to be matched against the form of the input (the letter string 'taught'). The term 'rule' used here can be treated as synonymous with the term 'vocabulary insertion' in the framework of Distributer Morphology (Halle and Marantz (1993).

The additional step of having to engage a morphological rule has, unsurprisingly, consequences. In the two experiments presented here, we see that at the initial stage of lexical activation which we measure neurally, morphological priming has the same effect as identity priming, and irregular allomorphy is irrelevant, but by the time the decision process is complete and the reaction time measure is taken, the pattern of activation associated with irregular allomorphy is different than that associated with identity or regular allomorphy.

The combined results of the two experiments also suggest that the activation of the irregular rule in the process of processing the prime can interfere with the subsequent recognition of the target. The extent to which recognition of one allomorph interferes with the recognition of its sister allomorphs seems to depend both on the modality of the first allomorph and the degree to which the two allomorphs are orthographically similar.

1.2 The M350: an index of root activation

The experiments reported here use a combination of neural and behvioral measures to investigate the complex time course of lexical activation and decision. The neural technology used is magnetoencephalography (MEG), which offers the best combination of spatial and temporal resolution of any available neuroimaging technique (see Hämäläinen et al, 1993; Eulitz et al, 1997; and Pylkkänen and Marantz, 2003, for discussion of how MEG compares to EEG).

Visually presented lexical stimuli reliably evoke a series of distinct electromagnetic response components (Embick, et al, 2001; Helenius, et al, 1998, 1999; Koyama, et al, 1998; Kuriki, et al, 1996; Pylkkänen, et al, 2000; Pylkkänen et al, 2002; Sekiguchi, et al, 2000). The component of interest in the research reported here is the M350.

The M350 is an evoked response component peaking roughly 350ms after the onset of visually presented lexical stimuli. It is associated with a left-lateralized distribution with a posterior outgoing and an anterior incoming electromagnetic field pattern. Source localization reveals it to originate in left superior temporal areas, adjacent to left hemisphere primary auditory cortex (Helenius et al, 1999; Makela et al, 2001; Pylkkänen et al, 2004).

Crucially, the M350 has been shown to reflect root activation prior to form competition (Pylkkänen et al, 2002, Stockall et al, 2004) and to be sensitive to early effects of morphological relatedness (Pylkkänen et al, 2004) and therefore is predicted to allow the dissociation of early effects of morphological priming from later effects of form or allomorph competition.

2. Experiment 1

Allen and Badecker (2002) show that there are differences between pairs of irregular past tense/regular stem allomorphs, which depend on the extent to which the two allomorphs share their orthographic form. In a cross-modal experiment they find that past tense forms with a high degree of overlap with their stems failed to facilitate lexical decision times to those stems, but that past tense forms with low formal overlap between the stem and past tense did evoke a priming response. In the current experiment, we investigate this difference further using MEG to track the time course of the priming response.

The detailed time course information provided by MEG allows us to contrast explicitly the full, across the board decomposition hypothesis our model makes with the predictions of either the single, full listing, mechanism model or the dual mechanism model. Both these models contend that the irregular past tense forms are not derived from a root which they share with their allomorphs, but are instead fully listed as discrete lexical items. The failure of irregular past tense forms to fully prime their stems in previous behavioural experiments is taken as evidence that the irregular past tense forms are not related to their stems by identity.

Conversely, the model of lexical organization and access argued for here makes specific predictions about the initial stages of lexical activation in response to irregular allomorphs. Specifically, the prediction is that at the earliest stages, an irregular past tense form like *taught* will activate its root TEACH just as the regular allomorph *teach* will, as the regular past tense *walked* will activate the root WALK, and as the unique allomorph of CAR (namely *car*) will activate its root.

The visual-visual design allows us to investigate the effect of prime modality on irregular priming effects.

2.1 Methods

2.1.1. Participants

Seventeen right-handed, English-speaking adults with normal or corrected-to-normal vision gave their informed consent to participate in the experiment (seven females and eight males ranging in age from 19 to 33, mean age 23.3). MEG and behavioral data was collected from nine subjects, while behavioral data alone was collected from an additional eight subjects.

2.1.2. Stimuli

A total of 400 stimulus pairs were prepared. There were four experimental conditions: an identity condition, a condition where the prime and target where orthographically, but not morphologically similar and two conditions where the related prime was the past tense of the stem target (one with low orthographic overlap between stem and target, the other with high). The irregular verb pairs and the orthographically related pairs are all taken from Allen and Badecker (2002). The identity condition is our own addition.

The metric used by Allen and Badecker to divide irregular verbs into the high and low overlap categories was based on the number of letters that the words do not share (rather than the number that they do share, as in Napps, 1989; Rueckl, et al 1997; Stanners et al 1979). The number of letters found in one item in a pair, but not the other was tallied for each pair (e.g. g**i**ve-g**a**ve = 2, ta**ug**h**t**-t**e**a**c**h = 5). Moreover, any mismatch in the linear ordering of the letters in the two items of a pair was counted as a violation. The *e* in *speak-spoke* that occurs in a different position relative to the *k*, and even the *t* in *meet-met* that occurs in a different positional slot both incur points, for example. A point was also added to any pair that did not match in length. Total scores ranged from 2 to 9. Pairs with scores of 4 of greater were classified as low overlap, and those with scores of less than 3 as high overlap items.

The items pairs in the orthographic overlap condition were selected by Allen and Badecker (2002) on the basis of the number and position of shared letters. The pairs were designed to exhibit the same kinds of similarity that the high-overlap irregular verbs do. So, for example, the pair *slam-slim* was included based on its similarity to *swam-swim*, and *book-bake* for its similarity to *took-take*. All the prime-target pairs in this condition were selected on the basis of analogy to existing irregular verb pairs, and therefore all the items in this condition share a syllabic onset and differ from their pair only in word-medial or final positions.

Because of the similarity metrics used, and in the case of the irregular verbs because of the small number of candidate pairs in the language, items in these conditions were not as carefully controlled for length or frequency as would usually be the case. However, the items were generally comparable. The targets were the same length across conditions (similar irregulars, 4.3; dissimilar irregulars, 4.2; orthographically related, 4.3; identity, 4.4; a 4 (category) x 1 ANOVA revealed no significant effect of target length ($p>0.8$)). The prime to target surface frequency ratios did not differ across conditions, primes were well matched in frequency to their targets (see Allen and Badecker, 2002 for more detailed discussions of stimulus properties).

Condition	Prime	Target	Number of Pairs
Irregular Low Overlap	taught	teach	27
Irregular High Overlap	Gave	give	27
Identity	Boil	boil	25
Orthographic Overlap	Curt	cart	25

Table 1. Example stimuli from Experiment 1.

The unrelated primes were a 50/50 mix of uninflected verbs and nouns, so as to reduce the likelihood of the subjects suspecting that the experiment might be about verbs in any way. In order to ensure that the lexicality of the prime did not predict the lexicality of the stem, 204 unrelated filler pairs were created in each of the three remaining lexicality configurations (NW-W, NW-NW, W-NW). Because all the fillers involved unrelated prime-target pairs, the overall percentage of trials that involved a related prime-target was only 25%. All filler words were uninflected and were not homophonous with other words.

The nonwords used as test items were generated by altering one or more segments of real words, so all items were possible words on English. Nonwords and filler words were matched in length with the test items. Two ANOVAs comparing item length were performed, one each for words and nonwords. There were no significant differences in item length across stimulus conditions.

2.1.3. Procedure

Stimuli were presented using PsyScope 1.2.5 (Cohen et al, 1993) in a randomized order. Each trial consisted of a fixation point (+) that lasted for 1000 ms followed by the presentation of the prime which appeared for 200 ms and then immediately by the target which disappeared at the button press response, or after 2500 ms if the subject did not respond in that time. The task was lexical decision to the target. Participants used their left index and middle fingers to press the response buttons (the left hand was used in order to minimize the amount of left hemisphere activity associated with motor control).

Neuromagnetic fields were recorded using an axial gradiometer whole-head 93 channel system (Kanazawa Institute of Technology, Japan). Data were sampled at 1000Hz, with acquisition between DC and 200Hz. The recording for each participant lasted approximately 20 minutes.

2.1.4. Data Analysis

Reaction times were calculated from the onset of the target stimulus. Incorrect trials and RTs deviating over 2SD from the mean for the particular participant were excluded from the analysis. This resulted in the exclusion of 7.7% of the data. These trials were also rejected from the MEG averages. Subjects with an overall error rate of higher than 10% were rejected from further analysis. The data from one behavioral participant did not survive this criterion, leaving 16 subjects whose reaction time data was analyzed. Only MEG averages consisting of more than 20 trials after artifact and error rejection were accepted for further analysis.

External noise sources were removed from the MEG data using the Continuously Adjusted Least-Squares Method (CALM, Adachi et al, 2001). Responses to stimuli were averaged by stimulus condition. In the averaging, artifact rejection was performed by excluding all responses to stimuli that contained signals exceeding ± 2.0pT in amplitude. Epochs were also excluded from further analysis based on reaction time criteria. Following averaging, data were baseline adjusted using a 100ms pre-stimulus interval and low pass filtered under 30Hz.

In the analysis of the MEG data, a grandaverage of the evoked responses to all target words in the experiment was created for each subject. This file was visually inspected to identify dipolar field distributions that showed consistency across experimental conditions and across participants. Since the aim of the present study was to investigate the effects of the stimulus variables on the timing of the M350, subjects for whom this response component was not identifiable in the grandaveraged file were not considered in the analysis. One subject was excluded on the basis of this criterion. Figure 3 shows the isofield contour map of the M350 response for a representative subject and the grandaveraged waveform that corresponds to it.

[figure 3 about here]

The amplitudes and latencies of the M350 were recorded by first determining the sensors of interest on the basis of the grandaverage of all word targets for each participant. The set of sensors chosen was the set that best captured the left hemisphere negative and positive field patterns associated with each component. The number of sensors chosen for each subjects ranged from 29 (31% of the total sensors) to 38 (41%)

(mean number of sensors = 34) (see filled circles in figure 3). The root mean square (RMS) field strength from these sensors was calculated for each experimental condition. All MEG values reported for this experiment are measurements of RMS amplitude and latency. For reporting purposes, significance is determined as $p<0.05$, while near significance is determined as $0.05<p<0.1$.

2.2 Results

2.2.1 Magnetoencephalography

A 4x2 factor ANOVA (4 experimental conditions x related vs. unrelated prime) revealed a significant main effect of priming on M350 latencies ($F=1,7$; $p<0.002$)(control x⇔=369.6ms, prime x⇔=341.2ms), as seen in figure 4.

[Figure 4 about here]

No other main effects were significant. Planned comparisons revealed significant differences in the latency of the M350 component for the identity condition ($F=1,7$; $p<0.01$)(control x⇔=355ms, prime x⇔=324ms), the *gave-give* condition ($F=1,7$; $p<0.05$) (control x⇔=374ms, prime x⇔=348ms) and the *taught-teach* condition ($F=1,7$; $p<0.05$) (control x⇔=371ms, prime x⇔=339ms). The *curt-cart* condition showed a trend towards priming, but the effect was not significant ($F=1,7$; $p>0.1$) (control x⇔=361ms, prime x⇔=343ms).

2.2.2. Reaction Time

A similar 4x2 factor ANOVA on reaction times revealed no significant main effect. However there was a significant interaction between condition type and prime relatedness (F=1,7 p<0.03) as seen in figure 5.

[Figure 5 about here]

Planned comparisons revealed significant effects of condition on reaction times. Reaction times were significantly faster for primed items in the identity condition (F=1,13; *p*<0.001) (control x⇔=666ms, prime x⇔=603ms) and in the *gave-give* condition (F=1,13; *p*<0.04) (control x⇔=605ms, prime x⇔=587ms). Reaction times were significantly delayed in the priming condition for the form-overlap items (F=1,13; *p*<0.01) (control x⇔=637ms, prime x⇔=665ms). There was no reliable effect of priming for the *taught-teach* condition (F=1,13; p>0.2).

2.3 Discussion

This experiment was specifically designed to test the hypothesis that the M350 would provide a reliable measure of morphological priming, regardless of whether that priming was apparent in behavioural measures. The results of the planned comparisons confirm that this hypothesis is correct. Both the high and the low form overlap irregular past tenses facilitate the stage in processing indexed by the M350.

For both the orthographic overlap condition and the irregular verbs with low overlap condition (taught-teach), we see a significant dissociation between the MEG and behavioural measures. In both cases, the M350 latencies are faster to the target following a related prime compared to an unrelated baseline, and the lexical decision times are slower. In the case of the orthographic overlap condition, the M350 priming is not significant and the RT inhibition is, while for the irregular verbs with low form overlap, the opposite is true. The M350 priming is significant and the behavioural inhibition is not.

[Figure 6 about here]

The evoked responses to the orthographic overlap condition are easy to make sense of in a model of lexical recognition in which an initial stage of lexical activation is followed by competition between activated candidates for selection. The high degree of orthographic similarity between the prime and target in the related condition initially boosts the activation level of the target, but then later interferes with and delays the process of recognition.

The effects observed for the two categories of irregular verb are exactly the opposite of those reported by Allen and Badecker (2002). The persistence of priming for the gave-give items, despite the form-overlap induced inhibition, is not so problematic. The effect of competition just seems to be weaker (or the amount of initial priming greater) so that not all the priming effects are cancelled out. The complete absence of any RT priming for taught-teach is more of a puzzle, as it is not explained by the activation-competition model outlined above.

There is a growing body of evidence that prime and target modality matter in determining the magnitude of morphological priming effects. Cross-modal experiments with auditory primes and visual targets seem to produce different results than other permutations of prime and target modality (see, for example, Feldman and Larabee, 2001). The opposite behavioural priming effects for the two categories of irregular verbs in visual-visual priming experiment reported here as compared to the audio-visual priming experiment reported in Allen and Badecker (2002) is therefore not entirely surprising. However, it is not clear that a modality effect explains why the high and low overlap irregulars are responded to so differently. This issue is discussed more fully in the conclusions.

3. Experiment 2

Experiment two is in large part an attempt to clarify the nature of the relationship between the irregular past tense forms and their stems. The direction of the priming is reversed in experiment two. This reversal has two goals. The first is to investigate whether the neural and behavioural responses will vary significantly as a function of priming directionality. Recall that the model argued for in the introduction strongly predicts there should be no asymmetries in initial lexical activation – root activation is root activation, whether the form on the basis of which it is activated is a regular or irregular allomorph.

But the model certainly allows later differences. The effect of having to activate a specific irregular rule in the recognition of the irregular allomorph could be what is responsible for the absence of any behavioural priming effect in the *taught~teach* condition in Experiment 1. Since this rule is not activated in the recognition of a regular allomorph prime, there should be no competition or interference effects in the *teach~taught* case, and the root priming advantage should persist in the reaction time measure.

In addition to the irregular past tense-stem pairs used in Experiment 1, Experiment 2 adds a regular past tense condition. The goal is to more explicitly show that at the stage in processing indexed by the M350, all morphologically related pairs elicit a priming effect, regardless of whether the past tense form is regular or irregular. The single mechanism, full decomposition model argued for in this dissertation predicts priming effects for both cases.

The dual mechanism account, on the other hand, predicts priming for the regular verbs, but little or no priming for the irregular past tense/stem pairs. Irregular past tense forms are only related to their stems by similarity in this model, not by the identity relations that relate regular allomorphs to their stems. Evidence that regulars and irregulars prime their stems equally at the stage indexed by the M350 would be evidence against an account that treats regular and irregular allomorphy as fundamentally different relations.

Experiment 2 also contains materials to explicitly investigate the extent to which morphological relatedness can be shown to be distinct from both semantic and phonological relatedness. Like Rastle et al (2000), we included a condition containing pairs of items that are related both in their meaning and their orthography, but without any plausible morphological relationship. The complete list of items in this condition is in Appendix 2, but examples include *boil-broil*, *flip-flop* and *crinkle-wrinkle.* Unlike Rastle et al (2000), we did not include portmanteau pairs like *brunch-lunch* (which may be parsed by speakers into their constituent pieces) or phonaesthemes like *glimmer-glisten* or *snout~snort* (which also might be related to one another in a special way that differs from either ordinary semantic relatedness or morphological relatedness, as argued for by

Bergen (2004) who presents evidence for a priming advantage for phonaesthemically related pairs).

3.1 Method

3.1.1. Participants

Thirteen right-handed, English-speaking adults with normal or corrected-to-normal vision gave their informed consent to participate in the experiment (eight females and five males ranging in age from 24 to 48, mean age 30.9). Participants were paid $10/hr for their participation.

3.1.2. Stimuli

The two irregular verb conditions in experiment 2 used identical stimuli to experiment 1, except that the direction of the priming was reversed. The past tense forms, which served as targets in experiment 1, were used as primes in experiment 2 and the stems from experiment 1 were used as targets. The identity condition and the orthographic overlap condition from experiment 1, were replaced by two new conditions in experiment 2.

The two novel conditions were (a) a regular verb priming condition, with the priming direction being from past tense to stem, and (b) a condition in which prime and target were semantically and orthographically similar, but not morphologically related (henceforth +S+O-M), such as *boil~broil*, or *screech~scream*. In order to ensure that the items in this condition were in fact semantically related, a rating study was conducted. in which participants were asked to rate the degree of semantic relatedness of pairs of words on a 9 point scale (with 1 as the least related end of the scale, and 9 as the most related score).

All the pairs included in the study had average scores of 7.5 or higher. The test pairs from the orthographic overlap condition in experiment one were also included in the rating study in order to ensure that orthographic overlap alone would not be used as a cue that the pair was semantically related. These items, which were orthographically similar to the same or a higher degree than the *boil~broil* type items, scored 2.5 or lower on the same 9 point scale.

Each condition had the same number of items as in experiment 1. Experiment 2 also used all the same filler items as experiment 1, so the ratio of words to nonwords was also 1:1 and the ratio of related pairs in the experiment was 25% of the total number of pairs.

Example Stimulus Set				
Condition		Prime	Target	Number of Pairs
I	Irregular Low Overlap	teach	taught	27
II	Irregular High Overlap	give	gave	27
III	Regular Verb	date	dated	25
IV	+S+O-M	boil	broil	25

Table 2. Example stimuli for experiment 2.

Two ANOVAs comparing item length were performed, one each for words and nonwords. There were no significant differences in item length across stimulus conditions.

3.1.3. Procedure

Stimulus presentation and behavioural data recording were controlled by the DMDX software (Forster and Forster, 1990) running on a Windows operating system on a Pentium 4 with a screen refresh rate of 16.73ms. Stimuli were randomized by DMDX for each participant. In every other respect, stimulus presentation and subject task were identical to experiment one.

Neuromagnetic fields were recorded using an axial gradiometer whole-head 160 channel system (Kanazawa Institute of Technology, Japan). Data were sampled at 500Hz, with acquisition between DC and 200Hz. The recording for each participant lasted approximately 20 minutes.

3.1.4. Data Analysis

Reaction times were calculated from the onset of the target stimulus. Incorrect trials and RTs deviating over 2SD from the mean for the particular participant were excluded from the analysis. This resulted in the exclusion of 4.2% of the data. These trials were also rejected from the MEG averages. Only MEG averages consisting of more than 20 trials after artifact and error rejection were accepted for further analysis.

Noise reduction was accomplished as in experiment one. As in experiment one, subjects for whom no M350 response component was identifiable in the grandaveraged file were not considered in the analysis. Three subjects were excluded on the basis of this criterion, so 10 subjects data was included in the analysis.

Sensors of interest were determined in the same manner as in experiment one. The number of sensors chosen ranged from 34 (21% of the total number of sensors) to 57 (36%) (mean = 44, median = 43). The root mean square (RMS) field strength from these sensors was calculated for each experimental condition. All MEG values reported for this experiment are measurements of RMS amplitude and latency.

3.2 Results

3.2.1 Magnetoencephalography

A 4x2 factor ANOVA (4 experimental conditions x related vs. unrelated prime) on M350 amplitudes and latencies revealed two significant main effects and one significant interaction on M350 latencies. The first main effect was an effect of condition. Items which were semantically and orthographically similar in the absence of morphological relatedness (+S+O-M) elicited slower M350 latencies overall than the other three conditions (F=1,9; p<0.029).

	Overall	Unrelated	Related
High Overlap Irreg	342.3	357.6	327
Low Overlap Irreg	340.4	360.2	334.4
Regular	347.3	354.4	331.4
+S+O-M	358	357.2	358.7
Average	346.5	355.1	337.9

Table 3. M350 Latencies by condition and relatedness, Exp 2.

The second main effect observed was an overall effect of priming. Targets evoked earlier M350 latencies when they were preceded by related primes than by unrelated control items (F=1,9; p<0.0003) (related x⇔= 355.1 vs. unrelated x⇔= 337.9), as seen in Table 3.

Finally an interaction was observed between condition type and relatedness. Figure 7 shows that whereas all three categories of stem-past tense pairs evoked earlier M350 latencies when the target was preceded by a related prime than by an unrelated control, the items in the +S+O-M condition did not show this difference. Planned comparisons revealed that the effect of priming was significant for both the irregular verbs with high stem/past tense orthographic overlap condition (F=1,9; p<0.004) (related x⇔= 355.1 vs. unrelated x⇔= 337.9) and the regular verb condition (F=1,9; p<0.018) (related x⇔= 360.2 vs. unrelated x⇔= 334.4).

[Figure 7 about here]

3.2.2. Reaction Time

A similar 4x2 factor ANOVA on reaction times revealed two significant main effects; one of condition and one of prime relatedness. The *boil-broil* condition and the regular verb condition are both significantly slower than the two irregular verb conditions. Planned comparisons reveal that every pair wise comparison between two conditions is significantly different (p<0.03) except that between the two irregular verb conditions (p>0.9).

The main effect of prime relatedness, seen in Table 4., is that across all experimental conditions, targets preceded by related primes were responded to faster than items preceded by unrelated primes (F(1,9), p<0.0008, 612ms vs. 634.8ms,).

	Overall	Unrelated	Related
High Overlap Irreg	601.7	616.8	594.9
Low Overlap Irreg	598.5	611	590
Regular	631.1	645.8	623.7
+S+O-M	662.3	673.4	674.7
Average	623.4	634.8	611.9

Table 4. Plot of mean RTs (ms) by condition and relatedness

However, as can also be seen in Table 4 not all conditions contributed equally to the overall effect of prime relatedness. Whereas the three verb conditions all do show differences of 25ms or more between the related and unrelated conditions, the *boil-broil* condition shows a difference of only 2.7ms, in the opposite direction (660.9ms vs. 663.6ms, $p>0.9$). The magnitude of the priming effect for each condition can be seen more clearly in Figure 7.

[Figure 7 about here]

3.2. Discussion

The results of this second experiment provide further support for a model of lexical organization in which regular past tenses and irregular past tenses are related to their stems via the same mechanism, namely decomposition. At the stage in processing indexed by the M350 response component, all three categories of verb evoked the same priming responses, while the items that were not morphologically related did not evoke this priming response.

The failure of the *boil-broil* items to evoke a priming response in either the neural of behavioural measures provides key support for a model of lexical organization wherein morphological relatedness can not be explained as a combination of semantic relatedness and phonological/orthographic relatedness. Pairs of items similar in both form and meaning, but with no plausible morphological relationship, are associated with fundamentally different neural and behavioural responses than pairs which are morphologically related. The neural and behavioural responses to the *boil-broil* condition could plausibly be the result of semantic facilitation and formal overlap inhibition cancelling each other out.

An important goal of the second experiment was to explore the effect directionality of priming might have on the morphological facilitation observed in the first experiment. Figure 8 plots the difference between the related and unrelated conditions for the two irregular verb categories, across the two experiments.

[Figure 8 about here]

For the high overlap irregulars (*gave-give*), the direction of the priming appears not to matter. The past tense form primes its stem both neurally and behaviourally, and the stem likewise primes its past tense allomorph. For the low overlap irregulars, however, the direction of the priming seems to matter considerably. In experiment one, when the irregular past tense served as the prime and the stem as the target, the M350 component was substantially facilitated by the related condition, but this priming advantage had completely disappeared by the stage in processing indexed by reaction time. In experiment two, where the prime directionality is reversed, no such dissociation between the neural and behavioural responses is apparent. The stem primes the past tense target with approximately equal magnitudes at both the neural and behavioural measures.

4 Conclusions

4.1 Full, Across the Board, Decomposition

Each of the three models of lexical organization and allomorphic alternation discussed in the introduction makes specific claims about the meaning of 'morphologically related'. The single mechanism, full listing account attributes no real meaning to it at all. The mechanisms by which lexical items are related to one another are semantic and phonological similarity, morphological relatedness is a special case of items being related by both phonological and semantic similarity. This model is unable to provide an explanation for why the *boil~broil* type pairs failed to prime one another even at the earliest stages of lexical activation, while even the irregular past tenses with very little formal overlap with their stems primed those stems robustly. The dual mechanism account, on the other hand, is a model in which irregular past tense forms are stored whole in the lexicon, and only related to their stem correlates by similarity matrices. Irregulars are predicted not to prime their stems with anything like the robustness of regulars, and should instead behave like the *boil~broil* pairs. Since clearly they do not, the dual mechanism model is challenged by the experiments reported here.

The primary motivation for the experimental manipulations reported in this paper was to provide clear, straightforward evidence that all inflected allomorphs of a root activate their stems equally in the early stages of lexical activation. The results reported here are clearly compatible with the single mechanism, full, across the board decomposition model. They are just as clearly incompatible with the dual mechanism model which treats morphological relations between irregular allomorphs and their stems as mere similarity, and as crucially distinct from the identity relations that obtain between regular allomorphs and their stems.

The robust priming effects observed for both categories of irregular verb, for regular verbs and for identical prime/target pairs (contrasted with the complete lack of priming for the pairs that were highly semantically and phonologically similar, but had no morphological relationship) provide a strong argument against the full listing approach. Morphological relatedness is clearly a different kind of relatedness than the phonological and semantic similarity relations that a model like Rumelhart and McClelland (1986) is based on.

Experiment 2 adds additional evidence for the psychological reality of morphological identity as distinct from semantic and phonological similarity. The semantically and phonologically related items that have no morphological relationship, like *boil~broil* and *tip~top*, are associated with significantly different neural and behavioural effects from any of the morphologically related conditions. The semantic facilitation and phonological competition seem to cancel each other out even at the earliest stages of lexical activation.

4.2 Early activation, later competition

Experiment 1 adds to the growing body of results showing that the M350 response component is sensitive to early stages of lexical activation, but **not** to post activation processes of inter-lexical competition and selection between phonologically and orthographically similar forms. Orthographically related pairs such as *curt~cart* were associated with a nearly significant priming advantage at the stage indexed by the M350, but with significant inhibition at the later stage indexed by the RT measure.

While the gave-give irregulars evoked roughly the same reaction time priming effects in both presentation directions, the taught-teach items did not. In experiment 1, where the direction is from past tense prime to stem target, the neural priming had no correlate in the reaction time measure. However, in experiment 2, the priming from stem *teach* to past tense allomorph *taught* was robust in both the M350 and RT measures.

A possible explanation for this asymmetry can be found if we consider the model sketched in Figure 5 above. There is a significant difference between the recognition of a regular, default allomorph of a particular root, and recognition of an irregular allomorph of the same root. In the first case, recognition requires looking up the phonological form stored with the root in the lexicon. In the second case, the irregular allomorph must actually be generated by the application of the specific morphological rule.

One clear prediction of this difference is that all other factors being equal, recognition of an irregular allomorph ought to take longer than activation of a regular allomorph. Since in practice many other factors known to affect the timing of lexical activation and decision distinguish regular from irregular allomorphs (such as frequency, length, regularity of grapheme to phoneme conversion, phonotactic probability, etc), this prediction may be untestable (at least in English).

However, this same difference may explain the priming asymmetry in the *taught~teach* vs *teach~taught* case. If the irregular allomorph is the prime, the rule generating the irregular allomorph will be activated by processing the prime. This rule, and the route linking the lexical entry TEACH to the irregular rule, would then be active. It's then plausible that when the root TEACH is reactivated by the target *teach*, the system is inclined to follow the link to the irregular rule again. Zeroing in on the regular allomorph as the correct target for recognition takes longer as a consequence of having to override this inclination.

In the opposite direction, the prime *teach* never activates the link to the irregular rule. The priming advantage for recognition of *taught* following *teach* is a straightforward consequence of the earlier priming advantage for the initial activation of the root TEACH.

Why the prior activation of the irregular rule should be a factor in the low overlap pairs like *taught~teach* but not in the high overlap pairs like *gave~give*, is not immediately clear. If further investigations replicate this directionality effect and continue to find that only the low overlap irregulars display the asymmetrical pattern, this effect may be an indication that the irregular rules activated by the different roots are not all equal. It's perhaps worth noting that of the pairs in the high overlap category, only *dealt~deal*, and *heard~hear* plausibly contain a non null allomorph of the past tense (the /t/ in *dealt* and the /d/ in *heard* could both be regular past tense allomorphs), while of the pairs in the low overlap category, 12 out of 27 pairs plausibly contain the /t/ or /d/ allomorph (*brought, bought, caught, did, fought, paid, said, sought, taught, told, thought* and *went*). The extent to which the prior activation of an irregular morphological rule interferes with the subsequent processing of a regular allomorph of the same root may depend on the number or type of other morphological rules activated by the prime, although this suggestion is nothing but speculation at this point.

4.3 The effect of prime modality

Allen and Badecker (2002) found that while the low overlap prime/target irregular pairs such as *taught~teach* were associated with a reaction time advantage, the high overlap irregular pairs like *gave~give* were not. Allen and Badecker presented primes aurally, and target visually. In Experiment 1, using the identical stimulus items, but presenting both primes and target visually, we found the opposite effect. The high overlap irregulars primed their stems robustly, but the low overlap irregulars did not.

There are other instances of cross-modal priming experiments producing different priming results than intermodal experiments (Feldman, 2001; Pastizzo and Feldman, 2002, Tsapkini et al, 2004). This growing body of results seems to suggest that processing a visual target immediately after processing an auditory prime engages processes or operations not required by other combinations of prime and target modality. The problem seems to be very particular. Marslen-Wilson and Zhou (1999) initially described the so called 'suffix-suffix interference effect': suffixed primes were shown not to prime differently suffixed target, where both are derivatives of the same root (ex: *darkly~darkness*), despite the fact that both derivatives prime their unsuffixed stems (both *darkly* and *darkness* prime *dark*) Feldman and Larabee (2001) show that this effect is specific to designs in which the prime is auditory and the target visual: in the other tested prime/target configurations (visual-auditory, visual-visual), *darkly* primes *darkness* as expected. The results of our experiments compared to those of Allen and Badecker (2002) suggest that irregular allomorphs also interact with modality in some way that depends on the degree to which the past tense allomorph is formally similar to its stem. But what *gave~give* and *darkly~darkness* have in common to the exclusion of all other morphologically related pairs is difficult to determine. Further MEG experiments are required to determine whether the modality effect is post root access, and reflects particular issues in the course of recognition and selection.

The experiments reported here show that at the relevant, early stage of lexical activation, all morphologically related forms activate the same underlying root form, and that there is no evidence for the separate lexical listing of irregular allomorphs. Moreover, these experiments provide a number of interesting starting points for further research.

We’ve only begun to understand the precise mechanisms involved in the recognition of different allomorphs of a single root, however it seems clear already that the processes are **not** the same as those involved in selecting between the phonological forms of several different roots. The experiments reported here have also added to the body of evidence that modality interacts with morphological priming in unexpected ways. And we’ve further enriched our growing understanding of the time course of lexical activation.

Clearly, then, more work remains to completely understand all the processes involved in processing morphologically complex words, but we can be certain that they involve full decomposition of all forms, regardless of irregularity, and that all related allomorphs are exponents of the same root.

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Figure 1. A schematic representation of the initial stage of root activation. Processing of the past tense form taught activates the root TEACH, and the functional morpheme [PAST]. The ★superscripts indicate specific morphological rules. Rule 129, for example, would be the rule: /itʃ/→[ɔt]/_[PAST], while rule 13 would be the rule generating a phonologically null allomorph of the past tense.

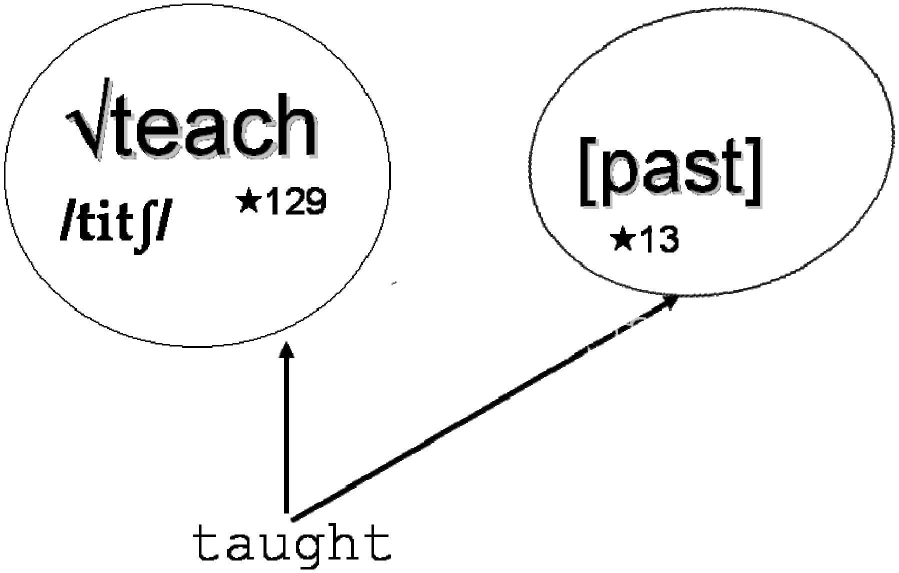

Figure 2. A schematic representation of process of recognition of morphologically complex form *taught*. The special diacritic that indicates that a lexical entry has a non default allomorph is activated and the particular morphological rule that it is associated with is engaged.

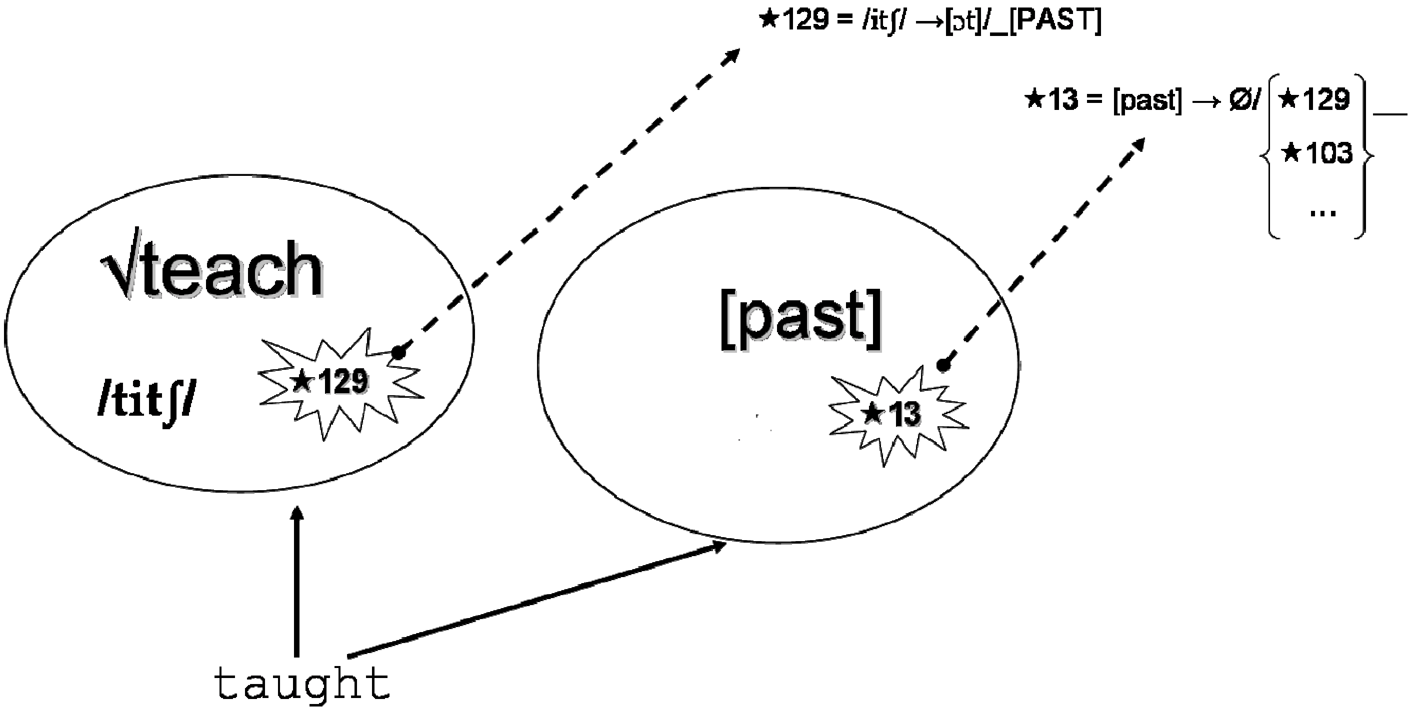

Figure 3: Magnetic field strength in grandaveraged file for representative subject. Filled in circles on contour map indicate sensors of interest corresponding to positive and negative peaks in waveform data.

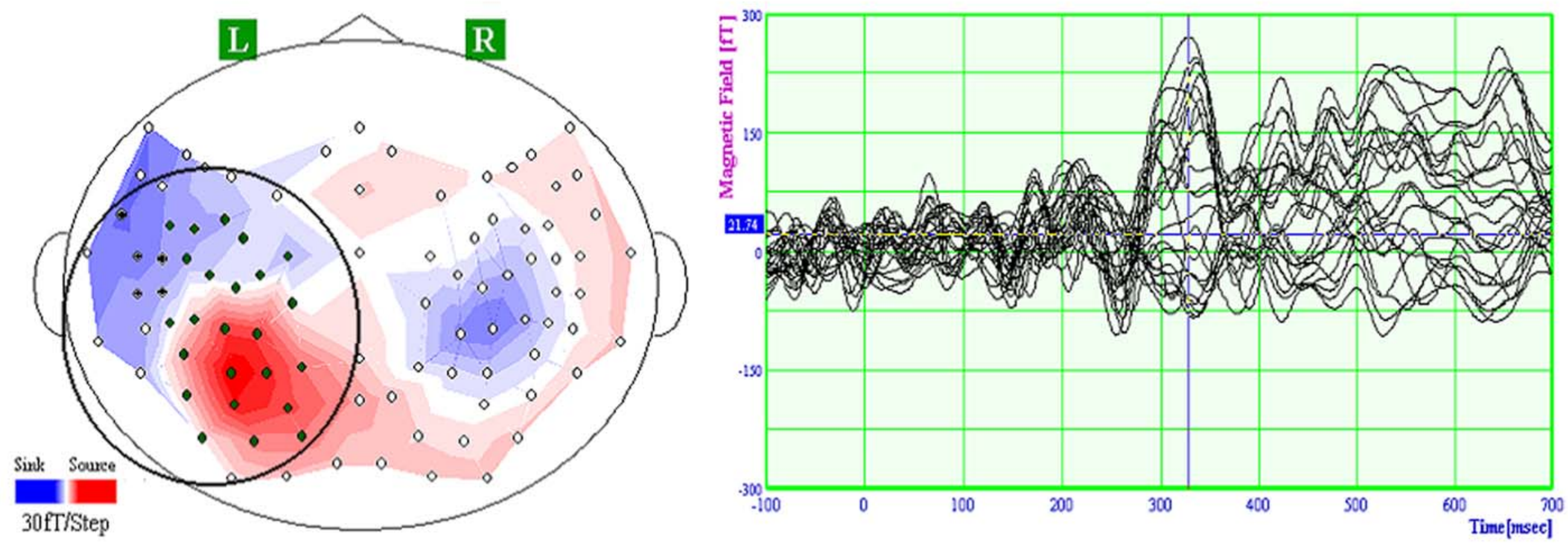

Figure 4. Plot of main effect of priming on M350 Latencies, exp 1

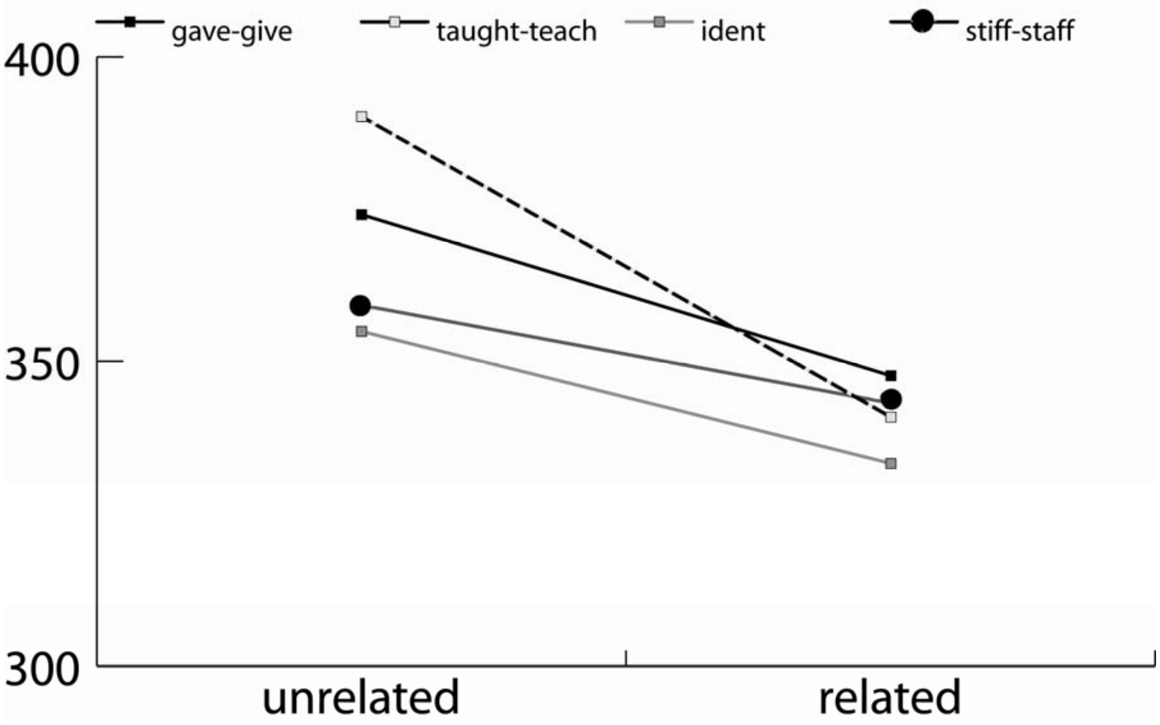

Figure 5. Plot of Interaction of Condition and Prime Relatedness on Reaction Time

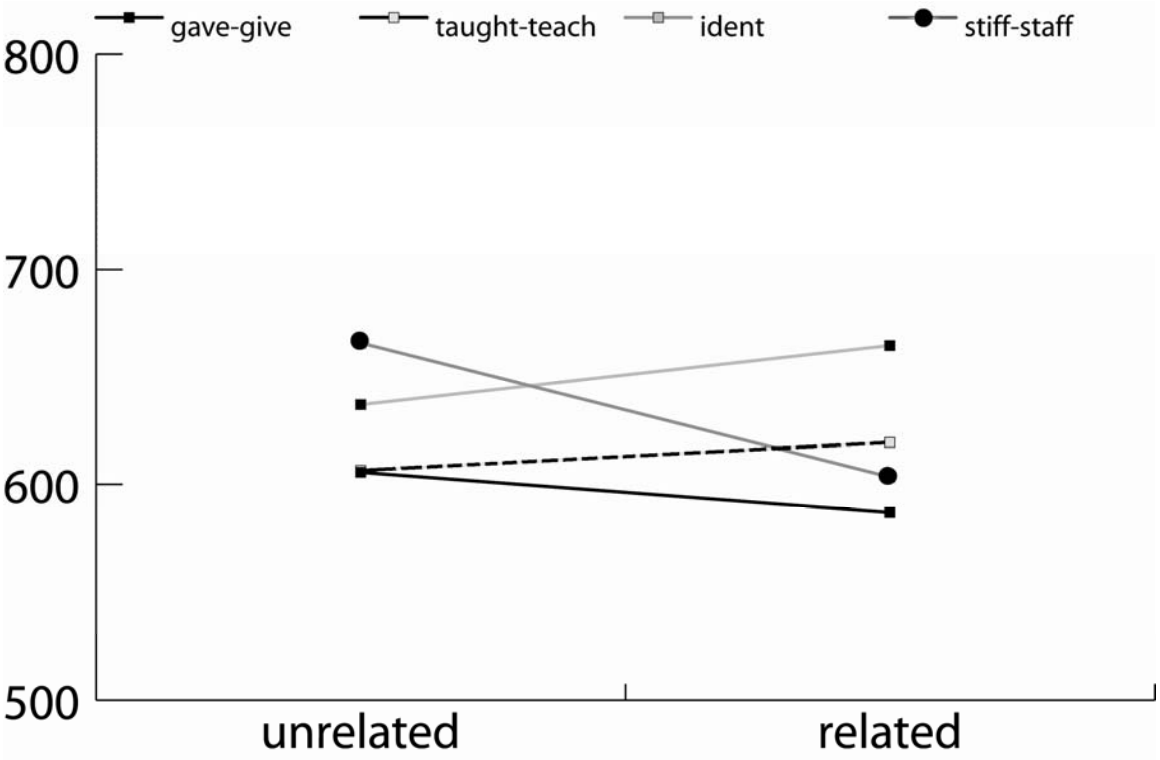

Figure 6. Plot of Neural and Behavioral Priming Effects. (amount of priming = related condition – control condition)

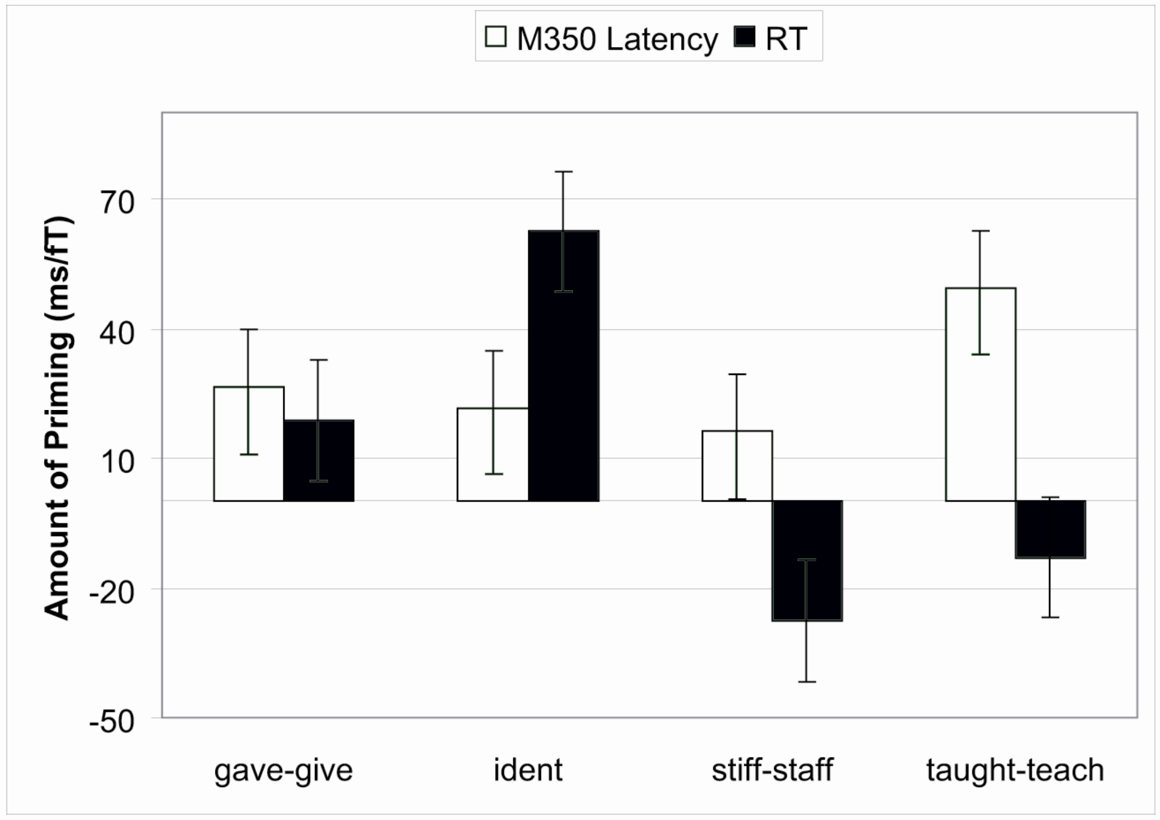

Figure 7. Significant neural interaction of relatedness on condition, Exp. 2.

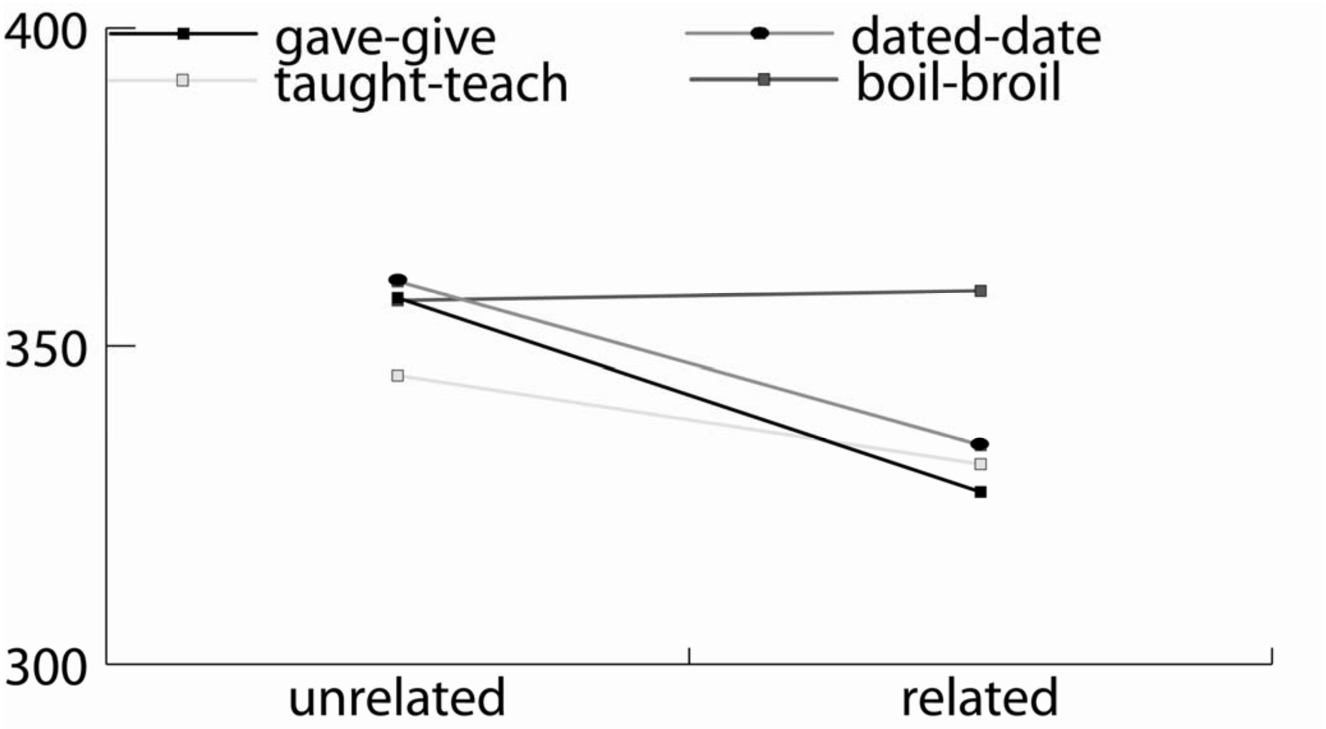

Figure 8. Summary of priming effects for the two irregular verb categories across the two experiments. Amount of priming = response to unrelated condition – response to unrelated condition