A single route, full decomposition model of morphological complexity

MEG evidence

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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 prime the root equally. These results are incompatible both with connectionist models that treat all morphological relatedness as similarity and with dual mechanism models in which only regular forms involve composition.

Keywords: morphology, magnetoencephalography, lexical access, decomposition, irregular allomorphy

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 model (Rumelhart and McClelland, 1986; Smolensky, 1995; Seidenberg and Gonnerman, 2000; Daugherty and Seidenberg, 2001, McClelland and Patterson, 2002a, 2002b, 2003) is a claim that an association-based network of similarity relations is the right way to model both 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 /i/ 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 generalization only happens when the system encounters a novel stem form. Once a stem/allomorph pair has been learned by the system, the notion of generation is no longer relevant. The connections between the two forms, mediated by their phonological and semantic associations, have stable, quantifiable strengths, just as other connections in the system do. Recognizing or producing a familiar past tense form involves no decomposition or composition mechanisms — processing *taught* certainly involves activation of *teach* by virtue of the shared semantics of the two forms, but processing *taught* also involves activation of other semantic relatives, such as *instruct*, *student*, and *textbook*.

The Dual-Mechanism model (Pinker and Prince, 1988; Pinker, 1999; Friederici *et al*, 1993; Ullman, *et al*, 1997; Baayen *et al*, 1997; Marslen-Wilson and Tyler, 1997, 1998, 2003, Clahsen, 1999, Ullman, 2001, Pinker and Ullman, 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]. Morpho-phonological spell-out rules determine which of the three possible variants of this

past tense morpheme (*-d, -t, -ed*) surface in any particular environment. 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,, just as in the single route, association based model.

The experimental results reported here provide evidence that neither of these two competing hypotheses correctly characterizes both regular and irregular morphology. We argue that the correct model of allomorphy relies, like the model advanced by McClelland and colleagues, on a single mechanism for generating and recognizing 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-governed concatenation of stems and affixes.

The model of lexical recognition this view of allomorphy requires is not fundamentally different from that proposed by Taft & Forster (1975) [see also Taft (1994, 2004) and de Almeida & Libben (2005)], who argue that all morphologically complex words are initially decomposed and that lexical activation is activation of roots or stems, rather than whole words. We differ from this model only in our contention that the same process of visual word form based decomposition followed by root based lexical access occurs during the processing of irregular allomorphs as well as regular.

1.1   Full, across the board decomposition

There is no shortage of evidence for the psychological status 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 independent words. They prime monomorphemic nominative singular nouns like *sormi* "finger" with three different primes: identical (*sormi*), bound stem allomorphs (*sorme* from *sormesta* "from finger"), and phonologically matched pseudowords 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 experiment, Järvikivi and Niemi (2002) show that whether the stem allomorph prime is bound or free is ir-

relevant to the priming effect. Both cases are associated with significantly decreased decision latencies to their targets.

In a series of experiments on Arabic, 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).

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. That the priming effect is found even in the masked priming paradigm is strong evidence for the effect being specifically morphological in nature, as semantic relatedness is not consistently correlated with a processing advantage when the prime is not available to conscious recognition (Rastle *et al*, 2000; Rastle and Davis, 2003; Dehaene *et al*, 2001). The results of these experiments provide support for a model in which even the most abstract morphemes function as units in on-line 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 straightforward 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 irregulars not seem to show the expected patterns?

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, the distinction between regular and 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 bare form or from the bare form to the past tense form.

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

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*
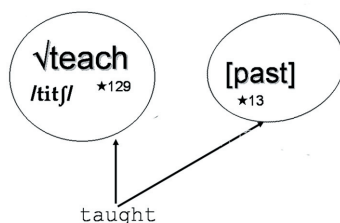

Figure 1. Schematic representation of initial stage of root activation. Processing the past tense form activates the root TEACH and the functional morpheme [PAST]. The *s indicate specific morphophonological rules. Rule 129, for example, would generate the irregular *taught* form in the past tense.

make known, deliver (a message).",[2] is expressed by the phonological form /tit∫/. 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)*" ↔ /gɪv/ represented by the root GIVE is sometimes realized as /gev/, while the sound meaning pair "*to be alive, to have life*" ↔ /lɪv/ has no /lev/ allomorph. That a specific root participates in an irregular morphophonological alternation is also idiosyncratic knowledge that must be learned and memorized.

The experiments reported here argue that in the earliest stages of lexical activation, whether a root sometimes surfaces displaying a non-default inflectional pattern is irrelevant. Root activation is root activation. Processing the letter string 'taught' involves activation of the root TEACH and of the functional morpheme that denotes the grammatical meaning 'past tense'.

In order for the letter string 'taught' to activate the root TEACH, the surface [ɔt] sound (or *aught* letter string) must be successfully recognized as the output of a rule that operates over underlying [it∫] sequences. This amounts to a claim that the earliest visual word form recognition processes must be sensitive not just to the patterns associated with regular allomorphy (as argued for by Rastle *et al* (2000), Boudelaa & Marslen-Wilson (2000, 2003) etc), but also to those associated with irregular allomorphy. The recent work of Albright (2002) and Albright & 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. Speakers are shown to be sensitive to rather subtle stochastic subregularities 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 & 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 in a Taft type model could plausibly detect possible irregular morphemes as well as regular.

Morphological priming in a full decomposition 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 stage of initial 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 affect only later stages of processing. Experiment 2 reverses the usual past tense prime/stem target pattern in part to test this hypothesis and in part to better understand just what those competition or interferences effects might be.

If Figure 1 represents the initial root activation involved in processing a morphologically complex word, what does recognition of an allomorph involve?

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'). These rules are "readjustment rules" in the framework of Distributed Morphology (Halle and Marantz (1993, i.e., a type of morphologically conditioned phonological rule).

The additional step of having to engage a morphological rule has, unsurprisingly, consequences. In the two experiments presented here, we see that at the early stage of lexical activation which we measure with MEG, 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.
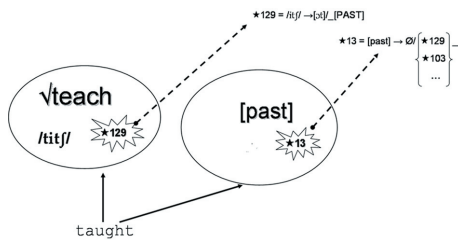

Figure 2. Schematic representation of process of recognition of morphologically complex form *taught*. The rule generating the non default allomorph is activated, and its output is checked against the form of the input.

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 behavioral measures to investigate the complex time course of lexical activation and decision. The brain-monitoring technology used is magnetoencephalography (MEG), which millisecond temporal resolution (see 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 third such component, 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).

A growing body of work (Embick *et al*, 2000 Pylkkänen *et al*, 2001, Pylkkänen, Stringfellow and Marantz, 2002, Pylkkänen *et al* (2003), Stockall, Stringfellow and Marantz (2004), Fiorentino and Poeppel, 2004, Beretta, Fiorentino & Poeppel, 2005 and Pylkkänen, Llinás and Murphy, in press) suggests that the M350 is the earliest component showing sensitivity to factors affecting the speed and accuracy of initial activation of lexical roots. Factors such as lexical frequency (Embick *et al*, 2000, Stockall, Stringfellow and Marantz, 2004), repetition priming (Pylkkänen *et al*, 2001), frequency of morphological constituents in compounds (Fiorentino & Poeppel, 2004), semantic relatedness in priming (Pylkkänen, Llinás & Murphy, in press), and the number of meanings associated with a phonological form and the number of related senses associated with a morphological root (Beretta, Fiorentino & Poeppel, 2005) all of which plausibly affect resting levels of root activation, have all been shown to affect the timing of the M350 evoked response component.

Crucially, the M350 has also been shown not to be sensitive to factors associated with post activation competition processes such as high phonological neighborhood density (Pylkkänen *et al*, 2002, Stockall, Stringfellow and Marantz, 2004). Pylkkänen *et al* (2002) found that stimulus items that had high phonotactic probabilities and were from dense phonological neighborhoods (two properties that are strongly correlated) were associated with delayed lexical decision times (plausibly the result of interlexical competition between a large number of similar activated lexical entries), but with *earlier* M350 latencies than low probability/density stimuli (the high sublexical frequencies of the high probability items are plausibly associated with higher resting levels of activation than lower probability items, thus facilitating initial activation). Stockall, Stringfellow and Marantz (2004) replicate the finding that sublexical frequency, but not neighborhood density, affect the latency of the M350 in an experiment that dissociates probability from density to investigate their effects independently. Pylkkänen *et al* (submitted) concluded therefore that, "the M350 must reflect initial activation of lexical hypotheses, prior to competition."

The finding that an evoked component peaking approximately 350ms after the onset of visually presented lexical stimuli is the **first** component to show sensitivity to factors affecting lexical access in some experimental manipulations seems hard to reconcile with a substantial body of results from self-paced reading, eye movement, and ERP experiments (summarized in Sereno & Rayner (2003)) that show that at least the initial stages of lexical activation are well underway within the first 250ms post stimulus onset. It's crucial to note, however, that the studies discussed by Sereno and Rayner involve reading words in sentences, while the M350 results discussed above all involve the reading of individual words presented in isolation (or, at most, preceded by a single prime), a situation in which there is no coherent context to generate predictions about upcoming material, or in any way facilitate the activation and recognition process.

In the experiments reported below, nothing crucial rests on the claim that initial activation of lexical hypotheses occurs approximately 350ms post stimulus onset. Instead what is crucial is that like lexical decision reaction times, the M350 evoked component is a dependent measure sensitive to a wide variety of factors known to affect the speed of lexical access, but that unlike reaction times, this neural measure is not affected by interlexical competition and selection processes. The M350 is therefore predicted to allow the dissociation of early effects of morphological priming from later effects of form or allomorph competition. Whether or not earlier activation, particularly in posterior brain

regions might also be sensitive to such lexical properties as root or word frequency [see Pylkkänen *et al* (submitted) for further discussion] is certainly interesting, but not directly relevant to the experiments reported here.

2.   Experiment 1

Allen and Badecker (2002) show that priming is affected by differences between pairs of irregular past tense/regular stem allomorphs depending 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 hypotheses of our model with the predictions of either the single mechanism, association based 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 stored whole 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, just as the regular past tense *walked* will activate the root WALK.In addition, 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 condition 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), although Allen and Badecker report no consequences of this minor difference in the way they counted). The number of letters found in one item in a pair, but not the other was tallied for each pair (e.g. **give**-**gave** = 2, ta**ught**-**teach** = 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 or greater were classified as low overlap, and those with scores of 3 or lower)as high overlap items.

The item 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 ir-

regulars, 4.2; orthographically related, 4.3; identity, 4.4; an ANOVA (length x condition) 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).

Table 1.   Example stimuli from Experiment 1.

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

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 pairs 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 wholehead 93 channel system (Kanazawa Institute of Technology, Japan). Data were sampled at 1000Hz, with acquisition between DC and 200Hz. External sources

of noise were removed online using an active compensation coil system (Vacuumshmelze, Hanau, Germany). 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. 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. The results reported below reflect the lexical decision behavior of 16 subjects and the neurally evoked behavior of 8 of those subjects.

Figure 3 shows a grandaveraged evoked waveform for a representative subject with the isofield contour map corresponding to the M350 response and the location of the single dipole that best models the evoked signal as measured by left hemisphere sensors. The red areas are those for which sensors recorded outgoing magnetic signal (source), while the blue areas represent the incoming component (sink) of the magnetic field generated by the M350 dipole source.

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
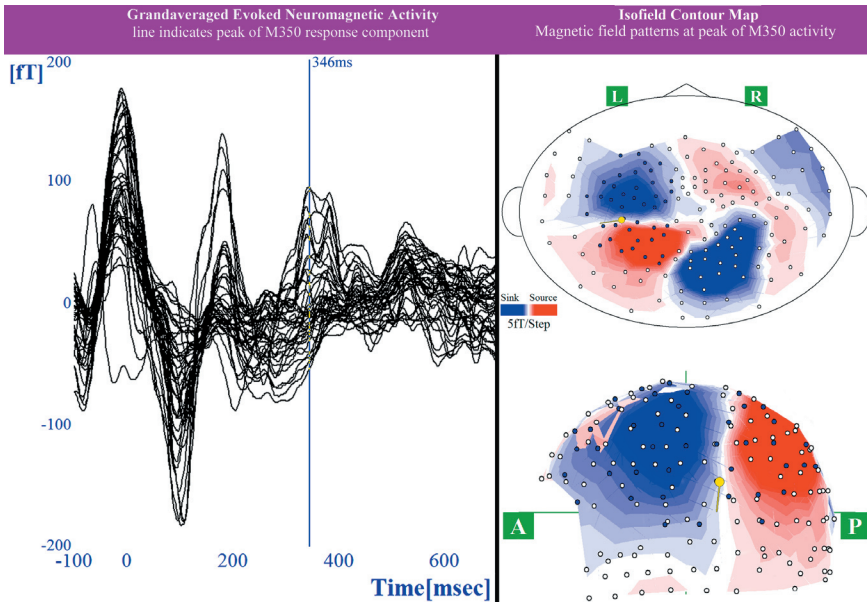
Figure 3. Evoked Neuromagnetic Activity from representative subject. Filled in circles on contour map indicate sensors of interest used in RMS analysis.

for each participant. The set of sensors chosen was the set that best captured the left hemisphere negative and positive field patterns associated with this component. This method of analysis conforms to that used in a number of other MEG word recognition studies (Beretta *et al.*, 2005, Embick *et al.*, 2001, Harada *et al.*, 2004, Helenius *et al.*, 2002, Pylkkänen *et al.*, 2002). The number of sensors chosen for each subject ranged from 29 (31% of the total sensors) to 38 (41%) (mean number of sensors = 34) (see darkened 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.

An equipment failure, undetected during the recording sessions, prevented acquisition of the subjects' precise head position within the sensor array, making a source activation analysis of the M350 impossible for this experiment and for experiment 2

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 ($F(1,7) = 15.39$, $P<0.002$) (unrelated x̄ = 369.6ms, related x̄ = 341.2ms). No other main effects were significant. Planned comparisons revealed significant differences in the latency of the M350 component for the identity condition ($p = 0.008$)(unrelated x̄ = 355ms, related x̄ = 324ms), the high overlap irregulars condition ($p = 0.047$) (unrelated x̄ = 374ms, related x̄ = 348ms) and the low overlap irregulars condition ($p = 0.045$) (unrelated x̄ = 371ms, related x̄ = 339ms). The (form overlap) condition showed a trend towards priming, but the effect was not significant ($p = 0.16$) (unrelated x̄ = 361ms, related x̄ = 343ms).

A similar 4x2 factor ANOVA on M350 amplitudes revealed no significant main effects ($F(1,7) = 0.725$), though the amplitudes evoked by the prime conditions tended to be lower than the amplitudes in the control conditions for all four stimulus categories.

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 ($F(1,7) = 8.1389$, $P<0.0002$).

Planned comparisons revealed significant effects of condition on reaction times.

Reaction times were significantly faster for primed items in the identity condition ($p = 0.0009$) (unrelated x̄ = 666ms, related x̄ = 603ms) and in the high

Table 2. Mean M350 Latencies and Lexical Decision Times (all in ms) Averaged Across Items in Experiment 1.

Condition	MEG			RT		
	Rel.*(SD)*	Unrel.*(SD)*	Dif.	Rel.*(SD)*	Unrel.*(SD)*	Dif.
Identity	323.2*(31.3)*	354.9*(26.2)*	−31.7*	603.4*(138)*	665.9*(171.1)*	−62.5**
Hi-O Irr						
(eg. *gave–give*)	347.6*(25.6)*	374.1*(48.2)*	−26.5*	586.9*(124.3)*	605.6*(142)*	−18.7*
Lo-O Irr						
(eg. *taught–teach*)	338.7*(57.4)*	371.1*(41.8)*	−32.4*	619.5*(184.4)*	606.5*(151.9)*	13
Ortho-O						
(eg. *stiff–staff*)	343.1*(28.9)*	359.2*(26.9)*	−16.1	664.7*(192.6)*	637.1*(162.5)*	27.6*

*$p<0.05$; **$p<0.001$

SD = standard deviation

overlap irregulars condition ($p = 0.038$) (unrelated x̄ = 605ms, prime x̄ = 587ms). Reaction times were significantly delayed in the priming condition for the form overlap items ($p = 0.009$) (unrelated x̄ = 637ms, prime x̄ = 665ms). There was no reliable effect of priming for the low overlap irregulars condition ($p = 0.23$)

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 behavioral 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 behavioral 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 effect is not significant and the RT effect is, while for the irregular verbs with low form overlap, the opposite is true. The M350 effect is significant and the behavioral effect is not.

The evoked responses to the orthographic overlap condition are expected 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 selection among activated candidates that is necessary for 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 high overlap irregulars, despite their high form overlap which could plausibly induce competition related processing difficulties, 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 low overlap irregulars like *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 behavioral 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 without precedent. 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 2. This reversal has two goals. The first is to investigate whether neural and behavioral responses 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 that activates it is a regular or irregular allomorph.

The model does, however, allow later differences. The effect of having to activate a specific irregular rule in the recognition of the irregular allomorph could explain the absence of any behavioral 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 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. 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. MEG and lexical decision time data was collected from all participants.

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. Participants were asked to

Table 3. Example Stimulus Set for Experiment 2

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

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 from this study included in the materials for experiment 2 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 related pairs in the experiment constituted 25% of the total number of pairs.

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. External sources of noise were removed online using an active compensation coil system (Vacuumshmelze, Hanau, Germany). 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 1. 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, leaving 10 subjects whose data was included in the analysis.

Sensors of interest were determined in the same manner as in experiment 1. 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.

As explained in Section 2.1.4, equivalent current dipole analysis was not possible for the majority of subjects who participated in this experiment.

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 ($F(1,9) = 3.62$, $P<0.029$).

Table 4. Mean M350 Latencies (in ms) Averaged Across Items in Experiment 2

Condition	Overall	Rel.*(SD)*	Unrel.*(SD)*	Dif.
Regular (eg. *jump–jumped*)	338.4*(26.0)*	331.4*(24.2)*	345.4*(27.1)*	−16*
Hi-Overlap Irr (eg. *give–gave*)	342.3*(44.6)*	327*(40.8)*	357.6*(44.9)*	−30.6*
Lo-Overlap Irr (eg. *teach–taught*)	347.3*(32.7)*	334.4*(28.2)*	360.2*(33.1)*	−25.8*
+S+O-M(eg. *boil–broil*)	358.13*(28.1)*	358.7*(36.9)*	357.2*(23.6)*	+1.5
Average	345.92	335.72	355.1	−17.73

*$p<0.05$
SD = standard deviation

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 ($F(1,9) = 18.146, P<0.0003$) (related x̄ = 355.1 vs. unrelated x̄ = 335.72).

Finally an interaction was observed between condition type and relatedness. 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, but 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 irregular verb conditions (high overlap related x̄ = 357.6 vs. high overlap unrelated x̄ = 327, $P<0.004$) (low overlap related x̄ = 334.4 vs. low overlap unrelated x̄ = 360.2, $p = 0.018$) and the regular verb condition (related x̄ = 331.4 vs. unrelated x̄ = 345.4, $p = 0.054$).

A second 4x2 factor ANOVA on M350 amplitudes revealed no significant main effects ($F(1,9) = 0.258$). though as in experiment 1, the conditions that were associated with M350 latency priming also evoked smaller M350 amplitudes in the related than the unrelated conditions.

3.2.2   Reaction Time

A similar 4x2 factor ANOVA on reaction times revealed two significant main effects; one of condition ($F(1,12) = 23.982$, $P<0.0001$) and one of prime relatedness ($F(1,12) = 5.681$, $P<0.02$). Planned comparisons reveal that every pair wise comparison between two conditions was significantly different ($P<0.03$) except the comparison between the two irregular verb conditions ($P>0.9$).

The main effect of prime relatedness, seen in Table 5, is that across all experimental conditions, targets preceded by related primes were responded to faster than items preceded by unrelated primes (613.83ms vs. 634.18ms, mean priming advantage of 13.78ms).

Table 5. Mean Lexical Decision Time (ms) Averaged Across Items in Experiment 2

Condition	Overall	Rel.(SD)	Unrel.(SD)	Diff.
Regular (eg. *jump–jumped*)	637.85(51.12)	649.43(49)	625.33(51.37)	–24.1
Hi-Overlap Irr (eg. *give–gave*)	600.48(46.15)	587.9(45.53)	613.06(44.05)	–25.16
Lo-Overlap Irr (eg. *teach–taught*)	600.32(44.01)	586.5(36.9)	614.14(46.8)	–27.64
+S+O-M(eg. *boil–broil*)	666.05(55.85)	666.13(50.44)	665.96(61.99)	–0.17
Average	624.10(55.75)	613.83(55.48)	634.18(54.41)	–13.78

*$p<0.05$
SD = standard deviation

However, as can also be seen in Table 5 not all conditions contributed equally to the overall effect of prime relatedness. Whereas the three verb conditions all show differences of 24ms or more between the related and unrelated conditions, the *boil–broil* condition shows a difference of only 0.17ms (666.13ms vs. 665.96ms, $p = 0.92$).

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 or 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.

Figure 4. Summary of Irregular Verb Priming Effects Across Exp. 1 & 2
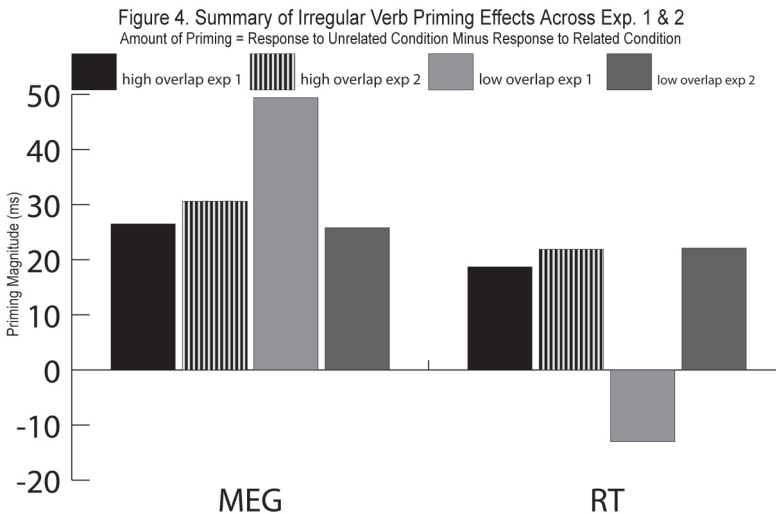Amount of Priming = Response to Unrelated Condition Minus Response to Related Condition

Figure 4. Summary of priming effects for the two categories of irregular verbs across the two experiments.

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 4 plots the difference between the related and unrelated conditions for the two irregular verb categories, across the two experiments.

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, association network 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 early 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 only irregular past tense forms are stored whole in the lexicon, and related to their stem correlates by similarity matrices, while regulars are fully decomposed and stored as roots and affixes. 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, and are instead associated with

priming magnitudes comparable to the regular verb and identity prime conditions, 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 full, across the board decomposition. They are just as clearly incompatible with any 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 association network 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 cognitive status 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 delay relative to the unrelated prime condition 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 2 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 mapping, 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 non-null generated by applying the past tense morpheme), 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 targets visually. In Experiment 1, using the identical stimulus items, but presenting both primes and targets 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 a differently suffixed target, where both are derivatives of the same root (ex: *darkly~darkness*), despite the fact that both suffixed allomorphs prime their unsuffixed stems robustly (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 types of morphological relatedness 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, or involves complications in the early visual recognition processes.

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.

4.4 The effect of form overlap

In addition to the unexpected patterning of responses to the *taught–teach* type items, which seems to relate to the issue of prime and target modality as discussed above, formal overlap also evoked a pattern of results not entirely easy to understand. In experiment 1, formal overlap was associated with significantly delayed lexical decision times as expected given the results of Allen & Badecker (2002). However, formal overlap was also associated with near significant priming at the stage of processing indexed by the M350 (the neural response to *cart* peaked 16ms earlier when it was preceded by *curt*, than when preceded by an unrelated baseline). This in itself is not hugely problematic as the high degree of formal overlap could conceivably facilitate the early process of activating stored lexical items, and only later cause delays by increasing the difficulty of competition and selection processes. However, the result stands in interesting contrast to the results for the +S+O-M items in experiment 2. These items also overlap to a high degree in their form, yet the related and unrelated conditions evoke neural responses with exactly the same latency (accessing *broil* when it is preceded by *boil* is neither faster or slower than accessing the same form when preceded by an unrelated prime). Of course the *boil–broil* type items are also semantically related, but semantic relatedness should facilitate initial activation.

Pylkkänen *et al* (submitted), in a study investing the effects of form overlap in bisyllabic words, find that when a target is presented following a prime with which it overlaps in medial material (ex: prime: *teacher* target: *reach*), it is associated with delayed reaction times, but earlier M350 peak activity, exactly as the *curt–cart* items in experiment 1 were. However, a target following a prime that matched in onset (ex: prime: *spinach*, target: *spin*), was associated with significantly delayed M350 latencies as well as delayed reaction times. Form overlap between prime and target, then, seems to facilitate lexical activation in some cases, but delay it in others, depending on the precise locus of the overlap. Since all the items in the form overlap condition in experiment 1, and all but 5 of the items in the +S+O-M condition in experiment 2 were monosyllables, it is not possible to directly relate the different results of the experiments reported here to the model of activation and competition argued for by Pyllkänen *et al.*

Processing the prime *boil* should involve activating *broil* via both semantic association and formal similarity. But the precise way in which these two kinds of activation should interact is not known. There are at least 4 distinct hypotheses about the way semantic relatedness activation and form overlap suppression could interact. Successfully recognizing *boil* could involve suppression of the activation of *broil* below resting levels (just as recognition of *spinach* seems to cause suppression of *spin*), such that no effect of the semantic spreading activation remains by the time the target *broil* is encountered. Alternately it could be that items connected by semantic links show more competition-related suppression, or, conversely that the semantic connections reduce the inhibition. And finally the effects of semantic relatedness activation and form overlap competition could be simply additive (subtractive) such that the competition induced suppression of *broil* cancels out the boost in activation resulting from semantic relatedness to *boil*. This final hypothesis best predicts the results we actually obtained. However, in addition to the possible interactive effects between semantic relatedness activation and form overlap suppression, a complete model of the priming effect would take into account the degree of form overlap suppression (determined by the similarity of the words and by the location of the similarities, in ways we don't fully understand yet (cf. the *spinach*/*spin teacher*/*reach* distinction) found in Pylkkänen *et al*, submitted).

Generating clear predictions for the effects of simultaneous form and semantic similarity would depend on a computational model that fixes the parameters for activation and suppression. Whatever the details of such a model, however, these complex interactions between form overlap and semantic relatedness for M350 priming are irrelevant to identity/morphological priming, where the same lexical entry is activated twice, without any suppression.

The experiments reported here show that at the relevant, early stage of lexical activation, all morphologically related forms activate their underlying root form, regardless of whether they are regular or irregular allomorphs of that root, and irrespective of the degree of formal overlap between past tense and root 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 initial decomposition of all forms, regardless of irregularity, and that all related allomorphs are exponents of the same root.

Notes

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 McClelland and colleagues in proposing a system of stochastic rules to derive allomorphs, rather than weighted associations. See McClelland and Patterson (2002) for further discussion of these two approaches.

2. All dictionary definitions cited in text are from the Oxford English Dictionary, 2nd Edition.

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Appendix: Stimuli

A. Stimuli Used in Experiment 1

Condition	Unrelated Prime	Related Prime	Target
Irregular High Overlap	beach	bit	bite
Irregular High Overlap	daily	bled	bleed
Irregular High Overlap	fate	chose	choose
Irregular High Overlap	faith	came	come
Irregular High Overlap	blood	dealt	deal
Irregular High Overlap	fault	dug	dig
Irregular High Overlap	dozen	drew	draw
Irregular High Overlap	luck	drove	drive
Irregular High Overlap	north	fed	feed
Irregular High Overlap	note	gave	give
Irregular High Overlap	fall	grew	grow
Irregular High Overlap	gift	hung	hang
Irregular High Overlap	holy	heard	hear
Irregular High Overlap	fear	held	hold
Irregular High Overlap	dance	met	meet
Irregular High Overlap	front	rang	ring
Irregular High Overlap	block	ran	run
Irregular High Overlap	lower	sent	send
Irregular High Overlap	hope	shot	shoot
Irregular High Overlap	large	sang	sing
Irregular High Overlap	crime	sank	sink
Irregular High Overlap	home	sat	sit
Irregular High Overlap	far	slid	slide
Irregular High Overlap	nose	spat	spit
Irregular High Overlap	fruit	swung	swing
Irregular High Overlap	daisy	woke	wake
Irregular High Overlap	food	wrote	write
Identity	bloom	grin	bloom
Identity	broil	still	broil
Identity	bust	rope	bust
Identity	clang	blue	clang
Identity	drip	paper	drip
Identity	file	ton	file
Identity	filth	tall	filth
Identity	flop	shoe	flop
Identity	ghoul	west	ghoul

A. Stimuli Used in Experiment 1 (continued)

Condition	Unrelated Prime	Related Prime	Target
Identity	glum	hat	glum
Identity	hot	wild	hot
Identity	link	pail	link
Identity	merge	peel	merge
Identity	mop	stove	mop
Identity	net	bend	net
Identity	pet	mist	pet
Identity	rug	mane	rug
Identity	sand	sort	sand
Identity	scorch	barn	scorch
Identity	scream	short	scream
Identity	shrink	race	shrink
Identity	sprain	car	sprain
Identity	tangle	pluck	tangle
Identity	tip	crane	tip
Identity	trim	shade	trim
Ortho Overlap	shoe	book	bake
Ortho Overlap	tire	bet	beet
Ortho Overlap	taste	bloke	bleak
Ortho Overlap	sting	brook	brake
Ortho Overlap	sock	brew	brow
Ortho Overlap	muck	carp	cart
Ortho Overlap	list	crept	crop
Ortho Overlap	tale	crew	cry
Ortho Overlap	howl	disk	desk
Ortho Overlap	guide	flesh	flash
Ortho Overlap	site	gore	gear
Ortho Overlap	pass	lane	line
Ortho Overlap	lint	pine	pane
Ortho Overlap	soil	pant	pint
Ortho Overlap	cling	plant	plane
Ortho Overlap	star	rope	ripe
Ortho Overlap	lock	shun	shin
Ortho Overlap	plot	slam	slim
Ortho Overlap	graft	slip	slope
Ortho Overlap	flour	stale	stall
Ortho Overlap	rocks	steps	steep
Ortho Overlap	tour	staff	stiff

A. Stimuli Used in Experiment 1 (continued)

Condition	Unrelated Prime	Related Prime	Target
Ortho Overlap	tone	stoop	stop
Ortho Overlap	cost	stew	stow
Ortho Overlap	rule	stroke	strike
Irregular Low Overlap	cause	bound	bind
Irregular Low Overlap	start	broke	break
Irregular Low Overlap	press	brought	bring
Irregular Low Overlap	fill	bought	buy
Irregular Low Overlap	turn	caught	catch
Irregular Low Overlap	tempt	did	do
Irregular Low Overlap	walk	fought	fight
Irregular Low Overlap	try	found	find
Irregular Low Overlap	move	froze	freeze
Irregular Low Overlap	boil	went	go
Irregular Low Overlap	keep	lay	lie
Irregular Low Overlap	need	lit	light
Irregular Low Overlap	shrug	paid	pay
Irregular Low Overlap	wait	said	say
Irregular Low Overlap	thank	sought	seek
Irregular Low Overlap	want	sold	sell
Irregular Low Overlap	dare	slew	slay
Irregular Low Overlap	kill	spoke	speak
Irregular Low Overlap	length	stood	stand
Irregular Low Overlap	pack	stole	steal
Irregular Low Overlap	crawl	struck	strike
Irregular Low Overlap	look	swore	swear
Irregular Low Overlap	spare	took	take
Irregular Low Overlap	call	taught	teach
Irregular Low Overlap	push	told	tell
Irregular Low Overlap	save	thought	think
Irregular Low Overlap	fail	wove	weave

B. Stimuli Used in Experiment 2

Condition	Unrelated Prime	Related Prime	Target
+S+O-M	shoe	blossom	bloom
+S+O-M	tire	boil	broil
+S+O-M	taste	burst	bust
+S+O-M	sting	converge	merge
+S+O-M	sock	crinkle	wrinkle

B. Stimuli Used in Experiment 2 (continued)

Condition	Unrelated Prime	Related Prime	Target
+S+O-M	muck	crumple	rumple
+S+O-M	list	flip	flop
+S+O-M	tale	ghost	ghoul
+S+O-M	howl	gloom	glum
+S+O-M	guide	mangle	tangle
+S+O-M	site	pat	pet
+S+O-M	tone	plunge	plummet
+S+O-M	lint	scald	scorch
+S+O-M	soil	scrape	scratch
+S+O-M	cling	screech	scream
+S+O-M	star	shimmer	glimmer
+S+O-M	lock	shrivel	shrink
+S+O-M	plot	slim	trim
+S+O-M	graft	strain	sprain
+S+O-M	rocks	squish	squash
+S+O-M	tour	drop	drip
+S+O-M	flour	clash	clang
Irregular Low Overlap	cause	bind	bound
Irregular Low Overlap	start	break	broke
Irregular Low Overlap	press	bring	brought
Irregular Low Overlap	fill	buy	bought
Irregular Low Overlap	turn	catch	caught
Irregular Low Overlap	tempt	do	did
Irregular Low Overlap	walk	fight	fought
Irregular Low Overlap	try	find	found
Irregular Low Overlap	move	freeze	froze
Irregular Low Overlap	boil	go	went
Irregular Low Overlap	keep	lie	lay
Irregular Low Overlap	need	light	lit
Irregular Low Overlap	shrug	pay	paid
Irregular Low Overlap	wait	say	said
Irregular Low Overlap	thank	seek	sought
Irregular Low Overlap	want	sell	sold
Irregular Low Overlap	dare	slay	slew
Irregular Low Overlap	kill	speak	spoke
Irregular Low Overlap	length	stand	stood
Irregular Low Overlap	pack	steal	stole
Irregular Low Overlap	crawl	strike	struck

B. Stimuli Used in Experiment 2 (continued)

Condition	Unrelated Prime	Related Prime	Target
Irregular Low Overlap	look	swear	swore
Irregular Low Overlap	spare	take	took
Irregular Low Overlap	call	teach	taught
Irregular Low Overlap	push	tell	told
Irregular Low Overlap	save	think	thought
Irregular Low Overlap	fail	weave	wove
Regular	mop	scour	scoured
Regular	rug	scowl	scowled
Regular	mane	balk	balked
Regular	shade	sop	sopped
Regular	car	lap	lapped
Regular	tip	chop	chopped
Regular	car	chase	chased
Regular	crane	dash	dashed
Regular	filth	slam	slammed
Regular	sand	bask	basked
Regular	link	look	looked
Regular	paper	lop	lopped
Regular	blue	cross	crossed
Regular	tall	push	pushed
Regular	crowd	drop	dropped
Regular	net	hop	hopped
Regular	file	nap	napped
Regular	pail	slap	slapped
Regular	grin	claim	claimed
Regular	still	sort	sorted
Regular	rope	clap	clapped
Regular	bend	prowl	prowled
Regular	hot	race	raced
Regular	ton	stop	stopped
Regular	west	toss	tossed
Irregular High Overlap	beach	bit	bite
Irregular High Overlap	daily	bled	bleed
Irregular High Overlap	fate	chose	choose
Irregular High Overlap	faith	came	come
Irregular High Overlap	blood	dealt	deal
Irregular High Overlap	fault	dug	dig
Irregular High Overlap	dozen	drew	draw

B. Stimuli Used in Experiment 2 (continued)

Condition	Unrelated Prime	Related Prime	Target
Irregular High Overlap	luck	drove	drive
Irregular High Overlap	north	fed	feed
Irregular High Overlap	note	gave	give
Irregular High Overlap	fall	grew	grow
Irregular High Overlap	gift	hung	hang
Irregular High Overlap	holy	heard	hear
Irregular High Overlap	fear	held	hold
Irregular High Overlap	dance	met	meet
Irregular High Overlap	front	rang	ring
Irregular High Overlap	block	ran	run
Irregular High Overlap	lower	sent	send
Irregular High Overlap	hope	shot	shoot
Irregular High Overlap	large	sang	sing
Irregular High Overlap	crime	sank	sink
Irregular High Overlap	home	sat	sit
Irregular High Overlap	far	slid	slide
Irregular High Overlap	nose	spat	spit
Irregular High Overlap	fruit	swung	swing
Irregular High Overlap	daisy	woke	wake
Irregular High Overlap	food	wrote	write