MAGENTOENCEPHALOGRAPHIC INVESTIGATIONS OF MORPHOLOGICAL IDENTITY AND IRREGULARITY

by

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ABSTRACT

This thesis addresses the longstanding debate in the psycholinguistics literature about the correct way to characterize the psychological status of morphological relatedness and irregular allomorphy. The model argued for here is one in which the mental lexicon consists of lexical roots (sound~meaning pairs that are arbitrary in the Saussurian sense, such as CAT: 'feline'↔/kæt/) and functional morphemes (affixes such as the plural marker *–s*, that carry purely grammatical information). Complex words are assembled by the grammar out of these roots and affixes. We argue that this is true even for words like *gave* which don't clearly separate into two pieces, but are abstractly parallel to *walked*, which does. Evidence for this full, across the board decomposition model is provided in a series of priming experiments that use magnetoencephalography to measure the earliest stages of lexical processing. Both regular and irregular allomorphs of a root are shown to access their root equally. These results, then, are incompatible both with connectionist models which treat all morphological relatedness as similarity, and with dual mechanism models which argue that regular allomorphy and irregular allomorphy arise from completely different systems, and only regular allomorphy involves root activation and composition.

In this model, morphological relatedness is argued to be an identity relation between various allomorphs of a single, shared root, and is therefore clearly distinguished from semantic and phonological relatedness, which merely involve similarity between the meaning, or form, of different roots. The experiments reported in this dissertation support this model: the neural responses evoked by identity are significantly distinct from the neural responses evoked by similarity.

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DEDICATION

- *To my mother and father for giving me a name to grow into and live up to and be forever inspired by.*

- *To Douglas Adams for first putting the idea in my head that mathematical modelling of biological systems could be the most beautiful music in the universe.*

- *And to my sweet Dixie-bear, for fearlessly travelling with me on this journey, and always, always being up for a game of fetch.*

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ACKNOWLEDGEMENTS

This dissertation began to be a possibility when I sat in my first Introduction to Linguistics course in 1996 at Concordia University. Professors Mark Hale, Ida Toivonen and Charles Reiss taught me how to think about language as a biological system and also the importance of never, ever taking oneself too seriously - two lessons that have served me well. Without their inspiration and encouragement, I never would have conceived of graduate school. So you can blame them a little for everything that's ensued.

Getting accepted to graduate school would have been immeasurably more stressful and miserable if I hadn't been able to share the process with Patrick Davidson, Jean-Philippe Marcotte, and Afton Lewis. Everyone needs cheerleaders, especially ones that look so good in short skirts.

The first year of graduate school is supposed to be awful. That mine wasn't has so very much to do with my fabulous luck in meeting and getting to live with Elizabeth Hale. For three years she was my friend, my flatmate and my mentor and I can't imagine better footsteps in the world to have followed in. Someday I'll follow them all the way to New South Wales.

The rest of graduate school was pretty darn fun too, thanks so very much to the Boston Dining Club (Cristina Cuervo, Daniel Harbour, Stephanie Harves, Tatjana Marvin and Michael Wagner) for great food, great wine and great conversation; to my fellow Ling-99ers (Teal Bissell Doggett, Ken Hiraiwa, Franny Hsiao, Yougjoo Lee, Lance Nathan and Shogo Suzuki) for being a lovely and idiosyncratic bunch – we suited each other well, somehow; to the lab beer crew (Liina Pylkkänen, Andrew Stringfellow, Karen Froud, Diana Sonnenreich and a rotating cast and crew of dozens), for teaching me that science makes you thirsty, and beer really is brain food; and also to my other dear MIT friends who don't quite fit in any of these categories: Paul Elbourne, Dan Giblin, Shinichiro Ishihara, Chris Naylor, Lea Nash, Bev Stohl and Pranav Anand.

I have to leave the place behind, but these people? I'll take with me always.

And finally, most importantly, I have to thank Alec Marantz, my teacher, employer, advisor, co-author and most importantly my friend, for opening my eyes to the possibilities of cognitive neuroscience and helping me to find my place in it, for being encouraging and patient and exacting in just the right measure. And for watering my plants and driving me to Pier One and buying me dinner when I needed it. Arigato gozaimashita.

XANDER: I've always been amazed with how Buffy fought, but... in a way, I feel like we took her punning for granted.

WILLOW: Xander, ***past tense rule****.*

XANDER: Oh, sorry. I just meant we in the past took it for granted and, uh... we won't when she gets back.

BtVS, Season 3, Episode 1 "Anne"

Chapter 1 Introduction

In an important sense, this thesis has only one goal. And that is to provide support for a model of the human linguistic system in which morphological decomposition is real (*walked* = *walk* + PAST) and across the board (*gave* = *give* + PAST).

1.1. The Past Tense 'Debate'

Full, across the board decomposition is not an uncontroversial claim. In fact 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. Although, as Table 1 illustrates, there are at least three possible models of inflectional allomorphy, the debate has essentially been between proponents of the two greyed in alternatives.

Single Mechanism, Full Listing	Dual Mechanism, Regulars Decompose, Irregulars are listed.
Single Mechanism, Full Decomposition	

Table 1. Possible Analyses of Inflectional Systems

For the most part this debate has centred on the status of the regular pattern. Both sides are in general agreement that irregular past tense forms are memorized as whole words and are related to their stem correlates on the basis of their semantic and phonological similarities (but see the standard linguistics literature on morphology and allomorphy, for example Halle and Marantz, 1993, for a very different account). The disagreement has been over whether regular past tenses are also stored as whole words, and also related to their stems via similarity matrices, or whether they are composed by a rule that adds the past tense morpheme –*ed* to verb stems.

It's this question that's really at the heart of the debate – in fact the status of the *irregular* past tense forms isn't generally up for discussion. James McClelland, the figure most strongly associated with the connectionist side of the debate, makes it clear in a recent *TiCS* review article (McClelland and Patterson, 2002a) that the real question is whether accounting for human linguistic knowledge and behaviour requires any rules, algorithms or symbolic computation of any sort:

> One view of language, originating with Chomsky, championed by Fodor and Pylyshyn and widely pursued by Pinker, holds that abstract symbolic rules play a central role in human language processing. This claim is part of a broader view that human cognitive mechanisms are symbolic, modular, innate, and domain-specific. And alternate view, from Rumelhart and McClelland, challenges the need for the use of rules.

The English past tense (and inflectional systems more generally) has been such a battle ground precisely because it's one domain in which some theorists who otherwise endorse a version of the Chomskian generative program argue that rules are inadequate for characterizing the system.

Proponents of the single mechanism, full listing model generally agree with the contention that an association based network of similarity relations is the right way to model the relationship between forms like *taught* and *teach*. However, they also argue that this kind of network is the correct way to account for the relationship between *walked* and *walk* as well.

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. Thus *help* would be represented by `'_ he'`, `'hel'`, `'elp'`, and `'lp_'`. The model uses intermediary units called 'Wickelfeatures' (WFs), each of which represents a feature from each of the phonemes in such triads. For example, there is a WF representing the feature sequence LIQUID–UNVOICED–END, which would be active in representing 'lp_'. In general, words ending in a unvoiced phoneme are represented by several WFs capturing the feature that the final phoneme is unvoiced.

For regular verbs in English, if the stem ends in a unvoiced sound (like the /p/ in help) the past tense will be formed by adding the unvoiced dental /t/. For the past tense output *helped*, the WFs that represent the 'lp_' sequence should be replaced with others representing the added unvoiced stop /t/ that forms the past-tense inflection. The more the system encounters LIQUID–UNVOICED–END inputs that map to LIQUID-UNVOICED-UNVOICED & UNVOICED-UNVOICED-END sequences in the output, the stronger the connection between these WFs will become and the more 'regular' the pattern becomes. 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*. Figure 1. schematizes the Rumelhart-McClelland model of past tense inflection.

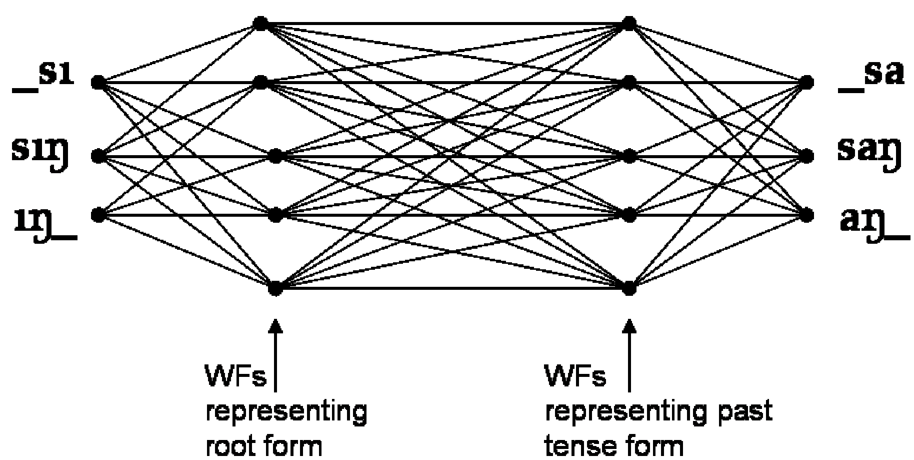

Figure 1. The Rumelhart-McClelland model of past tense inflection for the pair *sing~sang*.

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. The past tense output is 'generated' if its probability of being the past tense correlate of a particular stem is sufficiently high[1]. 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 WFs, have stable, quantifiable strengths, just as other connections in the system do, mediated either by phonological or semantic similarities.

Precisely what is meant by *connectionist modelling* varies substantially depending on who is doing the modelling. Smolensky (1995, p. 226), for instance, describes the aim of connectionist modelling of cognitive systems as to 'explain how symbolic computation is built upon neural computation'. This conception of the goal of connectionist modelling is far more compatible with the Chomskian generative position than what McClelland et al (2002a) have in mind in the passage quoted above.

It's far beyond the scope of this dissertation to argue that connectionist models, or parallel distributed processors, are categorically incapable of accurately modelling human cognitive capacities. I would tend to agree with Marcus (1998), who states, "My own view is that connectionism *can* ultimately make profound contributions to our understanding of cognition, albeit embedded in a more moderate view that seeks to explain rather than deny the existence of innate representations, innate modules, and innate machinery for manipulating symbols."(p. 157).

What I will argue is that an associative network relating a variety of different kinds of words based on their similarity to each other, with no distinction made between similarity and identity, is not tenable as a model of human morphological knowledge and processing.

[1] Exactly what the critical threshold is for generation in this sense varies from particular network to particular network.

The core of this dissertation is an argument that morphological relations necessarily involve identity, while other kinds of relatedness between words of a language such as symbolic and semantic relatedness, merely involve similarity.

Marcus et al (1995) provides one of the most persuasive and systematic sets of arguments that regular verbal morphology in English must necessarily be modelled as a system involving symbolic computation. They discuss in detail twenty-one separate instances in which accessing a stored memory representation is not possible and show that the regular inflection is applied in every case. These instances fall into six general categories, listed in (1).

(1). a. Lack of entry or similar entries in memory
b. Competing entries or similar entries in memory
c. Entry is not a canonical root
d. Root cannot be marked for inflectional feature
e. Features cannot percolate from root to whole word (exocentrism or headlessness)
f. Memory failures

The fact that every one of these cases results in the generation of a regular past tense form, and that the precise past tense ending is constrained by the morpho-phonological alternations that apply generally to the regular past tense in English, provides a strong argument in favour of a system with a default rule that combines with any verbal element.

Nonetheless, in English the regular past tense is far and away the most frequent of all the past tense allomorphs. Therefore Marcus et al also consider German in order to separate frequency from regularity. The crucial point is that the notion of default is **not** another way of saying 'most common', or 'most active pattern'– the default form is the one that occurs when no more specific rule produces an alternative.

German presents at least two morphological systems where the regular allomorph is not the most frequent: participles and plurals. In both cases, Marcus et al make the argument that the regular is nonetheless the default allomorph, just as they argued the case for the English regular past tense.

These arguments for the psychological reality of morphological rules, and the rich and varied body of work in theoretical linguistics over the past 35-40 years providing overwhelming evidence that words decompose into roots and affixes, are generally accepted by those who argue for the Dual-Mechanism model. This model is articulated in slightly different ways by it's different proponents (Pinker and Prince, 1988; Ullman, et al, 1997; Marslen-Wilson and Tyler (1998); Clahsen, 1999, etc). The consensus, however, is that 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.

Ullman et al (1997), for example, describe the model as follows:

> A simple theory is that irregular forms are memorized, and regular forms are generated by rule. Regulars and irregulars interact as follows: retrieval of an irregular blocks the rule (*dug* preempts *digged*); when an irregular is not successfully retrieved, the rule may be applied, resulting in "overregularization" errors such as *digged.* (p 267).

Figure 2. schematizes the model of the lexicon this dual mechanism approach argues for.

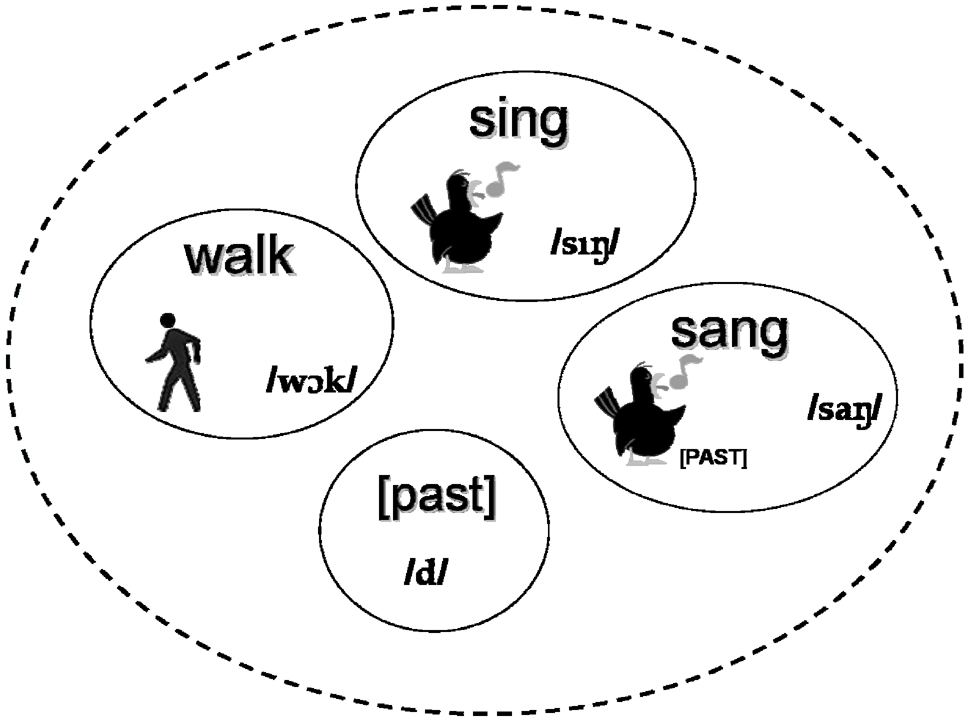

Figure 2. A schematic representation of the lexicon as envisioned by the dual mechanism hypothesis. Irregular allomorphs are stored as distinct lexical entries, while the regular past tense form is derived by combining the stored stem and the stored past tense morpheme according to the regular rule.

A variety of evidence is argued to support this dual-mechanism approach. One type is the fact that the regular patterns are productive and generalize to new forms (see the discussion of Berent, Pinker & Shimron, 2002 in §1.2.2 and the discussion of Marcus et al (1995) below, for two studies showing this difference in productivity). The investigation of different neurological disorders has also been taken to show that regular and irregular allomorphs are stored and accessed via fundamentally mechanisms. Some of this literature is discussed in §2.1.2.1.

And, most importantly in the context of the work presented in this dissertation, priming studies have been taken as support for the dual-mechanism model. From the earliest work on morphological priming by Stanners and colleagues (Stanners et al, 1979), irregular past tense/stem pairs have been found to be associated with less priming than regular past tense/stem pairs. Chapters 3 & 4 of this dissertation provide clear evidence that the behavioural differences between regular and irregular allomorphs when it comes to stem priming are not due to fundamentally different mechanisms of storage and retrieval. At early stages of lexical processing, all past tense forms prime their stem correlates.

This single mechanism, full decomposition, alternative to allomorphy, while not nearly as popular as the two other proposals, is not an innovation of this dissertation. One recent articulation of a model of allomorphy that is of the third type is that proposed by Adam Albright (Albright, 2002; Albright and Hayes, 2003). Albright and colleagues note that the English irregular past tense is not without patterns. This is not a new observation in and of itself. The most cursory examination of the set of irregular past tense forms turns up several subsets of items that seem to pattern together: for the set {*read, lead, bleed, breed, mislead, misread*} the front high tense vowel [i] maps to the front high lax vowel [ɪ] in the past tense forms , in the set {*speak, freeze, weave, interweave*, *bespeak*}, [i] maps to the back mid vowel [o] and the stems in the set {*ring, spring, sing, drink, shrink, sink, stink, swim, begin*} correspond to past tense forms with the low front vowel [æ] replacing the [ɪ].

However, Pinker (1999) voices the problem with attempting to make something contentful of these patterns:

> Just as we have a rule adding "ed" to form the regular past tense, we [could have] a suite of rules that generate irregular past tense forms by substituting vowels or consonants. For example, one rule changes "i" to "u" in verbs like "cling, clung"…A problem for this theory is the family resemblance among the verbs undergoing the rule, such as "string, strung", "sting, stung", "fling, flung", "cling, clung". How do you get the rule to apply to them?

And of course, the corollary of Pinker's question is 'how do you get the rule *not* to apply to *bring*, *sing*, or *ping*, all of which have different past tenses?'

The crucial property of Albright's proposal is that the rules which characterize all the past tense forms in a language, both regular and irregular, are stochastic. Albright shows that the phonological shape of verb stems plays an important role in determining what form they will take in the past tense. Rules simply have to include probabilistic confidence values based on how reliable different alternations are. An example of some of the rules Albright argues for is in Table 2.

Rule	Confidence Value	Successes/Failures	Output
Ø →əd/[X{d,t}_]$_{[+past]}$	.872	*want, need, start, wait, decide,* etc. /**get,* **find,* **put,* **set,* **stand,* etc.	*gleeded*
i →ɛ/[X{l,r}_d]$_{[+past]}$	.793	*read, lead, bleed, breed, mislead, misread/ *plead*	*gled*
i→o/[XC_[+cons]]$_{[+past]}$	.033	*speak, freeze, weave, interweave, bespeak/ *leak, teach, *leave,* etc	*glode*
no change/[X {d,t}_]$_{[+past]}$	.014	*shed, spread, put, let, set, cut, hit, beat, shut, hurt, cost, burst, split,* etc/ **get,* **want,* **need,* etc.	*gleed*

Table 2. Past tense rules[2] that could apply to *gleed* ranked by confidence value[3]. [Albright & Hayes, 2003]

The model outlined in Albright and Hayes (2003) is primarily a model for generating past tense forms for novel verbs, rather than a proposal for how existing verbs are actually processed. They are clear to point out that the set of existing English irregular past tense forms could still be listed as whole word forms, and that this whole word listing would serve to prevent it's members from being regularized. But note that whole word listing is not necessary in order to prevent the default rule applying to irregular forms and generating past tenses such as *helded* or *gived*. Blocking default rule application can also be accomplished by listing the set of roots a given rule applies to as part of the definition of the rule and having a system in which more specific rules are applied first and the more general rules only apply when no more specific rule can apply. Halle and Marantz (1993) is an example of a system in which blocking is accomplished in this manner. Whole word form listing is not required in their system.

The Albright and Hayes model has two key properties that distinguish it from either the dual-mechanism accounts, or the single-mechanism, pattern-associator accounts. First,

[2] Note that Albright and Hayes' (2003) notion of rule is similar to that of Anderson (1992). The past tense rule doesn't add the affix *–d*, the past tense rule specifies in what way the past tense feature already attached to the stem should be realized phonologically. This is a system *with* rule based allomorphy, but *without* affixes and must be distinguished from most other theories of morphology (from Chomsky and Halle

[3] The confidence value is a score based on the ratio between the number of targets in the language the rule could apply to and the number it actually applies to. See Albright and Hayes (2003) for a detailed discussion of how these scores are calculated.

Albright and Hayes argue against a clear dissociation between regular and irregular past tenses. They provide experimental evidence that the regular past tense forms are not a homogeneous class. Certain patterns of regularization are more robust (have a greater confidence value) than others. For example, every verb of English that ends in a voiceless fricative ([f, θ, s, ʃ]) is regular. A rule covering just this subset of cases, formulated as in (2). has a confidence of .988, far higher than the confidence of the more general past tense rules in (3). In Albright and Hayes terms, this subset of cases forms an *Island of Reliability*.

(2) $$\emptyset \rightarrow t / X \begin{bmatrix} \text{-sonorant} \\ \text{+continuant} \\ \text{-voice} \end{bmatrix} \_\_]_{[+past]}$$

(3) a. $\emptyset \rightarrow d /\ [X[\text{+voice}]\_\_]_{[+past]}$

b. $\emptyset \rightarrow t /\ [X[\text{-voice}]\_\_]_{[+past]}$

c. $$\emptyset \rightarrow \text{əd} /\ [X \begin{bmatrix} \text{-coronal} \\ \text{+anterior} \\ \text{-continuant} \\ \text{-nasal} \end{bmatrix} \_\_]_{[+past]}$$

In two experiments in which participants generated and also rated past tense forms of novel verbs, Albright and Hayes found that even for the regulars, the extent to which a verb falls inside an island of reliability is an important factor in determining which past tense forms were generated and how well various alternatives were ranked.

The second feature of the Albright and Hayes proposal is that they explicitly demonstrate that a model that generates past tense forms on the basis of analogy to existing patterns is inferior to a rule based model, even for the irregulars.

Although Albright and Hayes do not make the point themselves, it's clear that allowing that the irregular past tense forms may be listed whole is not equivalent to endorsing the dual-mechanism model. The dual mechanism model treats irregular past tenses as unanalysed wholes related to one another on the basis of analogy and related to their stems by similarity relations, rather than by identity. For Albright and Hayes, *gave* is not merely related to *give*; *gave* **is** *give* in the environment of the past tense.

1.2. The Third Way – What is *Morphological Relatedness*

As already stated, this dissertation is primarily an attempt to argue that morphological relatedness, such as that between an irregular past tense form and the bare infinitive of the same root, is an identity relation, not a similarity relation. The experiments reported in Chapters 3-5, taken together with many of the experimental results discussed in various sections of Chapter 2, offer strong evidence that recognizing the form *gave* involves activating the root GIVE just as surely as accessing the form *give* involves activating that same root.

Where we part company with the specific formulation of morphological identity proposed in Albright and Hayes (2002), is in the status of affixes. Albright and Hayes follow Anderson (1992) and adopt an affixless system. Rules provide the mechanism whereby functional material is realized, so that in 3.a. above, repeated here as (4), the rule can be paraphrased as in (5).

(4) $\varnothing \rightarrow d /\ [X[+voice]\_\_]_{[+past]}$

(5) A word whose final segment is voiced and which occurs in the environment of the feature [+past] is realized with a final [d]

Anderson calls his system A-Morphous morphology precisely because it does not involve morphemes which can be combined together to form complex words.

By contrast, in the system argued for in this dissertation morphemes are very real. The past tense of *walk* consists of two morphemes, the root (WALK) which contributes the essential semantics of not-especially-hurried bipedal locomotion and the past tense marker, which surfaces in one variant of its default form as *-ed*. Rules are the mechanism by which these pieces are put together to form words.

1.2.1. In Defence of Decomposition

There is no shortage of evidence for the existence of morphemes. In §2.2.1.1.1., I discuss two experiments that show that regular allomorphs 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 treated as distinct units as well, even when they never surface as such. They use a visual-visual priming paradigm to investigate the status of bound stem allomorphs in Finnish. They prime monomorphemic nominative singular nouns like *sormi* "finger" with three different kinds of primes: identitical primes (*sormi*), bound stem allomorphs of the target (*sorme* from *sormesta* "from finger"), and phonologically matched pseudo-words like *sorma*. Even though the bound stem is in fact a non-word 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 similar experiment also reported in Järvikivi and Niemi (2002), the authors find 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 persuasive 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.

McCarthy (1981) argues that the correct analysis of Arabic morphology involves the combination of three separate morphological pieces: a triconsonantal root which, like roots in all other languages, provides the core semantic meaning of the word ; a vocalic melody which contributes syntactic information such as voice, and an abstract CV skeleton which specifies what phonological shape the combination of the root consonants and the melodic vowels will take. This three component model is exemplified in figure 3. for the form [batar] (*cut*).

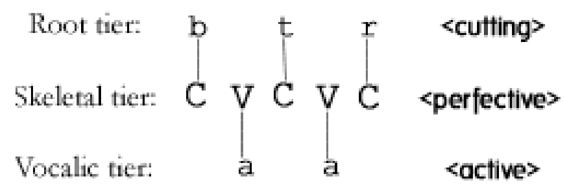

Figure 3. Multi-linear representation of the complex from [batat] (*cut*) [Boudelaa & Marslen-Wilson, 2003]

A crucial property of this model is that the skeletal tier is (a) a morpheme[4] and (b) devoid of phonological content until it's associated with a root and a vocalic melody.

Arabic skeletal morphemes are therefore, as Boudelaa and Marslen-Wilson point out, a perfect test case for establishing the status of morphemes independent of the overlaps in form and meaning that generally characterize morphological relations. If there is evidence for morphological priming where morphemes have no phonetic content, the priming cannot be based on phonological or orthographic similarities between items.

Priming effects are well established for discontinuous triconsonantal roots in Semitic languages (see: Boudelaa and Marslen-Wilson, 2000 and Frost et al 1997).

In their 2003 paper, Boudelaa and Marslen-Wilson 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 discussed in §2.1.1.3., semantic relatedness is not correlated with a processing advantage when the prime is not available to conscious recognition.

[4] There are other analyses of Semitic morphology that do not treat the prosodic template as a morpheme, but McCarthy explicitly claims that the CV skeleton is "a morpheme or a string of morphemes" (McCarthy, 1982, p.192).

It's worthwhile noting that the modality of the prime made no difference in whether or not the skeletal tier morphological priming effect was observed, in contrast to several cases discussed in §2.1.1.2., where cross-modal priming seems to interact with morphological priming effects in curious ways.

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. And, as we will see in §2.2.1.1.1., in the case that those constituent morphemes are regular and robustly attested in the language (whether they are linear strings like *–er*, or abstract CV templates) the decomposition happens within the first 200ms of processing, well before lexical access.

1.2.2. Roots and allomorphs and rules, oh my!

The effects of regular morphological relatedness can be dissociated both from the effects of orthographic or phonological similarity and the effects of semantic similarity. In case after case, morphological relatedness is shown to pattern with identity, in ways that are not predictable on the basis of phonological or semantic relatedness.

And 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. And neuropsychological investigations of impaired populations reliably find dissociations between regular allomorphy and regular allomorphy. 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 in Chapters 3-5 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 in Chapters 2 & 3 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 spreading activation do we find effects of irregular allomorphy. And 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[5].

Making sense of these complications requires a model in which we carefully distinguish roots from allomorphs and similarity from identity. I sketch the basic properties of this model in figure 4. and return to it in the discussion of various experimental results.

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[5] Note that a surface form *run* or *walk* shouldn't really be analyzed as a bare, monomorphemic form. English is a morphologically impoverished language, so that the phonological exponent of the present tense morpheme is null for all persons and number except 3rd person, singular (just as the past tense is null in forms like *hit*). This makes it easy to call a present tense form in English a stem, or basic, form. But in most languages in the world, the stem, or base, form actually never surfaces on its own. Many linguistic theories of allomorphy explicitly include zero (Ø) morphemes in the system, so that, for example, 'teach-Ø' is morphologically complex, just as are 'teach-ing' or 'teach-es'.

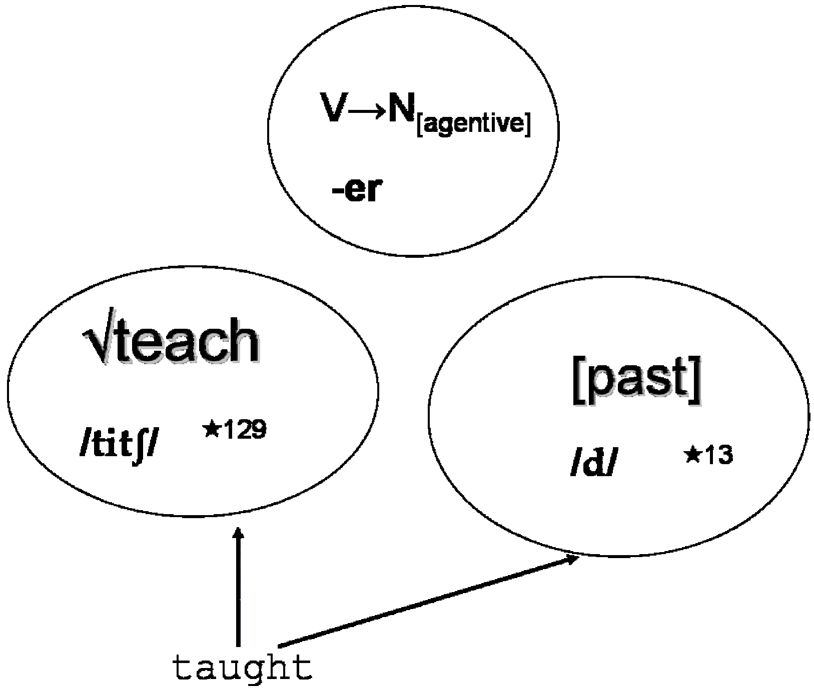

Figure 4. A schematic representation of the initial stage of root activation. Processing of the past tense form `taught` activates the root TEACH, and the functional morpheme [PAST]. The ★superscripts indicate specific morphological rules. Rule 129, for example, would be the rule: /itʃ/→[ɔt]/_[PAST][6], while rule 13 would be the rule generating a phonologically null allomorph of the past tense.

A root 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[7] "*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 /titʃ/. 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

[6] I've here chosen to represent the allomorph of TEACH that occurs in the past tense and in the participle form as *taught* and the allomorph of the past tense that occurs with the root TEACH as null. However, it's at least as plausible that the irregular allomorph of TEACH is *taugh* ([tɔ] phonetically), and that the past tense allomorph –*t* is affixed to it. Either alternative is compatible with the model sketched here and with the experimental results reported in later chapters.

[7] All definitions are taken from the online version of the Oxford English Dictionary, 2nd Ed.

participates in an irregular morphological alternation is also idiosyncratic knowledge that must be learned and memorized.

Note that the term *irregular*, when applied to the English past tense, actually refers to an agglomeration of irregular and unpredictable facts about a set of English verbs. First, which items are irregular is not predictable on the basis of the phonological form of the stem: the past tense of *give* is *gave*, but the past tense of *live* is *lived*, and the past tense forms of the triplet *hit, sit, pit* are, variously, *hit*, *sat,* and *pitted.*

Second, the phonological exponent of the functional morpheme is not easy to identify: the past tense is expressed by a Ø in *hit~hit*, by a vowel change in *sit~sat*, by a vowel change plus a suffix in *keep~kept*, by vowel change, truncation and suffixation in *bring~brought* and by complete suppletion in *go~went*. And finally the number of verbs in the language subject to irregular patterns is very small (approximately 180 verbs in English, some of them very low frequency like *smite-smote*).

Because the English irregular past tense is taken as the canonical case of irregularity in the experimental and modelling literature, the fact that this system conflates three distinct properties into the notion 'irregular' is unfortunate.

As discussed above in §1.1, German is a language in which the third property is not true – irregular forms are much more prevalent and the regular allomorph is sometimes the less frequent of the two. Sonnenstuhl et al (1999), discussed in §2.1.1.1., investigates irregularity in the German participial system.

An example of another system in which *irregularity* has different properties than it does in English is Modern Hebrew. Berent, Pinker & Shimron (2002) investigate irregularities in Hebrew noun inflection. In this system, stem change and regular vs. irregular affixation are dissociated. A noun with an irregular stem change can take regular inflection and vice versa All four possibilities are illustrated in (6).

(6). a. *gamál* (camel) ~ *gmalim* (camels) STEM CHANGE – REGULAR INFLECTION

b. *gamád* (dwarf) ~ *gamadim* (dwarves) NO STEM CHANGE, REGULAR INFLECTION

c. *zanav* (tail) ~ *znavot* (tails) STEM CHANGE, IRREGULAR INFLECTION

d. *kinor* (violin) ~ *kinorot* (violins) NO STEM CHANGE, IRREGULAR INFLECTION

Using a generation task, in which participants are asked to create plural form of nonce words, Berent and colleagues find that the use of regular inflection did not depend on analogies to existing forms, whereas use of irregular inflection was highly correlated with degree of correspondence between nonce form and existing irregulars in language

They argue that this constitutes evidence that the regular inflection is the default, since it applies without regard for the phonological properties of the stem. They also evince the correlation between the use of irregular inflection on novel noun forms and the resemblance of that novel form to one or more existing irregulars as evidence that irregular forms are fully listed and that irregular formation proceeds by analogy. But recall that Albright and Hayes (2003) convincingly argue that apparent analogy effects in this kind of nonce word generation task are much better modelled using stochastic rules that derive allomorphs from stem forms than actual analogy.

Another language where irregularity is not so entangled a notion as in English is Japanese. Japanese verbs can be divided into typical verbs and atypical verbs, depending on which inflectional pattern they take. The typical pattern applies to roughly 2/3rd of the verbs in Japanese, while the atypical pattern applies to the remaining 1/3rd[8]. Which category a verb is in is not, for the most part, arbitrary. Typical verbs have stems ending in a consonant, while atypical verbs have stems ending in a vowel. Moreover, once a verb is assigned to one category or another, its behaviour in all inflectional paradigms is completely predictable. So the Japanese verbal system seems to be completely regular.

However, there is a small set of verbs in Japanese that end in a vowel, but exceptionally are assigned to the typical paradigm. For verbs ending in /a/, /o/ or /u/, there is no

[8] With the notable exception of the two light verbs *kuru* and *suru* and complex forms that contain them.

unpredictability. All such verbs are always atypical. However, for verbs ending in a CV sequence where the consonant is /r/ and the final vowel is /i/ or /e/, there is unpredictability. Verbs whose stems end in either /ri/ or /ru/ are still mostly assigned to the atypical paradigm[9], but there is a small set of verbs with these stem ending which are not, and are instead assigned to the typical paradigm.

Clearly, then, these exceptional verbs need to be stored with the information that they are assigned to the typical paradigm, even though their phonological form would predict otherwise. But just as clearly, the actual form these verbs take in various inflectional paradigms does not need to be stored. Once the verb is assigned to the typical class, its behaviour is completely predictable.

It is the contention of this thesis that English irregularity is no different from Japanese in the relevant respects. The irregularity in the system is that there are a small class of roots which need to be stored with the information that they are in a specific atypical class when it comes to verbal inflection. But what the non-default allomorph of a particular root is, is not completely idiosyncratic or unpredictable, and is not lexically listed[10]. As discussed above, even for English, where the past tense is associated with multiple allomorphic alternations that apply to a small number of roots each, Albright and Hayes (2003) show that the phonological form of verbs in the past tense is derivable by rule. And this can be seen even more clearly in a language like Japanese.

The only difference between Japanese and English that matters here is that Japanese has only two classes of inflectional patterns, whereas English, as a consequence of its unique and complicated history, has several of them.

Moreover, it is the contention of this thesis that in the earliest stages of lexical processing, whether a root sometimes surfaces displaying a non-default inflectional pattern is irrelevant.

[9] Based on the Amando and Kondo (1999) corpus, 1360 out of a total of 1564 /ri/ and /re/ final stems are assigned to the atypical paradigm (87%), with 13% assigned exceptionally to the typical paradigm.

[10] Fully suppletive allomorphy such as *go/went* or *is/was* is unlikely to be generated by phonological rule, and therefore the actual form of the irregular allomorphs must be stored with the root.

Root activation is root activation. Figure 4 above depicts the processing of the letter string `taught`, as a process that involves the activation of the root TEACH and the functional morpheme that denotes the grammatical meaning 'past tense'.

Presumably 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 [itʃ] sequences. However, the exact mechanism by which root lexical activation is effected is beyond the scope of the current research.

1.2.3. So what is morphological priming?

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 facilitated in the primed case relative to an unrelated baseline. Experiment 1 (Chapter 3) is an attempt to test this prediction by using a tool that allows us to measure the earliest stages of lexical processing (magnetoencephalography, discussed in detail in §2.2)

This model of lexical storage and activation predicts that the precise form the root takes in its prime and target instantiations should be irrelevant. 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 will only affect later stages of processing. Experiment 2, (Chapter 4) reverses the usual past tense prime/stem target pattern precisely to test this hypothesis and to begin attempting to understand just what those competition or interferences effects might be.

If Figure 4 represents initial activation, what does recognition look like in this model?

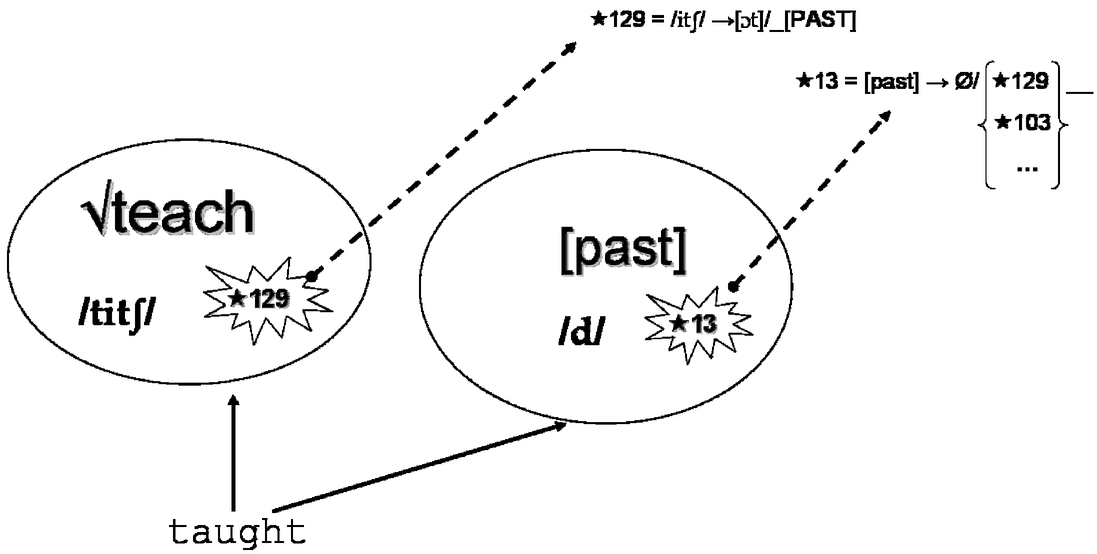

Figure 5. A schematic representation of process of recognition of morphologically complex form *taught*. The special diacritic that indicates that a lexical entry has a non default allomorph is activated and the particular morphological rule that it is associated with is engaged.

Figure 3 is a 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 additional step of having to engage a morphological rule has, unsurprisingly, consequences. In the two MEG experiments presented in this dissertation, we see that whereas 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.

1.3 Outline of this Thesis

The remainder of this thesis is divided into the following sections:

Chapter 2 lays out the necessary background for understanding the motivation for and results of the three experiments discussed in this dissertation. I focus my discussion on attempting to unravel some of the confounds and confusion that permeate the experimental literature on irregular allomorphy.

I survey a range of priming experiments, from a range of languages, featuring both behavioural and neural measures of priming that raise and settle issues of particular relevance to the priming methodology.

I also devote a section of Chapter 2 to reviewing in detail the literature on using magnetoencephalography to investigate a range of factors that affect the time course of visual word activation and recognition.

Chapters 3, 4 and 5 describe the 3 experiments carried out to find evidence for across the board decomposition. Chapters 3 & 4 report the results of a pair of immediate priming experiments using both MEG and reaction time as dependent measures. Chapter 5 reports on a long lag priming study using only reaction time as a measure.

The first experiment uses MEG to show that irregular past tense forms do prime their stem correlates, regardless of degree of overlap between stem and past tense form. And that this priming effect is similar in magnitude to the effect of identity priming.

The second experiment compares the same two sets of irregular past tense-stem pairs with regular past tenses and their stems to provide further support for the single mechanism model. Additionally, this experiment includes a set of prime-target pairs that allow us to find explicit support for the claim that morphological relatedness is qualitatively different than semantic and phonological similarity.

The third experiment uses a different approach in an attempt to provide support for this dissociation. The effects of semantic and phonological relatedness are known to be short lived as compared to the effects of identity priming. The goal of this experiment, then, was to show that the priming advantage conferred by morphological relatedness is also long lived, and that therefore morphological relatedness is a kind of identity, not mere similarity. The experiment did not actually produce the predicted results, although the results it did produce nonetheless do show an effect of morphological relatedness. Some discussion of these results is in chapter 3, while some more speculative considerations are raised in chapter 6..

The final chapter, 6, discusses the results of all three experiments and ends with some concluding remarks.

Chapter 2 Background

In this chapter, I review the necessary background for understanding precisely why we conducted the experiments we did and why we conducted them in the way we did. The first half of the chapter summarizes a number of issues in the literature on morphological priming. The second half summarizes a growing body of literature investigating the time course of lexical activation using magnetoencephalography (MEG).

2.1 Morphological Priming Experiments

The general result of repetition priming is that the second presentation of a given word (the target), results in a substantially reduced decision latency, even when the first word (the prime) is separated from the target by several minutes (Scarborough, Cortese & Scarborough, 1977; Forbach, Stanners & Hochhaus, 1974).

Priming as a method of investigating lexical organization and relatedness has one very important advantage over other methods. Because the exact same item is compared in two different conditions (once when it is preceded by a related prime, once when it is not), each item serves as it’s own control. This is a very important advantage when dealing with specific sub-components of linguistic systems where it is not always possible to control perfectly for factors such as length, frequency, neighbourhood density, phonological probability, imageability, orthography to phonology mapping, etc., that are all known the affect lexical decision times.

2.1.1 Behavioural Priming Experiments

Stanners et al (1979) were the first to use the priming methodology to investigate the status of past tense allomorphs in English. This experiment uses a long-lag priming paradigm, with, on average 10 intervening items between prime and target.

This experiment established the basic profile of results that provide the genesis of the dual-mechanism theory, namely that regular past tense priming looks like repetition priming, while irregular past tense priming does not (it is a smaller effect).

Interestingly, Stanners et al get a significant difference in the magnitude of the priming effect with long lag priming, whereas Marslen-Wilson et al (1998) find no difference between regulars and irregulars in long lag priming. Marslen-Wilson et al find that both categories of allomorph prime their stems at a distance, whereas semantically related prime target pairs are associated with no such advantage. In Chapter 3, I discuss our own unsuccessful attempt to find priming for irregular verbs with long lags between prime and target.

As Allen and Badecker (2002) did more than 20 years later, Stanners et al also divided irregulars into two categories based on the extent to which they were formally similar to their stems. The exact metric used to assign verbs to one category or another was different than Allen and Badecker's[11]. Unlike Allen and Badecker's cross-modal experiment and our immediate visual-visual experiments, Stanners et al find no effect of degree of overlap on reaction times.

Since the foundational work of Stanners and colleagues, experiments investigating morphological relatedness and the status of irregularity have been carried out in a variety of languages and priming paradigms. A significant number of them have replicated the basic result – a different effect of priming for irregular allomorphs than for regular. A representative example of one of these experiments, Sonnenstahl et al (1999) is discussed in

[11] See §2.1.1.2 for a more detailed discussion of Allen and Badecker (2002)

§2.1.1.1. Also in this section, a recent experiment investigating stem allomorphy in French by Meunier and Segui (2002) is reviewed.

One issue that arises in connection with many priming experiments is that of modality. The original work of Stanners et al, and much of the subsequent work, presents both primes and targets visually. However, many priming experiments have also used a cross-modal design. The use of the cross-modal priming paradigm is generally motivated by the thought that if an auditory prime affects responses to a visual target, the nature of the relationship must involve a higher level of abstraction than surface or formal resemblance between prime and target. While this claim has an intuitive appeal, §2.1.1.2 presents a number of experiments that suggest a more complicated relationship between modality and priming effects. The topic is also discussed in §6.4, as the experiments reported in Chapters 3 & 4 also address this issue.

2.1.1.1 Regularity & Irregularity Cross Linguistically

Sonnenstuhl et al (1999) is a typical example of the results that are taken in support of the dual-mechanism model. The experiment compares regularly and irregularly inflected German participles in a cross-modal priming experiment. As Marcus (1995) carefully argues, German is a language where frequency is disassociated from regularity. The *–t* participle ending is the regular, default allomorph, despite being less frequent than it's irregular analog, *-(e)n*.

Sonnenstuhl et al (1999) employ a triplet design, so that each target occurs in three environments. Once when the spoken prime is identical to the target, once when the prime is the participial form of the target and once when the prime is completely unrelated to the target. Sonnenstuhl find the expected pattern of morphological priming for the regulars: there is no difference between the identity condition and the participle condition in the amount of priming they are associated with, and both evoke significantly more priming that the unrelated baseline condition does.

However, for the irregulars, all three conditions are different. The identity condition evokes the greatest amount of priming, the unrelated condition evokes none, and the participle condition falls in between the two.

Meunier and Segui (2002) investigate allomorphy in French in a cross-modal, immediate priming experiment. The stimulus pairs include prefixed/stem pairs and suffixed/stem pairs. Half the pairs involve only affixation, half involve affixation plus stem change.

The prefixed primes are always associated with a priming advantage for their stem targets in a lexical decision task, regardless of whether the allomorph in the prime and the allmorph in the stem are the same. So, for example, *incrédule* (incredulous) primes *croire* (believe) just as robustly as *refaire* (redo) primes *faire* (do).

For suffixed primes, however, which allomorph is suffixed matters. A form like *frontal* (frontal) primes its stem *front* (forehead) when the same allomorph of the root FRONT is used in both the prime and target, but *circulaire* (circular) does not prime its allomorphic variant stem *cercle* (circle).

The two key results of the Meunier and Segui experiment are that they find priming effects even for irregular stem~allomorph pairs and that suffixed forms appear to behave oddly in a cross-modal priming experiment. Marslen-Wilson et al (1995) and Feldman and Larabee (2001) provide other instances of the peculiar interaction of suffixation and prime modality, as discussed in the next section on modality and priming generally.

2.1.1.2. Issues with Modality

Kyrana Tsapkini and colleagues have investigated the interaction of prime modality and irregular verb priming. They report a series of experiments on Modern Greek, a language where the orthographic and phonological overlap between stems and past tense forms is the same for both regular and irregular verbs. They compared the priming elicited by two regular verb conditions (verbs with an orthographically salient morphemic aspectual marker and those without such a marker) and one irregular verb condition in both a visual-visual priming experiment (Tsapkini, Kehayia and Jarema, 2002) and a cross-modal priming experiment (Tsapkini, Jarema and Kehayia, 2004). They found that whereas in the visual-visual priming experiment, the two categories of regular verb were associated with different amounts of priming, with significantly less priming being found for the regular verbs lacking an orthographically overt aspectual marker, in the cross modal experiment, there were no significant differences between the two verb categories[12]. Both categories of verb reliably primed their stems. They also find that irregular verbs in Greek do not seem to be sensitive to the difference in prime modality: In both experiments the irregular verbs were associated with significantly less priming than the regulars.

These results for regulars suggest that orthographic representations are not accessed during phonological processing. Cross-modal priming is often advocated for this reason. Marslen-Wilson et al (1994, p6) specifically state of cross-modal priming that "if there are to be any priming effects, then they will have to be mediated through [the central, modality independent] level of the system and not through the lower level overlap in modality specific access pathways and representations." This position is fairly common in the cross-modal priming literature (see, for example, Clahsen, 1999; Katz, Rexer & Lukatela, 1991; Moss, McCormick & Tyler, 1997; and Sonnenstuhl, Eisenbeiss & Clahsen, 1999, discussed above in §2.2.1.1).

[12] The aspect marker –*s* is always phonologically overt. The orthographic opaqueness derives from the Greek alphabet, which uses the single letters ξ and ψ to represent the sound sequences [ks] and [ps] respectively. Therefore, when the aspect marker is added to a stem ending in a [k] or [p], the resulting orthographic representation does not overtly contain the –*s* realization of the morpheme.

Allen and Badecker (2002), however, call this suggestion into question. They explicitly test this hypothesis with a cross-modal priming experiment in which they compare the lexical decision times to a visually presented target immediately preceded by a spoken prime that was highly orthographically similar to the target, with the response to the same target when preceded by an unrelated prime. They find that even in the cross-modal paradigm, where participants do not see the orthographically related prime, lexical decision times are significantly delayed in the prime condition relative to the unrelated baseline.

Allen & Badecker argue on the basis of this result that spoken word processing involves the rapid and automatic activation of orthographic representations. However, since the orthographically related pairs are also phonologically similar, and since phonological similarity between prime and target has also been found to have an inhibitory effect on lexical decision times in auditory-auditory priming experiments (e.g. Goldinger, Luce, Pisoni & Marcario, 1992; Radeau, Morais & Dewier, 1989; Radeau, Morais & Segui, 1995; Slowiaczek & Hamburger, 1992), this claim is contestable.

Allen & Badecker (2002) also investigate the extent to which orthographic overlap and irregular allomorphy interact. On the basis of the finding that orthographic similarity has an inhibitory effect cross-modally, they divide English irregular past tense verbs into two categories: those that share a high degree of orthographic overlap between stem and past tense and those whose overlap is minimal. The precise method of categorization used in this experiment is discussed in detail in §3.1.2.

The key point of relevance to the issue of modality independent activation is that orthographic similarity and phonological similarity are not highly correlated in the English irregular past tense. While some pairs like *gave-give* differ orthographically and phonologically to the same extent, there are pairs like *light-lit* and *bound-bind* that differ phonologically only in the vowel quality, but orthographically to a much larger extent, or pairs like *heard-hear*, which involve only one orthographic mismatch, but two sound changes. To the extent that the two groups of irregular past tenses are associated with different priming results, this effect must be attributed to the degree of *orthographic* overlap with the stem, not to the degree of *phonological* overlap with the stem.

Allen & Badecker find that the irregular past tenses with a high degree of orthographic overlap with their stems fail to prime those stems, just as irregular verbs do in general in so many other past tense priming experiments. However, the low overlap irregulars do prime their stems. Chapter 3, 4 & 5 of this dissertation further investigate the effects of form overlap on irregular verb priming.

The dissociation between the two categories of irregular in the cross-modal priming paradigm provides support for Allen & Badecker's proposal that orthographic representations are automatically accessed during lexical activation and processing, even when the item being processed is presented aurally. Marslen-Wilson's claim that cross-modal priming does not involve low level representations seems not to be correct.

Feldman and Larabee (2001) address the issue of prime modality by manipulating it as a variable. They compare the degree of priming of an inflected target (*payment)* by three kinds of morphologically related primes (stem: *pay,* stem+prefix: *prepay* and stem+suffix: *payable*) in three different priming paradigms (visual prime-auditory target, auditory prime-visual target and visual prime-visual target). They find that for the visual-visual paradigm, there is no difference in the amount of priming from any of the three prime types. All three prime types facilitate lexical decision times to the target. In the two cross-modal paradigms, however, they find differences between the prime types. When the prime and the target are not presented in the same modality, the stem+suffix forms fail to prime the suffixed targets. Simple stems and prefixed stems consistently prime the suffixed targets regardless of prime or target modality.

This failure of a suffixed form to prime another suffixed form containing the same stem replicates the results of Marslen-Wilson, Zhou et al (1997), who used only a cross-modal (auditory prime-visual target) paradigm.

The results of Feldman & Larabee's experiments present a complicated picture of the interactions between prime-target modality mismatches and prime-target affixal variation. The invariant priming from stem+prefix primes to stem+suffix targets across all modality combinations is a strong argument for a modality neutral lexical architecture. But the failure of suffixed stems to prime transparently morphologically related suffixed targets when the prime and target are not presented in the same modality requires a modality specific dimension to lexical relatedness.

2.1.1.3. Attempts at dissociating Morphology from Semantics and Form

Feldman (2000) compares the priming effects associated with semantic, orthographic and morphological relatedness at four different SOAs: 66ms, 116ms, 300ms and long lag. She finds that whereas at the three shorter SOAs, all three types of relatedness affect the processing times of their stem targets (semantic and morphological relatedness being associated with facilitation, orthographic overlap with inhibition), in the long lag priming paradigm, only morphological priming effects persist.

Feldman also compares the magnitudes of priming associated with each type of relatedness. In a model where morphological relatedness has no special status, and is instead merely the result of the summed effect of semantic relatedness and orthographic (or phonological) relatedness, morphological priming effects ought to look like semantic priming + orthographic inhibition. Feldman shows that at the longest SOA (300ms), the magnitude of the morphological priming effect is significantly greater than would be predicted by summing the effects of semantic and orthographic relatedness. At the shorter SOAs, this difference is not significant.

Rastle et al (2000) (discussed further in §2.2.1.1.1) explicitly test the possibility that morphological relatedness is in fact the combination of semantic relatedness and phonological relatedness. They do this by comparing morphologically related pairs like *departure~depart* with pairs of items that share meaning and phonological form, but are not plausibly morphologically related. Items in this condition include portmanteaus like *brunch~lunch*, so called phonaesthemes like *glimmer~glisten* (words that belong to clusters of semantically related words which share some components of their sound structure, like *snout,* *snort, sneeze, sniffle*), and other pairs of words that idiosyncratically overlap in sound and meaning like *ghost~ghoul*, *tip~top*, etc

Using a cross-modal priming paradigm, with varying SOAs between prime and target, Rastle et al find that although both morphologically related pairs and pairs in the +semantics, +orthography, -morphology condition (henceforth +S+O-M) both show priming effects at the longest SOA (230ms), at the shorter SOAs (43ms and 72ms), the two conditions produced different results.

At these short SOAs, only the morphologically related primes were associated with a significant decrease in reaction time relative to an unrelated baseline. The primes that were related to their targets by unsystematic meaning and form resemblances did not facilitate lexical decision to their targets at the short latencies.

The different priming effects associated with the +S+O-M condition at the different SOAs echoes the pattern Rastle et al find for their pure semantic relatedness condition in the same experiment. A prime like *violin* primes it's target *cello* at the longest SOA, but not at the two shorter SOAs[13].

This result, then, provides convincing evidence that morphological relatedness is not merely a simple summation of semantic and phonological relatedness.

Marslen-Wilson & Tyler (1998) report the results from two previously unpublished studies that find dissociations between morphological priming and semantic priming. The first experiment they summarize is a long lag priming experiment with 12 items intervening between prime and target. They compare irregular past tense prime-target pairs, regular past tense prime-target pairs, and semantically related prime-target pairs.

[13] The absence of semantic priming in paradigms where the prime is not available for conscious recognition is well attested in the literature. For example, Ko et al (2004) replicate this effect behaviourally and neurally. A model in which semantic spreading activation is a consequence of recognition of specific lexical item, and therefore a relatively late process, makes sense of this fact.

They find clear effects of reaction time facilitation for both categories of verb, with no significant difference between the two categories. However, they find no effect of semantic relatedness in the long lag experiment. Morphological relatedness clearly has a different psychological status than semantic priming and persists in a way that is more reminiscent of identity priming (recall, for example, Stanners et al 1979, discussed in §2.1.1 above).

Marslen-Wilson and Tyler (1998) also summarize the results of a cross-modal priming experiment in which EEG measurements of participants priming responses were recorded. Again, regular and irregular past tense-stem priming was compared to semantic priming. And as in the long-lag experiment, the two categories of irregular pattern together, while the semantic condition was associated with a different neural response pattern.

Both regular and irregular morphological priming was associated with left anterior negativities in the 200-400ms time window, while semantic priming elicited no such response.

2.1.2. Neural Priming Experiments

A small, but growing number of researchers have attempted to investigate morphological priming neurologically. In the following three sections I summarize some of the research in this area.

2.1.2.1. Neurological Disorders: evidence from dissociations

Marslen-Wilson, Tyler and colleagues have done a number of priming studies with neurologically impaired populations. Marlsen-Wilson and Tyler (1997) reports the results of a verb priming experiment involving three patients with two different patterns of neural damage. Two of the patients had only left hemisphere damage and a third had both left and right hemisphere damage. The experiment also involved the participation of 6 controls matched in age with the impaired participants and 25 undergraduates.

Both the primes and the targets were single words presented aurally and participants performed a lexical decision task. Marslen-Wilson and Tyler (1997) found that for the two agrammatic patients, a robust priming advantage was associated with the regular past tense/stem pairs, but that for the irregulars, an inhibitory effect on reaction times was observed. Conversely, for the other patient, the pattern was essentially reversed. The priming advantage was robust for the irregulars, but null for the regulars. This kind of double dissociation can be taken as support for a model in which regulars and irregulars are fundamentally different kinds of grammatical objects. If regular verbs involve both lexical access and the application of a grammatical rule, while irregular verbs require accessing relatively infrequent forms from memory, but no grammatical operations, it's not surprising that one or the other type of allomorph could be selectively impaired.

Note, however, that the model argued for in this dissertation also makes distinctions between regular and irregular allomorphs that could underlie selective impairments in patient populations, particularly on lexical decision tasks.

Although the focus of the investigation in Marslen-Wilson and Tyler (1997) was the double dissociation between the different impaired participants, it's worth noting the results found for the control participants. For the unimpaired participants, Marslen-Wilson and Tyler found significant priming for both categories of verb, with no difference between the regulars and irregulars. The fact that in this experiment both primes and target were presented aurally provides further support for the emerging generalization discussed in §2.1.1.3 that the apparently distinct priming effects associated with regular and irregular allomorphy are actually only found in the cross-modal priming paradigm.

Tyler, deMornay-Davies, Anokhina, Longworth, Randall and Marslen-Wilson (2002) finds essentially the same results as Marslen-Wilson and Tyler (1997), for two different impaired populations. In this second experiment, they find that non fluent aphasics show no priming effect for regular verbs, but they do exhibit significant priming for the irregulars. They also conduct and elicitation task with Herpes Simplex Encephalitis patients characterized as having generalized semantic deficits. The HSE patients were significantly impaired on the irregulars in the elicitation task, but not on the regulars.

In response to arguments that the selective impairments on regulars found in these studies and others are not *morpho*logical, but instead can be accounted for by more general *phono*logical deficits, Tyler, Randall and Marslen-Wilson (2002) uses a speeded judgement task to disambiguate the two possibilities. Pairs of words and nonwords were presented aurally to four patients who have previously documented impairments on the regular past tense (see Tyler et al 2002b for more details on these patients). Stimulus categories included the regular past tense (*called/call*), the irregular past tense category (*wrote/write*), a pseudo-regular past tense (*bald/ball*), a pseudo-irregular past tense (*boat/bite*) and two conditions to monitor sensitivity to small phonological changes: single feature difference (*rope/robe*) and additional phoneme (*claim/clay*). Non-word variants of each condition were also included.

Performance on the speeded same-different judgment task showed that subjects were specifically impaired on the regular morphology condition & the pseudo-regular condition, but not on the irregulars or any of the pure phonological conditions. This provides evidence, then, that the deficits associated with impaired performance on the regular past tense are morpho-phonological in nature and cannot be explained purely on the basis of phonological processing difficulties.

2.1.2.2. Morphological priming: EEG investigations

Barber, Dominguez and de Vega (2002) investigate morphological and phonological relatedness in Spanish. They compare morphologically related pairs like *loca* (madwoman) ~ *loco* (madman) with stem homograph pairs like *rata* (rat) ~ *rato* (moment) in a visual-visual priming experiment. Using electroencephalography to measure the neuroelectrical activity associated with the priming effect, they found that whereas the prime condition for both types of relatedness was associated with an attenuated N400 effect, only the homography priming condition evoked a late negativity in the 500-600ms time window.

This result is consistent with the results of the MEG experiments reported below (see the discussion of Pylkkänen et al, 2002b in §2.1.2.3., where (some kinds of) phonological relatedness, as well as morphological relatedness are associated with early facilitation, but with significantly different effects later in the time course. The late negativity found by Barber, Dominguez and de Vega could plausibly be reflecting post-access competition for recognition among phonological neighbours.

Recall also the discussion of Marslen-Wilson and Tyler (1998) in §2.1.1.3. The authors summarize the results of an ERP experiment in which they find a distinction between morphological relatedness and semantic relatedness, but no differences between regulars and irregulars in activation patterns.

This finding is contrasted with that of Münte et al (1999), who measure the effect of priming in a long-lag priming paradigm (5-9 interveners) in German with EEG. Participants performed a reading task with regular and irregular verb priming pairs hidden in the material. ERPs were recorded from the onset of each target item and compared to the response to that item in a control condition. Münte et al find that for the regular verbs, the N400 response is reduced in the priming condition, just as in the Barber, Dominguez and de Vega (2002) experiment. However, Münte et al find no such reduction for the primed irregular verbs. This difference between immediate and long lag priming is discussed further in §6.6 in light of the results reported in chapters 3-5.

Rodriguez-Fornells, et al (2002), also find a regular/irregular distinction for Spanish in the ERPs evoked by regular and irregular prime target pairs in a long lag paradigm. Like Münte et al (1999), they vary the number of interveners between prime and target between 5 and 9. And like Münte et al, they find a reduced N400 effect for the regular priming condition and no such attenuation for the irregulars.

The ERP literature on morphological priming effects, then, is consistent with the MEG literature and the results of our experiment 3 – in immediate priming paradigms, regulars and irregulars pattern alike, but at long lags there are differences[14].

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[14] The ERP literature also includes a small number of experiments investigating the neural correlates of morphological decomposition with other paradigms. For example, Gross et al (1998) use an error detection paradigm to investigate the Italian participle system. They contrast regular

2.1.2.3. Morphological priming: MEG investigations

In work presented at the Cognitive Neuroscience Annual Meeting, Pylkännen et al (2002b) explore the sensitivity of the M350 component (see §2.2.1.2.1 for discussion of this component) to various kinds of similarity relationships that are known to elicit behavioural priming and inhibitory effects. The experimental materials included semantically related pairs (*idea~notion*), two kinds of phonologically related pairs: onset matching (*spinach~spin*) and rhyme matching (*teacher~reach*), morphologically related pairs (*teacher~teach*) and two kinds of pairs related by pseudo or quasi morphology: pairs like *dresser~dress* that are often called 'opaque' in the literature (see for example Marslen-Wilson et al 1994 (apartment-apart)) because although they could conceivably be analyzed as morphologically complex, the meaning of the whole word is not transparently derived from the meaning of it's constituent morphemes, and pairs like *corner~corn* which accidentally bear a formal resemblance to morphologically complex words, but aren't actually plausibly[15] complex. Materials used in this study are from Laura Gonnerman's 1999 dissertation, with the addition of the *teacher~teach* condition..

Using a cross-modal design, Pylkkänen et al found that the M350 was sensitive to the effects of the different kinds of relatedness in different ways.

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conjugations and irregular conjugations. They find that errors in the irregular forms evoked a large negativity in the 400-700ms time window, while errors in the regulars did not. Penke et al (1997) also employed the error detection paradigm to investigate the German participle endings, regular *–t* and irregular *–en*. They find that irregular errors are associated with an early left frontal negativity, but that there is no effect for regulars

[15] Plausibility is a somewhat rough metric to employ. The distinction between the opaque morphology items and the pseudo-morphology items is usually that the former were historically transparently decomposable while the latter were never historically complex. Compare, for example, *apartment*, which was still used with the sense of *'separate, proper, or special place of abode'* as late as 1791 (OED, 2nd edition), with *corner* which actually ultimately derives from the same late Latin *cornu* (horn) which gives us *cornucopia*, and who's meaning has never been related to *corn*. Because speakers of a language do not typically have detailed knowledge about the etymologies of all the words in their language, the precise status of the split between the two types of words is questionable. The split is usually based on rating studies, in which participants are asked to rate pairs of words on a 5 or 7 point scale based on how related they think the two words are. These same kinds of rating studies are widely used to create sets of items for semantic relatedness investigations as well.

For the semantically related condition, the neural reflex of the priming effect mirrored the behavioural effect found in this study and quite generally in the literature. Hearing a semantically related prime before seeing the target was associated with a significantly faster M350 response, as shown in figure 6[16].

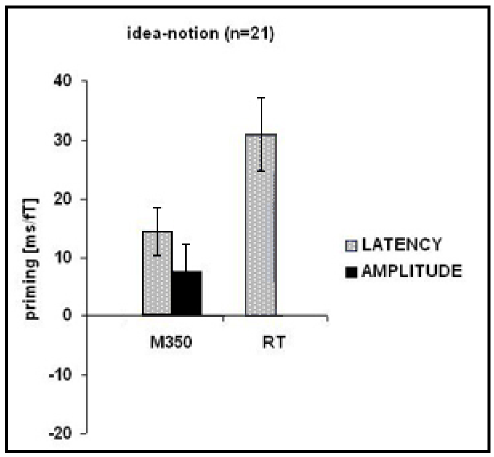

Figure 6. Plot of Semantic Priming Effect. Bars show difference between the responses to the target in the control condition and the responses in the primed condition. [from Pylkkänen et al, 2002b]

The two types of phonological relatedness had two different effects on the M350 response component. Both kinds of phonological overlap were associated with reaction time slow downs, relative to the control condition. However, while this slow down was also seen in the M350 response for the onset matching items (*spinach~spin*), the rhyme matching items were associated with an M350 facilitation effect. The latencies and amplitudes of the M350 responses evoked by this condition were earlier and smaller than those to the matched controls. Figure 7 shows the overall differences between the two types of phonological overlap on the right, and the neuromagnetic differences for one representative subject on the left.

[16] Unless otherwise noted, figures used in the discussion of Pylkkänen et al (2002b) are adapted from figures created by Liina Pylkkänen and are used here by permission of the author.

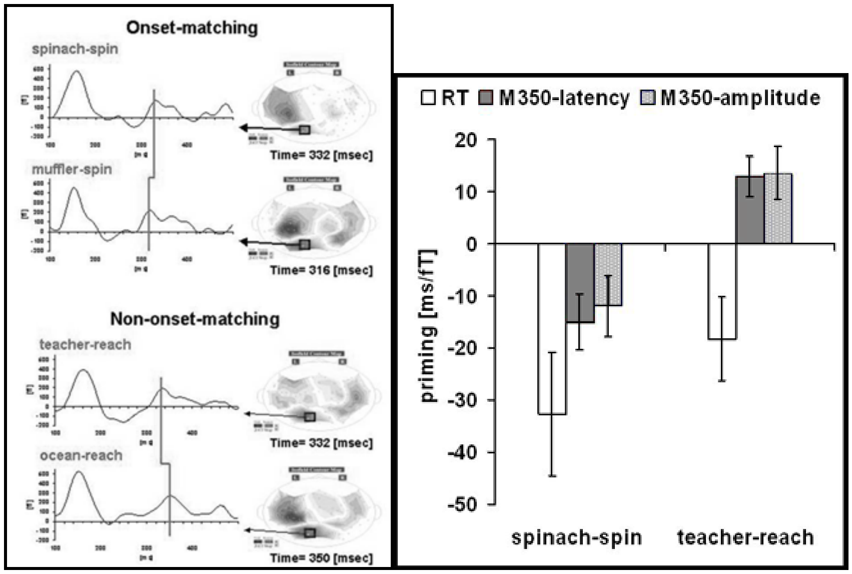

Figure 7. Neural and Behavioural Responses to Phonological Overlap. The box on the right shows that while both kinds of overlap inhibited reaction time (bars represent difference between prime and control conditions), their effect on the stage of processing indexed by the M350 is significantly different. The box on the left shows precisely what that difference looks like at a single sensor for one representative subject. [from Pylkkänen et al, 2002b]

Understanding the different effects of the two types of phonological overlap on target processing at the stage indexed by the M350 requires an explicit model of the time course of lexical activation and competition.

The evidence is that at the point of initial lexical activation, prior processing of *teacher* actually facilitates activation of *reach*, while prior processing of *spinach* inhibits activation of *spin*. This would suggest that successful recognition of *spinach* involves competition with, and inhibition of the candidate *spin*, but that recognition of *teacher* does not likewise involve inhibition of *reach*. A schematic representation of the time course of the two different cases is given in figure 8.

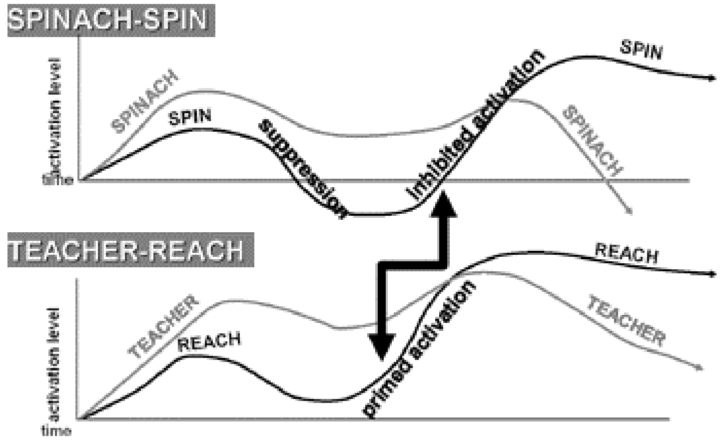

Figure 6. A schematic representation of the time course of activation and competition that precede recognition, with the different prime effects for the two kinds of phonological overlap attributed to different consequences of prime recognition. [from Pylkkänen et al, 2002b].

Because *spin* shares an onset with *spinach*, it is a competitor for access at the stage when *spinach* itself is competing for recognition. It's activation, along with that of other competitors such as *spit*, *spinal*, *spill*, etc is suppressed, which leads to a delay in initial lexical activation of *spin* (as indexed by the M350 component). This delay in initial activation is also responsible for the delay in the lexical decision response.

Reach on the other hand, while activated by *teacher* on the basis of their phonological similarities, and therefore a competitor for recognition, is apparently not inhibited in the process of recognition of *teacher*. It's activation is not suppressed, and therefore it is already at a higher level of activation than it's ordinary resting state. Initial lexical activation of *reach* is facilitated. The eventual reaction time delay in response to the target *reach* is due instead to the post access competition engendered by the high residual activation of *teacher* and other competitors activated by *teacher*.

The importance of using MEG to investigate the time course of lexical activation is emphasized by these results: a single behavioural effect (phonological inhibition) turns out to correspond to two very different patterns of activation and competition.

In the same experiment, Pylkkänen et al also investigated morphological relatedness. The effect of hearing a prime like *teacher* on the processing of a target like *teach* is illustrated in figure 9.

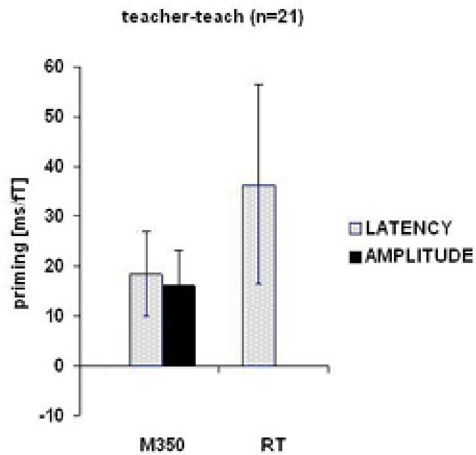

Figure 9. Neural and behavioural priming effect associated with morphological priming. Bars represent the magnitude of the difference between the primed condition and the unrelated baseline condition. M350 latency and Reaction Time are measured in milliseconds, while M350 amplitude is measured in femtoTeslas. [from Pylkkänen et al, 2002b]

Using essentially the same logic that motivated the conclusions of Feldman (2000), discussed above in §2.1.1.3, Pylkkänen et al argue that the priming effect associated with morphological relatedness is *not* the effect that would be predicted if morphological relatedness was the combination of semantic and phonological relatedness. The semantic priming observed for *idea~notion* and the phonological inhibition observed for *spinach~spin*, ought to cancel each other out, and *teacher~teach* ought to be associated with a null priming effect.

This is clearly not the case. In fact the magnitude of priming at the M350 for *teacher~teach* is greater than the magnitude of semantic priming, and is reminiscent of the effect observed for identity priming in previous experiments (Pylkkänen et al 2002a).

2.2. MEG as a tool for investigating the time course of lexical access

Visually presented lexical stimuli reliably evoke a series of distinct electromagnetic response components (Embick, Hackl, Schaeffer, Kelepir, & Marantz, (2001); Helenius, Salmelin, Service, & Connolly, 1998, 1999; Koyama, Kakigi, Hoshiyama, & Kitamura, 1998; Kuriki, Takauchi, Fujimaki, & Kobayashi, 1996; Pylkkänen, Stringfellow, Flagg, & Marantz, 2000; Pylkkänen et al., 2002a; Sekiguchi, Koyama, & Kakigi, 2000).
Figure 10 provides an example of these response components.

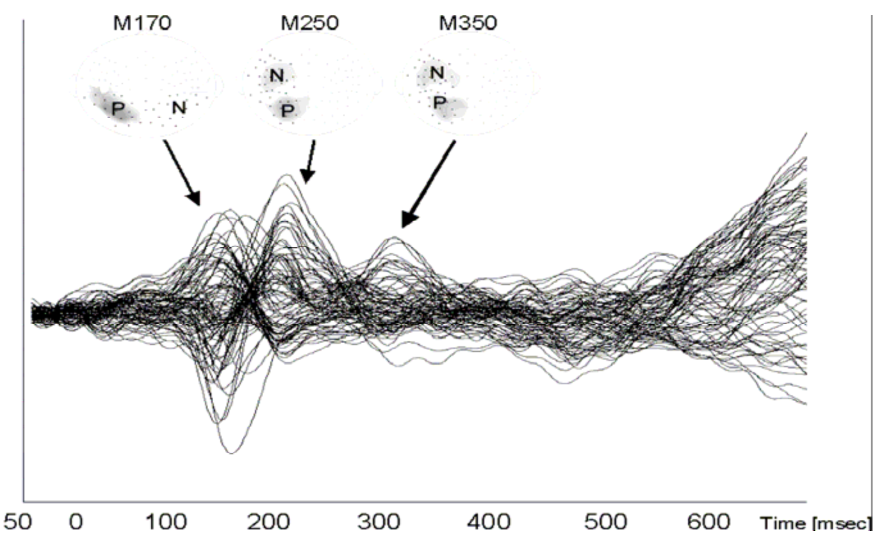

Fig. 10. The magnetic field distributions of the M170, M250, and M350 response components at the time of component peak in one representative participant. The letter P indicates the positive field (i.e., the magnetic field emerging from the brain) and the letter N the negative field (i.e., the magnetic field entering the brain) of the magnetic field around the current source. [Figure from Stockall, Stringfellow & Marantz, 2004]

Each of these response components is discussed below in turn, with a particular focus on what stage in lexical activation is indexed at each point.

2.2.1. Components evoked by visually presented lexical stimuli

2.2.1.1 The M100 & The M170 – the earliest stages of language specific processing

Cohen et al (2000) used a combination of fMRI and EEG to investigate the earliest stages of processing of visual lexical stimuli and the contribution of each hemisphere to this process.

Using a series of split-field presentation reading tasks, they found that the earliest stages of visual processing that were sensitive to the task manipulations corresponded to activations contralateral to stimulation, located by fMRI in the inferior occipitotemporal region (coincident with Visual Cortex Area 4 [on which see Buchner et al 1994]). Using EEG, a negative wave occurring 150-160ms post-stimulus was recorded over posterior electrodes. This response was also strictly contralateral.

In MEG, an evoked component peaking at approximately 100ms post stimulus onset, originating bilaterally in extrastriate cortex, has been associated with early, automatic visual pattern recognition processes. Liu, Harris & Kanwisher, (2004), for example, find that this component is sensitive to factors involved in face recognition.

In contrast, Cohen et al found a second stage of the neural response to visual lexical stimuli that was a strictly left hemisphere activation, invariant across hemisphere of presentation. This activation was located in the middle portion of the left fusiform gyrus. Cohen et al found that the electrical signature of this Visual Word Form area was a unilateral sharp negativity, recorded 180-200ms post-stimulus onset over left inferior temporal electrodes. The location of this VWF response is shown in figure 11.

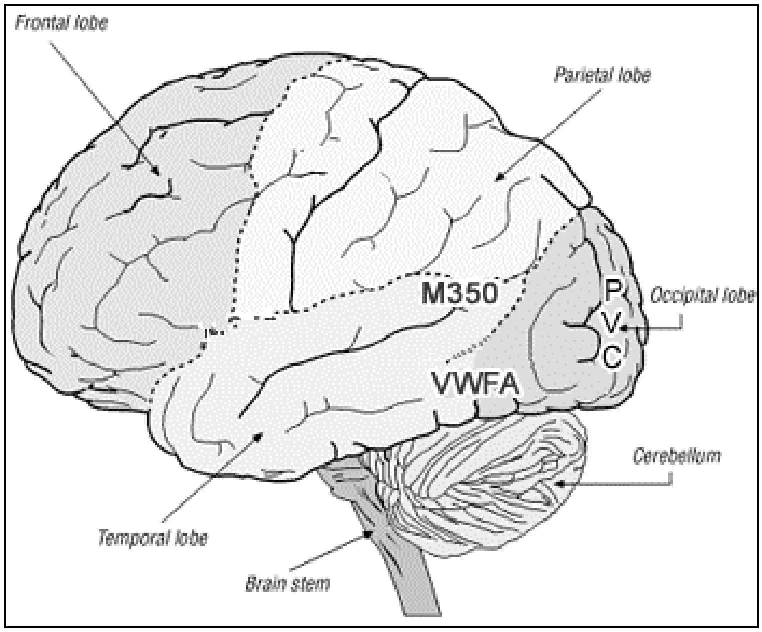

Figure 11. Human Brain with approximate locations of modelled M350 source and M170/VWFA source. Primary Visual Cortex (PVC) is also indicated as a reference point.

The M170 response measured by MEG is associated with a bilateral field distribution over occipito-temporal sensors and most likely originates from two sources, one in each hemisphere. Tarkiainen, Helenius, Hansen, Cornelissen & Salmelin (1999) found evidence that the left hemisphere M170 activity reflects pre-lexical visual processing that is specific to letter strings, while the right hemisphere activity is associated with aspects of visual processing common to both letters and symbols.

2.2.1.1.1 Pre-lexical Access: affix stripping

Rastle et al (2000) investigate the sensitivity of the lexical decision process to the difference between words like *brother* and *brothel*. The word *brother* contains the word final sequence *–er*, a common, productive morpheme in English (cf: *runner, swimmer, javelin-thrower, high-jumper,* etc), and *brother* could potentially be a morphologically complex word formed from the verbal stem *broth* (whatever it might mean as a verb), and the *–er* agentive nominalizing suffix.

Brothel on the other hand could not plausibly be decomposed - *-el* is not a morpheme of English.

Rastle et al use a priming paradigm to probe for the sensitivity of the system to this difference. If the *–er* in *brother* leads to some kind of segmentation of the word, while the *–el* in *brothel* does not, *brother* should plausibly affect the processing of *broth* differently than *brothel* does. Three different SOAs between prime and target were used to investigate whether the duration of the prime would affect the results.

Rastle et al found that at the shortest SOA (43ms), the pseudoaffixed words primed their pseudostems, while the items that could not be parsed into a stem and an affix did not.

Ko et al (2004) explored the possibility that the availability of the morphological stripping process would modulate the early visual response component. Using a modified version of the Rastle et al materials, and the masked priming paradigm, Ko et al replicated the behavioural differences between the two categories of prime. Ko et al also included an identity condition to provide a baseline for any neural priming effects.

Ko et al analysed the evoked responses in two separate time windows (the M100 & the M170) for each subject and each condition. Figure 12. shows the electromagnetic wave form for a single subject.

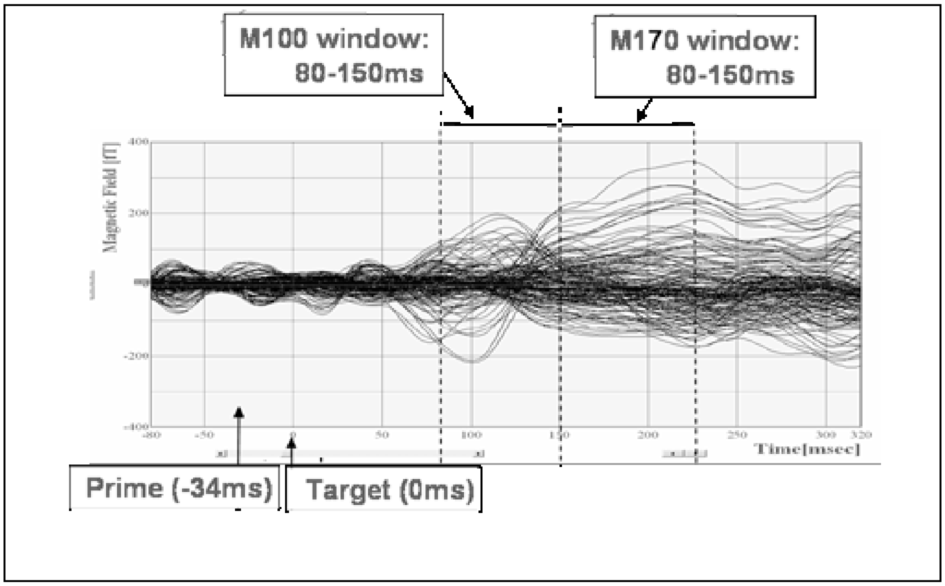

Figure 12. Averaged evoked magnetic activity from sensors of interest for one condition from a single subject. [Ko et al, 2004]

Table 3 shows the average amplitudes of the two early MEG components in response to the various stimulus conditions.

Identity Priming	M100 Amp	M170 Amp	Morphological Stripping	M100 Amp	M170 Amp
bowel-bowel	-15.29	16.73	brother-broth	-15.82	16.8
abyss-bowel	-14.81	16.95	brothel-broth	-15.42	16.83
			trifle-broth	-14.53	17.02

Table 3. Amplitude of Evoked Electromagnetic Activity in M100 & M170 Time Windows by for each condition (averaged across items and subjects) [Ko et al, 2004]

For both the identity vs. control manipulation and the pseudo-morphological overlap vs. orthographic overlap vs. control manipulation, subject x time x condition ANOVAs were carried out.

For experiment 1, the difference between the two conditions was significant in both time windows (M100 window, $p<0.0001$, M170 window, $p<0.03$). The identity condition evoked greater M100 responses and smaller M170 responses than the control condition.

For experiment 2, each pair wise comparison between two conditions was significant in the M100 time window (all comparisons $p<0.0001$), and the comparison between the control condition and the pseudo-morphology condition was significant in the M170 time window ($p<0.032$). The form overlap condition was not significantly different from the control condition in the M170 measure.

The neural and behavioural results together provide convincing evidence that the earliest stages of visual word form processing involve some kind of affix stripping process that operates purely in the surface properties of words. How this mechanism might operate and what other evidence there is for its effects are discussed in §6.8.

2.2.1.2 The M250 & M350 – Early Lexical Activation

Of the two later response components shown in Figure 10 above, the M350 has proven to be the more interesting. The M250 response has been associated with the processing of sublexical phonotactic properties of lexical stimuli (Pylkkänen et al 2002a, Stockall et al 2004), however, it has not clearly been established what processes it indexes. What we do know about its behaviour is discussed in the course of describing the experiments reported in §2.2.3.1 & §2.2.3.2.

2.2.1.2.1. 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, Pylkkänen et al 2004).

In §2.2.2, I discuss a number of experiments aimed at determining precisely what stage(s) in linguistic processing the M350 indexes.

2.2.2 Factors Affecting the Timing of the M350

Initial investigations of the M350 effect focussed on discovering which known behavioural and electrophysiological effects the component was sensitive to. The following three sections review three of those experiments.

2.2.2.1 Lexical Frequency

Embick et al (1999) were the first to identity the M350 component by name. They manipulated lexical frequency as a stimulus variable in a single word lexical decision task. The effect of frequency on lexical decision times is well established since at least Scarborough, et al (1977): words with that are highly frequent are recognized faster than words that are infrequent, all other factors being equal.

Embick et al sought to establish a neural correlate of this behavioural effect. The experiment used six categories of lexical frequency, ranging from category 1, composed of items whose mean frequency was 700/million (all frequencies are from the Cobuild corpus of 320 million words), to category 6, with a mean frequency of just 0.2/million.

Embick et al replicated the frequency effect behaviourally as expected, and found that the peak latencies of the M350 evoked component mirrored the reaction time effects. The higher the lexical frequency of an item, the earlier the M350 component peaked. Neither the M170, nor the M250 components were affected by the stimulus manipulation.

2.2.2.2. Repetition Priming

Pylkkänen, Stringfellow, Flagg and Marantz (2000) used a repetition priming paradigm to further explore the sensitivity of the M350 response component to factors affecting lexical activation. As in the Embick et al (1999) study, they find that the M350 component reliably reflects the reaction time effect. The M350 latencies are significantly earlier in response to targets that are immediately preceded by identical primes as compared to targets preceded by unrelated primes. And as in Embick et al, the M350 component is the first evoked component to be affected by the stimulus manipulations.

2.2.2.3 Cloze Probability

Helenius, Salmelin, Service & Connolly (1998) find that the M350 response is the neuromagnetic correlate of the N400 effect found in ERPs. The standard N400 paradigm, originating in work by Kutas & Hillyard (1984) manipulates the predictability of the final word in a sentence. When contextually constrained sentences end with a semantically inappropriate word, an event-related potential is elicited 300-500ms after the onset of the final word. Further research has shown that semantic inappropriateness is not critical for obtaining this response. Unexpected sentence endings of many sorts, even when they are semantically plausible elicit an N400 effect. In fact N400 ERPs are evoked by every word, but the magnitude of the response varies depending on many stimulus manipulations [see Pylkkänen & Marantz, 2003 for a review of the issues surrounding the N400 literature].

The N400 response is thought to arise from many generators, which may be both spatially (Halgren et al, 1994; McCarthy et al, 1995) and functionally distinct (Nobre and McCarthy, 1994). Because of the significant blurring of the electric signal by conductivity changes at the skull and scalp, source localization is difficult in EEG.

MEG provides superior spatial resolution, with no distortion in the magnetic signal by the surrounding tissues. Source localization is therefore much more straightforward and precise.

Helenius et al employ four sentence types, exemplified in (7), to investigate the cortical correlates of semantic processing in 10 individual subjects. In addition to the MEG recordings of subject's responses to the sentence final words, Helenius et al measured baseline auditory and somatosensory responses to serve as anatomical landmarks for source localization.

7.a. The piano was out of tune. (probable)
b. When the power went out, the house became quiet. (rare)
c. The pizza was too hot to sing. (anomalous)
d. The gambler had a streak of bad luggage. (phonological)

As expected, the anomalous endings (7.a & d a) evoked sustained left hemisphere responses peaking at approximately 400ms relative to the congruent sentence endings (7.b. & c.). The source of this activity was localized within the upper bank of either the superior or middle temporal gyrus in the left hemisphere in 7 out of 10 subjects.

This source localization is consistent with the sources modelled for the M350 activity by Pylkkänen and colleagues (Pylkkänen, Stringfellow and Marantz, 2002; Pylkkänen, Feintuch et al 2004), discussed in §2.2.3.1. & §2.2.3.3.

2.2.3. Dissociating Activation from Competition

Each of the experiments discussed in §2.2.3. provides evidence that that M350 is the first evoked electromagnetic response component to be affected by properties known to affect lexical activation. However, none of these results precludes the possibility that the M350 modulations are secondary effects (just as the reaction time measure in these experiments clearly is). Initial lexical activation could be occurring earlier in the time course at some as yet unidentified time point, and the M350 could be an index of post-lexical processing.

2.2.3.1 Pylkkänen et al 2002(a) - Phonotactic probability and neighbourhood density.

Pylkkänen et al. (2002a) investigated the factors affecting the timing of the M350 by manipulating the relative phonotactic probability and phonological neighborhood density of visually presented letter stings in a lexical decision experiment. Phonotactic probability is the probability of occurrences of individual phonemes and the probability of pairs or sequences of phonemes. Phoneme frequency depends on the number of words in a language that contain the phoneme and the frequency of occurrence of those words. The probability of phoneme pairs reflects the sequential probabilities of phonemes of words in a language. The neighborhood density of a word is a measure of the number and frequency of similar words in a language. Following Vitevitch and Luce (1999), phonological neighbors were defined as an item that could be converted to the stimulus by one phoneme substitution, deletion or addition in any position. For example, *cat, jar* and *cur* and *scar* are all neighbors of *car*.

Neighborhood density and phonotactic probability are highly correlated in natural language – words whose constituent bi-phones are very common in the language tend to be similar to a large number of other words in the language. Pylkkänen et al found that stimuli that are high in both phonotactic probability and neighborhood density elicited longer response times in lexical decision relative to stimuli with lower probabilities and neighborhood densities. This result replicates the findings of Vitevitch and Luce (1999).

The inhibitory effect of neighborhood density on lexical decision times can plausibly be attributed to the fact that high density items necessarily resemble, and hence activate, more actual lexical entries than low density items, and the more competing lexical entries an item activates, the longer the time needed for determining whether one of them can be selected as the "winner" in a competition for recognition.

The key finding of Pylkkänen et al. (2002a) was that the same high probability, high density items which elicited delayed RTs were associated with earlier M350 latencies (facilitation) than the low probability/density stimuli. The M350 component is, then, not only the first component sensitive to factors affecting lexical activation (repetition, frequency, cloze probability), but seems to index a stage of activation prior to processes of competition and selection. If the M350 were sensitive to competition among activated lexical items, it should show inhibition for the high density items rather than facilitation.

Pylkkänen et al. also found that high probability/density stimuli were correlated with decreased M250 amplitudes, suggesting that sub-lexical frequency information affects earlier stages of processing than lexical frequency. Decreased amplitude of an evoked brain response constitutes a facilitory effect. The later facilitation indexed by the latency of the M350 response is then plausibly a consequence of the earlier M250 facilitation.

Pylkkänen et al localized the source of the M350 response component using equivalent current dipoles (ECD). Following Helenius et al (1998), the left hemisphere auditory M100 response component, evoked by recording the neural response to 1KhZ tones, was localized for each subject. The M100 and M350 sources consistently localize to within 2cm of each other in the superior temporal and medial temporal gyri area

2.2.3.2 Stockall et al 2004 – Probability, Frequency & Density

This experiment was a direct follow up of Pylkkänen et al (2002a). In that experiment, the dissociation between the M350 facilitation and the reaction time inhibition in response to the high probability/density stimuli was attributed to probability and density having differential effects at different stages in the processing of lexical items. Stockall, Stringfellow and Marantz (2004) explicitly test this explanation by varying biphone probability and neighbourhood density independently.

The experiment also varied lexical frequency independently of sub-lexical frequency in order to further explore the possibility raised by Pylkkänen et al (2002a) that sublexical frequency effects precede lexical frequency effects. Table 4. shows the range of stimulus items used in the experiment.

LEXICALITY	WORD				NONWORD			
PROBABILITY	HIGH		LOW		HIGH		LOW	
DENSITY	HIGH	LOW	HIGH	LOW	HIGH **fape**	LOW **wurg**	HIGH **jeek**	LOW **shaf**
FREQUENCY	HIGH **deep** LOW **pave**	HIGH **wash** LOW **lure**	HIGH **curt** LOW **pout**	HIGH **fish** LOW **turf**	N/A			

Table 4. Sample stimulus items [Stockall et al, 2004]

Stockall et al found the predicted dissociation between phonotactic probability and neighbourhood density. Only probability had a significant main effect on the M350 component. High probability items elicited reliably earlier M350 latencies than low probability items. Likewise, only density had a significant effect on reaction times. Density and frequency were found to participate in an interaction on reaction times, such that for low frequency items like *pave* and *turf*, high neighbourhood density had the predicted inhibitory effect. But for the high frequency items, density had no significant effect on reaction times.

There was also a significant interaction between probability and density on M350 latencies, which is might suggest an early effect of neighbourhoods than had previously been assumed.

However, the density measure in this experiment was not frequency weighted and therefore was essentially a different measure than was used in the previous experiments.

The conclusion to draw from Stockall et al (2004) is that the interaction of various properties of lexical stimuli is more complicated than had previously been assumed, but that leaving some of these complications aside, the claim that the M350 indexes early stages of lexical activation is supported.

2.2.3.3 Pylkkänen et al 2004 - Morphological Family Size and Family Frequency

Pylkkänen et al (2004) exploit the established sensitivity of the M350 to lexical frequency (Embick et al, 1999) and morphological relatedness (Pylkkänen et al 2003) to investigate a puzzling result in the behavioural literature. Although the cumulative frequency of inflectional variants of a word has been shown to affect lexical decision times, just as the frequency of a particular form does (Baayen, Dijkstra & Schreuder, 1997; Schreuder & Baayen, 1997; Taft, 1979), no such effect has been found in the domain of derivation. High cumulative frequency of derivatives has not been found to facilitate behavioural responses to the stem as a free form. Either no effect at all is found (Schreuder & Baayen, 1997) or a trend towards inhibition for high cumulative frequency is exhibited (Baayen, Tweedie & Schreuder, 2002; Colé, Segui & Taft, 1979).

These findings run counter to the predictions of a decompositional model of lexical organization, in which derivatives of a stem count as instantiations of that stem. The frequencies of each derivative of a root should contribute to the total frequency of that root, and high frequency roots should facilitate the lexical decision process.

Pylkkänen et al (2003) hypothesized that the absence of a facilitory effect for cumulative derivational frequency might be due to competition among members of a morphological family for selection. Given the results of Pylkkänen et al (2000), the M350 is predicted not to show the effects of competition among lexical items. Therefore the M350 should show a facilitory effect for high cumulative morphological frequency items, even if that effect is attenuated in the reaction time measure.

Pylkkänen et al (2003) manipulated two stimulus variables: morphological family frequency, and morphological family size (the number of derivatives in a family). Family size has been found to have an effect on lexical decision times in previous behavioural experiments (Schreuder & Baayen, 1997): lexical decision times to nouns with many derivatives were faster than lexical decision times to nouns with few derivatives. The effect of family size has been taken to be a late decision-stage effect, arising from stronger semantic activation associated with items in large morphological families, and is therefore hypothesized not to affect the M350 component.

Behaviourally, Pylkkänen and colleagues replicated the results of Baayen, Djikstra and Schreuder (1997) for Dutch: the cumulative morphological family frequency of a noun had no effect on reaction times. Interestingly, Pylkkänen et al actually found an inhibitory effect of morphological frequency on the M350 component. Nouns from high frequency morphological families were associated with larger M350 amplitudes than nouns from low frequency families. Also surprisingly, morphological family size *did* affect the M350 component: nouns from large morphological families evoked significantly earlier M350 responses than nouns from small families.

Taken together, these two results suggest that competition among morphologically related items occurs earlier in the time course than competition among phonologically or orthographically related items.

Although not the results originally predicted for the experimental manipulations, evidence for an earlier effect of morphological competition is evidence that morphologically related items stand in a qualitatively different relationship to each other than items that share similar forms, but no morphological relationship.

Additionally, evidence that morphological processing follows an earlier time course than phonological processing is consistent with the results of Ko et al (2004), who show that a kind of morphological decomposition based solely on formal properties of the stimulus can occur within 100-200ms of stimulus presentation. See §2.2.1.1.1. for discussion of these results.

Chapter 3 Experiment 1

In the context, then, of the previous experiments investigating irregular verb priming and the evidence showing that the M350 is a reliable measure of initial lexical activation, the motivation for the two MEG experiments reported in this dissertation is not hard to understand.

As explained in §1.2, the model of lexical organization and access argued for in this dissertation 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 jas the unique allomorph of CAR (namely *car*) will activate its root.

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 the cross-modal experiment they conducted, only the past tense forms with a high degree of overlap with their stems failed to facilitate lexical decision to those stems as indexed by the time it took to press a response button. In the current experiment, we add the evoked M350 response component as a second dependent measure and present the primes as well as the targets visually.

These two modulations of the Allen and Badecker experiment allow 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 that 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.

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

3.1 Methods

3.1.1. 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). Participants were all students or employees at the Massachusetts Institute of Technology or at Harvard University and were paid $10/hr for their participation. MEG and behavioral data was collected from nine subjects, while behavioral data alone was collected from an additional eight subjects.

3.1.2. 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. *give-gave* = 2, *taught-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). And a point was also added to any pair that did not match in length. Total scores ranged from 2 to 9, and 4 was decided on as the cut off point. Pairs with scores of 4 or higher were classified as low overlap, while those with scores of 3 or lower became the low overlap items.

Allen and Badecker (2002) selected the items pairs in the orthographic overlap 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)). And 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).

Example Stimulus Set				
Condition		Prime	Target	Number of Pairs
I	Irregular Low Overlap	taught	teach	27
II	Irregular High Overlap	gave	give	27
III	Identity	boil	boil	25
IV	Orthographic Overlap	curt	cart	25

Table 5. Example stimuli from Experiment 1.

The irregular verb conditions each consisted of 27 stem targets, 27 related primes and 27 unrelated primes. The orthographic overlap condition and the identity condition consisted of

25 triplets (target, related prime, unrelated prime). Since each subject saw each target with both it's related and unrelated primes, they each saw 204 experimental pairs.

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. Non-words 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.

3.1.3. Procedure

Stimuli were presented using PsyScope 1.2.5 (Cohen, MacWhinney, Flatt & Provost 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).

Participants for whom MEG data was recorded lay prone inside a magnetically shielded room on a specially designed bed. Stimuli were projected onto a ground glass screen 8 inches above the participants head. Stimuli were presented in nonproportional Courier font, and subtended approximately 1.28 of visual angle vertically and 1.28 per character horizontally.

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.

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 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 behavioural 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, Shimogawara, Higuchi, Haruta & Ochiai, 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.

The amplitudes and latencies of the three evoked response components (the M170, M250 and M350) were recorded by first picking two sets of sensors 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 negative and positive field patterns associated with each component. The root mean square (RMS) field strength from these two 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) revealed a significant main effect of priming on M350 latencies ($F=1,7$; $p<0.002$)(control $\bar{x}=369.6$ms, prime $\bar{x}=341.2$ms), as seen in figure 13.

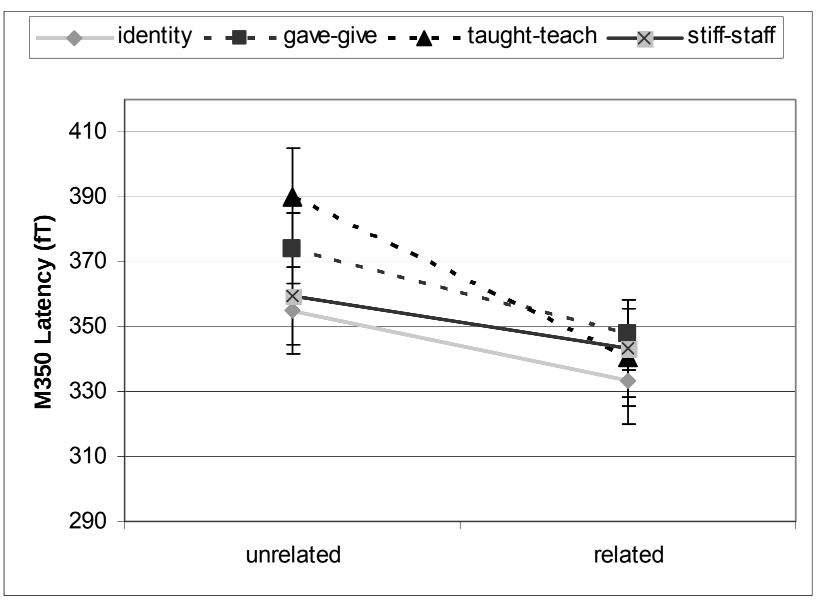

Figure 13. Plot of main effect of priming on M350 Latencies, Exp. 1

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 $\bar{x}$=355ms, prime $\bar{x}$=324ms), the *gave-give* condition (F=1,7; p<0.05) (control $\bar{x}$=374ms, prime $\bar{x}$=348ms) and the *taught-teach* condition (F=1,7; p<0.05) (control $\bar{x}$=371ms, prime $\bar{x}$=339ms). The *curt-cart* condition showed a trend towards priming, but the effect was not significant (F=1,7; p>0.1) (control $\bar{x}$=361ms, prime $\bar{x}$=343ms).

3.2.2. 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=1,13 p<0.004)[figure 14]. Planned comparisons revealed significant effects of condition on reaction times.

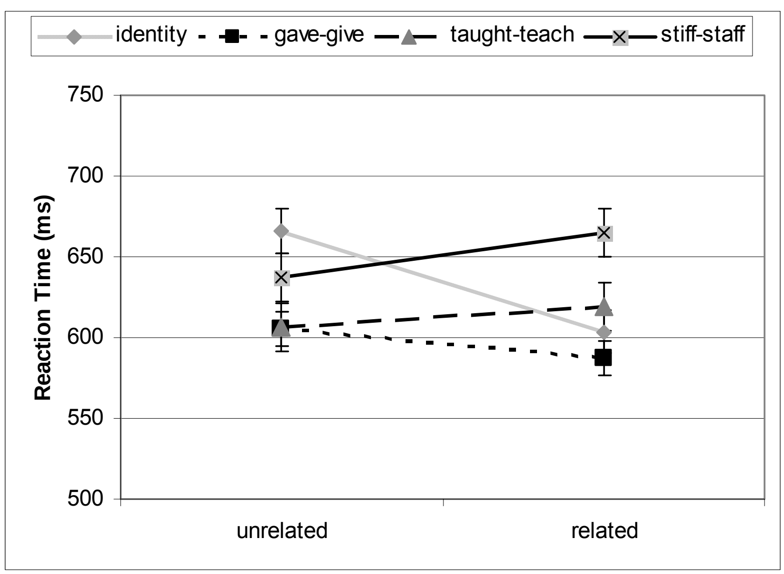

Figure 14. Plot of Interaction of Condition and Prime Relatedness on Reaction Time, Exp. 1.

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

3.3 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.

The M350 priming for the irregular verbs with high orthographic overlap (*gave-give*) is attenuated in the RT measure, but not significantly. In contrast, the M350 priming for the identity condition is significantly increased in the RT measure.

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.

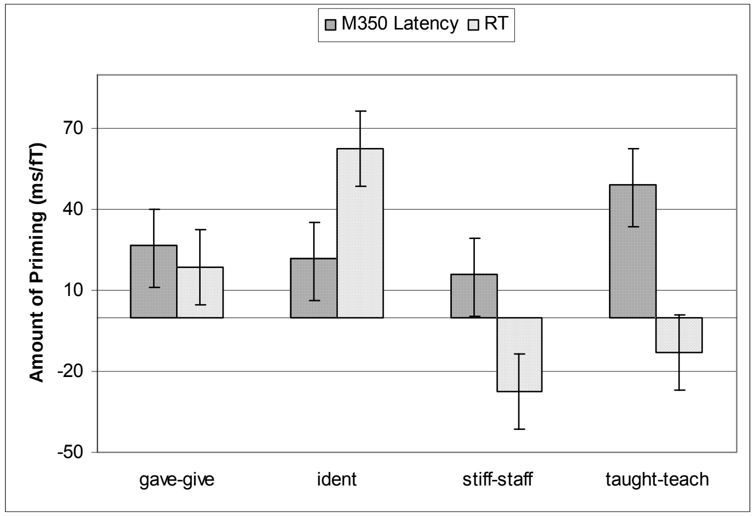

Figure 15. Plot of Neural and Behavioral Priming Effects, Exp. 1.
(amount of priming = related condition – control condition)

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 [see Pylkkänen et al. 2002a for more extensive discussion of this model].

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.

As discussed in §2.1.1.2, 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 §6.4.

Chapter 4 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. First 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 added 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 not 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.

The second goal of reversing the priming direction was that it was hoped that the use of the low overlap irregular past tenses as targets would allow us to determine more precisely why the neural priming for pairs like *taught-teach* was completely attenuated in the reaction time measure in Experiment 1.

One possibility is that the specific items in the low overlap condition are to blame. In Experiment 1, the related condition is the only one in which items with very irregular sound to orthography correspondences are found. Items like 'taught', 'brought', 'thought' etc are intuitively difficult to read. Since the only time the subjects encounter these items is when they are presented as primes in the *taught-teach* condition, it's possible that their presence is itself responsible for entirely cancelling out the processing advantage incurred by morphological identity.

In Experiment 2, the 'difficult' items are the targets, and therefore participants see them twice. This allows us to establish a baseline measure of the difficulty of processing the low overlap past tense items. If they are responded to significantly slower overall than the other experimental items, the orthography to phonology mismatch explanation would be supported.

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, on which see Bergen (2004) who presents evidence for a priming advantage for phonaesthemically related pairs).

4.1 Method

4.1.1. 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.

4.1.2. 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*. Half the items in this second condition were taken directly from the Rastle et al (2000) study, and therefore met their criteria for semantic relatedness (scoring an average of 7.5 or higher on a 9 point scale relatedness rating task).

The remaining half of the items were included in a rating study of out own, 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 number of related pairs in the experiment also did not exceed 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 6. Example stimuli for experiment 2.

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. Non-words 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.

4.1.3. 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. 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).

Participants for whom MEG data was recorded lay prone inside a magnetically shielded room on a specially designed bed. Stimuli were projected onto a ground glass screen 8 inches above the participant's head. Stimuli were presented in nonproportional Courier font, and subtended approximately 1.28 of visual angle vertically and 1.28 per character horizontally.

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.

4.1.4. 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.

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. Three subjects were excluded on the basis of this criterion.

The amplitudes and latencies of the M350 evoked response components were recorded by first picking two sets of sensors on the basis of the grandaverage file 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 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. For reporting purposes, significance is determined as $p<0.05$, while near significance is determined as $0.05<p<0.1$.

4.2 Results

4.2.1 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. The condition consisting of 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 ($F=1,9$; $p<0.029$) [see figure 16]. Planned comparisons reveal that the difference between the M350 latencies evoked by the +S+O-M condition were significantly slower than the latencies evoked by the buy-bought condition (irregular verbs with low orthographic overlap) ($F=1,9$; $p<0.039$)($\bar{x}=358$ vs. $\bar{x}=338$).

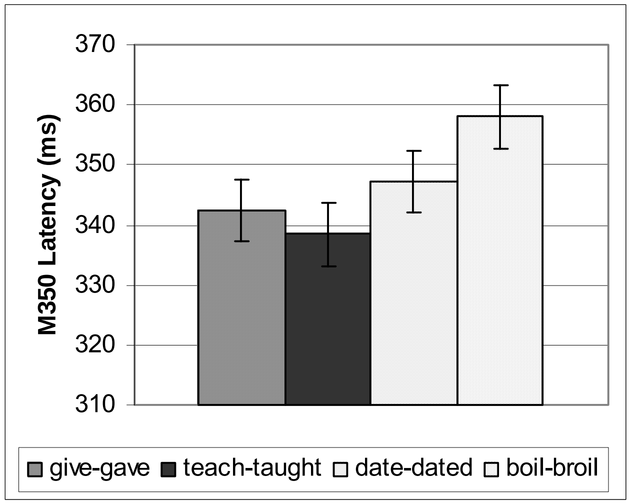

Figure 16. Main effect of condition on M350 latencies, Exp. 2.

The second main effect observed was an 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 $\bar{x}$= 355.1 vs. unrelated $\bar{x}$= 337.9), as shown in Figure 17.

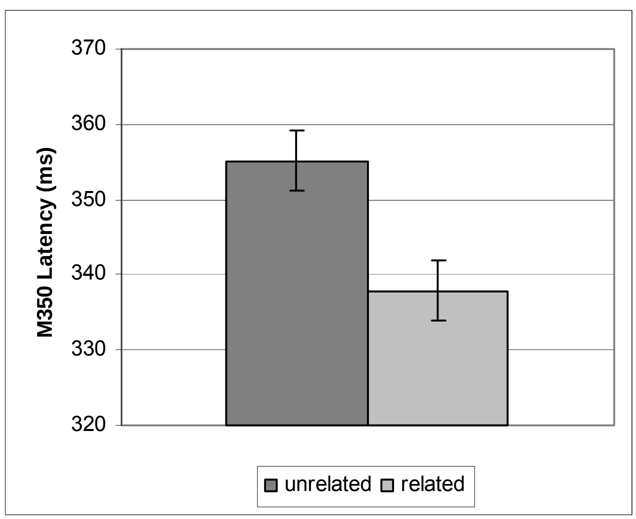

Figure 17. Main effect of relatedness on M350 latencies, Exp. 2.

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

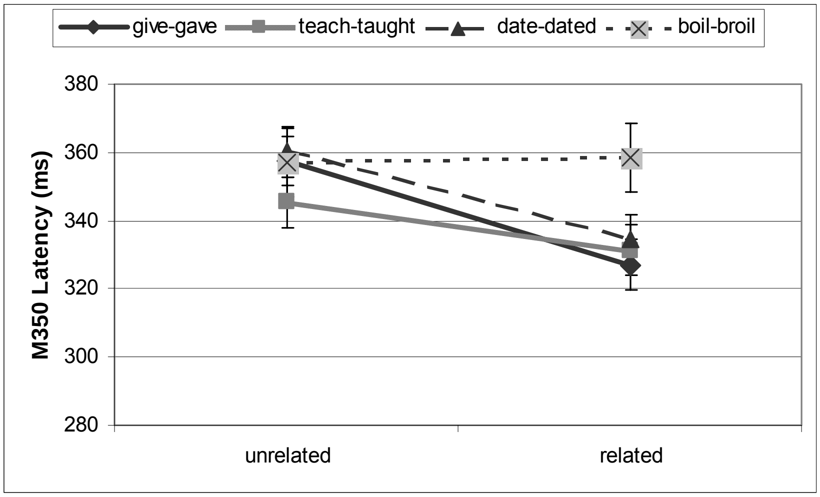

Figure 18. Significant neural interaction of relatedness on condition, Exp. 2.

4.2.2. Reaction Time

A similar 4x2 factor ANOVA on reaction times revealed two significant main effects: one of condition and one of prime relatedness. As figure 19 shows, the *boil-broil* condition and the regular verb condition are both significantly faster than the two irregular verb conditions.

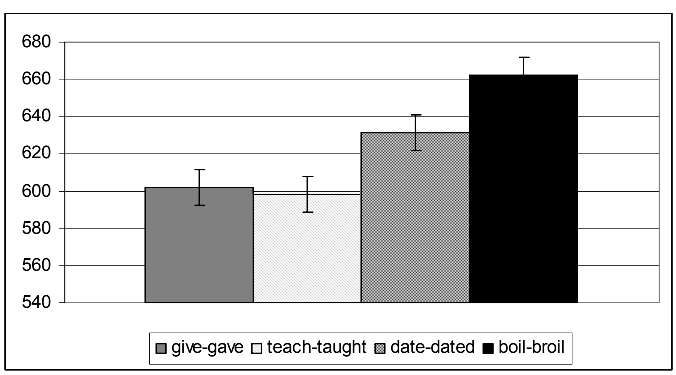

Figure 19. Plot of mean RTs (ms) for each experimental condition, Exp. 2.

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 Figure 20 is that across all experimental conditions, targets preceded by related primes were responded to faster than items preceded by unrelated primes (612ms vs. 634.8ms, $p<0.0008$).

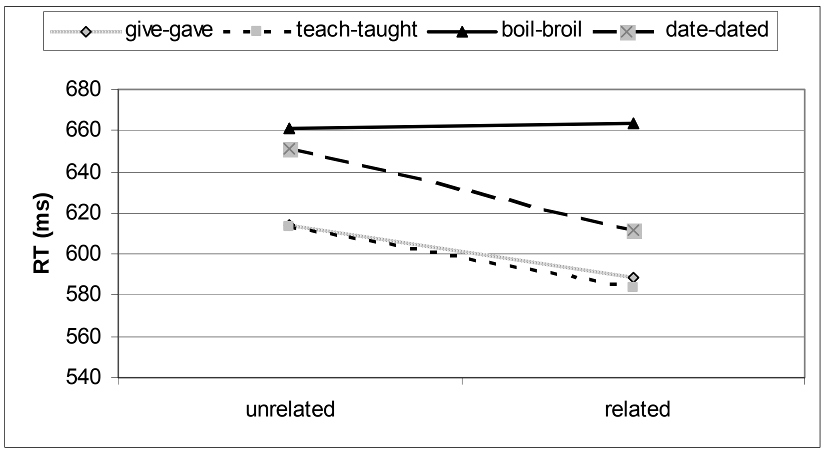

Figure 20. Plot of effect of prime relatedness on RT for each condition, Exp. 2.

However, as can also be seen in Figure 20 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 21.

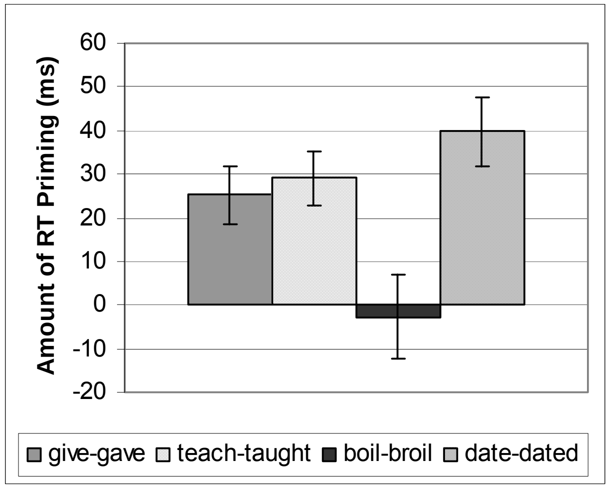

Figure 21. Plot of difference between RTs to targets in related condition and RTs to targets in unrelated condition, Exp. 2.

4.4 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 [illustrated in figure 20] provides key support for a model of lexical organization wherein morphological relatedness cannot 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 that are morphologically related.

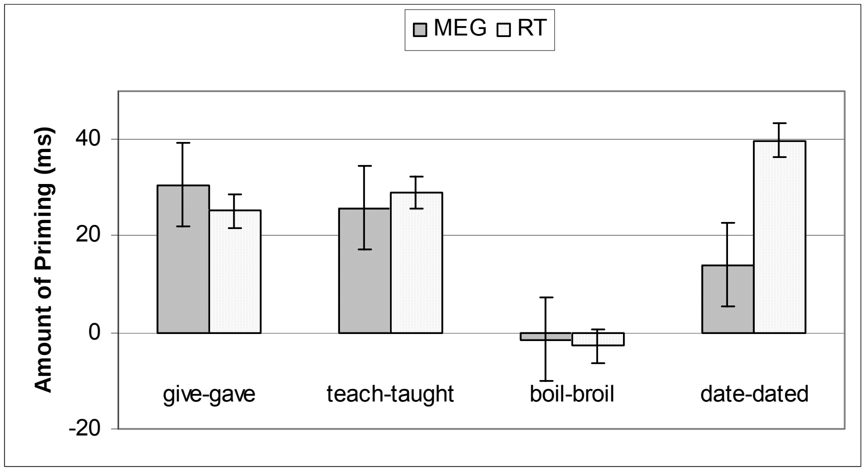

Figure 22. Comparison between M350 priming and RT priming effects, Exp. 2. Amount of Priming is a measure of the difference between the response to the target items in the unrelated condition and the target items in the related condition.

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. Recall the results of Pylkkänen et al (2002b), in which the M350 response was modulated both by the semantically related pairs (*idea* facilitated the activation to *notion*) and by the onset matched phonologically overlapping pairs (*spinach* inhibited the timing of the M350 activity associated with *spin*). The items in the +S+O-M condition are not all onset matchers and therefore not all necessarily associated with the kind of M350 inhibition the *spinach~spin* pairs are, but the net effect of the formal overlap seems to be to interfere in some way with the expected semantic facilitation for the pairs in this condition.

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

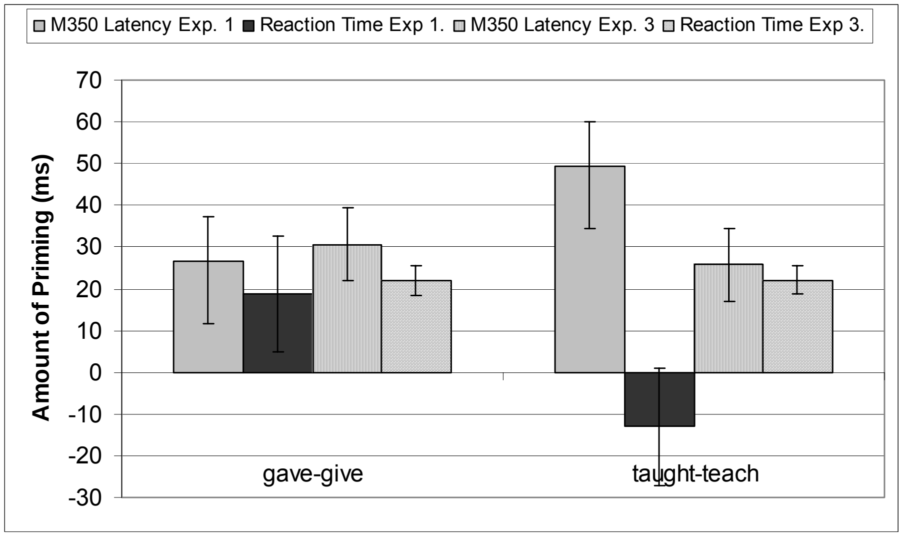

Figure 22. Summary of priming effects for the two irregular verb categories across the two experiments. Amount of priming = response to unrelated condition – response to unrelated condition

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 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.

Chapter 5 Experiment 3

Experiment three returns to the materials of experiment one, and employs a long lag priming paradigm in an effort to find an additional means of dissociating morphological relatedness from orthographic or semantic relatedness. The long lag priming paradigm is one in which several items intervene between the prime and target. Marslen-Wilson & Tyler (1998) show that semantic priming drops off sharply and does not survive over intervening items to prime a long lag target, but that both regular and irregular past tenses do continue to prime their stem correlates, even when separated by several items (see also Stanner et al, 1977 for another long lag experiment finding robust priming for both kinds of past tense form). This difference in the persistence of the activation between semantically related items and morphologically related items provides support for a model in which these kinds of relatedness are distinct.

We sought to similarly dissociate morphological relatedness from orthographic relatedness and to show that the persistence of morphological priming is similar to identity priming effects.

5.1. Method

5.1.1 Participants

Sixty-nine English-speaking adults gave their informed consent to participate in the experiment (thirty-seven females and thirty-two males ranging in age from 18 to 36, mean age 23.5). Participants were all students or employees at the Massachusetts Institute of Technology and were paid $10/hr for their participation.

5.1.2 Stimuli

The stimulus items and experimental conditions were the same as for experiment one. Because the design of this experiment did not overtly pair primes and targets, there was no need for any word fillers, so all filler items were non-words. The word filler items from experiment one were altered by substitution of one or more segments to create the additional non-word fillers needed for experiment two.

5.1.3. Procedure

Stimuli were presented using DMDX (Forster and Forster, 1990). Each trial consisted of a letter string target that 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 right index and middle fingers to press the response buttons.

Stimulus items were divided between two blocks, so that each target item appeared only once per block and each block was evenly balanced in terms of conditions and prime-target relatedness. Subjects were arbitrarily divided into two groups such that thirty-three subjects saw the first block of the experiment and thirty-six subjects saw the second block. In this way, no subject saw any test item more than once.

In order to assure that each target item appeared exactly 20 items after it's prime, the relative order of items within the experiment was fixed.

5.1.4. 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 5.7% of the data. Subjects with an overall error rate of higher than 15% were rejected from further analysis. The data from 8 participants did not survive this criterion, leaving 61 subjects whose reaction time data was analyzed.

5.2 Results

5.2.1 Reaction Time

A 4x2 factor ANOVA (4 categories: high overlap irregular, low overlap irregular, identity and orthographic overlap, related vs unrelated condition) on reaction time to target items revealed several significant main effects and interactions. Stimulus category had a significant effect on reaction times, independent of whether an item was a prime or a target, or whether it was in the related or unrelated condition. Table 7 reports the mean reaction times for each category of stimuli.

Stimulus Category	Mean RT
high overlap irregular	572.1
low overlap irregular	587.7
identity	631.9
orthographic overlap	633.8

Table 7. Mean lexical decision times by stimulus category, Exp. 3.

Planned comparisons reveal that the two irregular verb categories are not significantly different from one another and that the identity category and the orthographic overlap category are not significantly different from one another, but that all other pairwise comparisons are reliably different ((F 1,60), $p<0.000001$).

And relatedness also had an overall effect on reaction time, with items in the related condition being responded to faster than items in the unrelated condition. Figure 24 shows the difference between targets preceded by related primes and targets in the unrelated condition for each stimulus category.

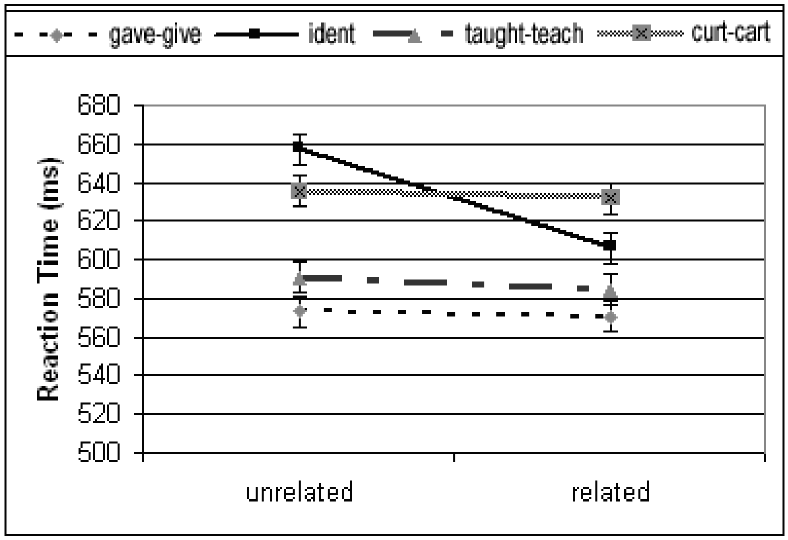

Figure 24. Plot of effect of relatedness on lexical decision times for each stimulus category, Exp. 3.

Although relatedness is a significant factor independent of stimulus category (unrelated condition $\bar{x}$=598.4 vs related condition $\bar{x}$=614.3, F=1,60 p<0.0001), figure n. clearly shows that this effect is driven entirely by the items in the identity category.

Planned comparisons between the related and unrelated items in each category confirm that this is the case. Only the response times to items in the identity category are reliably effected by whether they are preceded by a related prime or not (unrelated $\bar{x}$=657.4 vs. related $\bar{x}$=606.3, p<0.0000001). None of the other comparisons even approaches significance.

5.3 Discussion

The experiment would seem to have failed. No evidence of a facilitory effect for morphological relatedness was found, and no difference between the morphological conditions and the pure formal overlap condition was found. This would seem to suggest that morphological relatedness is not in fact like identity, and is instead like orthographic relatedness or semantic relatedness.

However, further analysis of the reaction time results suggests that this is necessarily the case. When we look at the difference between the primed response and the unprimed response (item not preceded by related prime) for individual stimulus items, we actually find that there is significant priming for some items and significant inhibition for others. The overall effect is for these two responses to cancel each other out.

category	item	difference	category	Item	difference
hi overlap	grew-grow	-122.15	lo overlap	bought-buy	-78.98
hi overlap	hung-hang	-90.94	lo overlap	said-say	-70.20
hi overlap	ran-run	-84.12	lo overlap	Bound-bind	-66.12
hi overlap	gave-give	-69.10	lo overlap	caught-catch	-60.56
hi overlap	shot-shoot	-63.65	lo overlap	lit-light	-51.76
hi overlap	bit-bite	-52.96	lo overlap	went-go	-42.34
hi overlap	sent-send	-43.71	lo overlap	fought-fight	-41.52
hi overlap	dug-dig	-43.71	lo overlap	froze-freeze	-39.28
hi overlap	fed-feed	-39.43	lo overlap	thought-think	-38.70
hi overlap	met-meet	-28.91	lo overlap	stole-steal	-37.51
hi overlap	rang-ring	-18.41	lo overlap	taught-teach	-35.45
hi overlap	chose-choose	-18.28	lo overlap	Stood-stand	-30.54
hi overlap	dealt-deal	3.18	lo overlap	told-tell	-10.61
hi overlap	heard-hear	5.95	lo overlap	Found-find	-3.22
hi overlap	swung-swing	14.02	lo overlap	Spoke-speak	-1.44
hi overlap	held-hold	15.98	lo overlap	brought-bring	-0.67
hi overlap	drove-drive	17.26	lo overlap	did-do	11.30
hi overlap	wrote-write	18.01	lo overlap	Struck-strike	14.55
hi overlap	came-come	28.04	lo overlap	took-take	20.45
hi overlap	sat-sit	34.64	lo overlap	sought-seek	24.65
hi overlap	spat-spit	47.28	lo overlap	sold-sell	25.13
hi overlap	drew-draw	49.07	lo overlap	lied-lie	28.01
hi overlap	slid-side	51.33	lo overlap	wove-weave	30.62
hi overlap	sang-sing	72.21	lo overlap	slew-slay	43.11
hi overlap	sank-sink	81.46	lo overlap	Broke-break	60.15
hi overlap	bled-bleed	81.73	lo overlap	Swore-swear	74.46
hi overlap	woke-wake	87.49	lo overlap	paid-pay	88.95

Table 8. Effect of priming for each irregular verb stimulus pair, Exp. 3. Difference = (response to target in prime condition) – (response to target in prime condition). Negative numbers indicate a facilitory effect, positive numbers an inhibitory effect.

Table 8 shows the numerical differences between the targets in the related condition and the targets in the unrelated condition for all 54 irregular past tense-stem pairs in the experiment. The shaded areas at the two extrema of the table indicate the irregular verbs for which there is a clear effect of prime relatedness on the lexical decision response to the target. Negative numbers represent a facilitory effect of prime relatedness, with primed targets being responded to faster than unprimed targets. Positive numbers, on the other hand, reflect an inhibitory effect of prime relatedness. For irregular verbs such as *wake* and *pay*, the effect of the past tense being activated and an intervening lag between prime and target is to cause processing delays for the stem.

Given that that irregular verbs are quite cleanly split into those that prime their stems and those that inhibit them and those that show no effect either way in the long lag paradigm, there must be some factor that can explain these differences in behaviour. Speculations as to what factor, or factors those might be and how the split between priming items and inhibiting items might inform a detailed model of how multiple allomorphs of a single root might be represented will be dealt with in the section on long lag priming in Chapter 6 (§6.6).

Chapter 6 General Discussion & Conclusions

6.1 Clear evidence for irregular verb priming

The primary motivation for the experimental manipulations reported in this dissertation was to provide clear, straightforward evidence that all allomorphs of a root activate their root equally and therefore that all inflected allomorphs prime their stems equally in the early stages of lexical activation. Irregularity is irrelevant at the stage in processing indexed by the M350.

This finding is clearly compatible with the single mechanism, full, across the board decomposition model articulated in chapter 1. It is just as clearly incompatible with the dual mechanism model that 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 the Rumelhart and McClelland (1986) type models are based on.

Regular verbs are associated with the exact same pattern of priming responses that the repetition priming condition is – an M350 priming advantage of 15-20ms and a reaction time priming advantage of 50-60ms. The magnitudes of priming associated with the irregular verbs are slightly different, in that the magnitude of reaction time priming is less than the magnitude of neural priming. This post activation difference between regulars and irregulars is seen particularly clearly for the *taught~teach* pairs, as discussed in the next section.

6.2 Dissociation between M350 and RT measures

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. The 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.

A similar dissociation was found by Pylkkänen et al (2002a) as discussed in §2.2.3.1., for phonological neighbourhood size (items from high density neighbourhoods evoked earlier M350s and delayed RTs) and Pylkkänen et al (2002b), discussed in §2.1.1.3., in which non onset-matching phonologically related prime-target pairs like *teacher~reach* produced M350 facilitation and RT delays.

6.3 Directionality Effect

As Figure 25 shows, 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 one, where the direction is from past tense prime to stem target, the neural priming had completely disappeared by the time the lexical decision button press was registered. However, in experiment 2, the priming from stem *teach* to past tense allomorph *taught* was robust in both the M350 and RT measures.

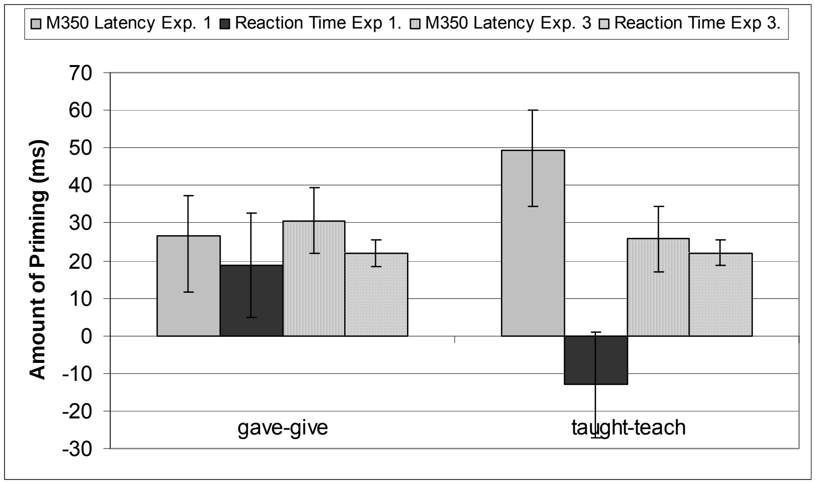

Figure 25. Plot of neural and behavioural priming effects for irregular verb/stem pairs in experiment 1 & 2. Amount of priming = prime condition – control condition.

A possible explanation for this asymmetry can be found if we consider the model sketched in Figure 5 in §1.2.3 above (repeated here).

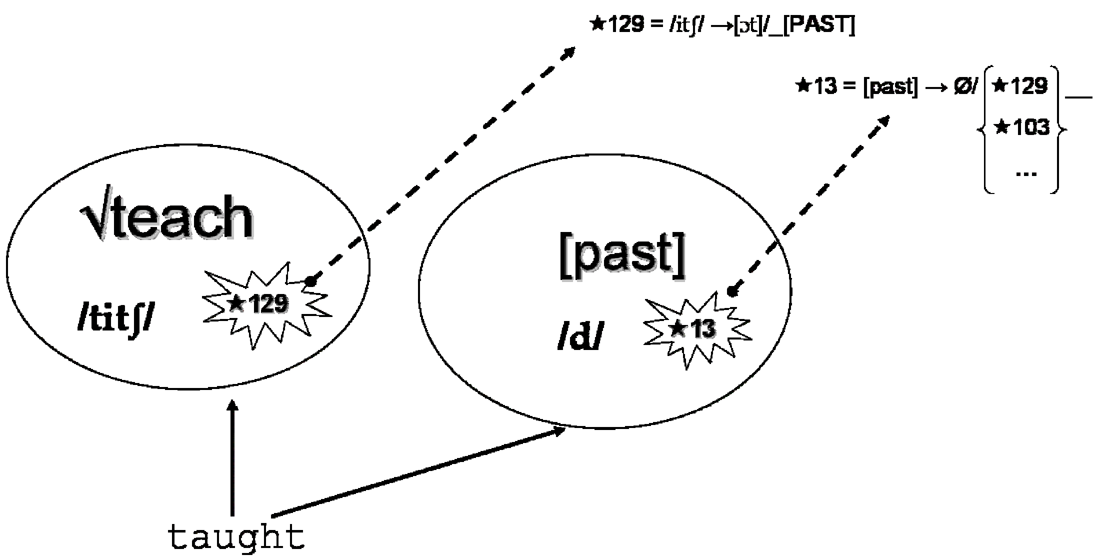

Figure 5. A schematic model of the processes involved in the recognition of an irregular allomorph.

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 is probably untestable.

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 in the process of 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.

6.4 Modality of Prime

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, some of which are discussed in §2.1.1.2 above. This growing body of results seems to suggest that there is something about processing a visual target immediately after processing an auditory prime that is weird. We need more MEG experiments to clarify that the modality effect is post root access, and reflects particular issues in the course of recognition and selection.

The problem seems to be very particular. Marslen-Wilson and Zhou (1999) initially described the so called 'suffix-suffix interference effect'. Feldman and Larabee (2001) show that this effect, wherein a suffixed prime fails to prime a differently suffixed target, where both are derivatives of the same root, is specific to cross-modal. 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.

6.5 Dissociation between Morphology and Semantics+Phonology

The Feldman (2000) and Rastle et al (2000) experiments discussed in §2.1.1.3 offer convincing evidence that the behavioural effect produced by morphological priming can not be accounted for by a model in which morphological relatedness is merely a convenient umbrella term that really reduces to a combination of phonological and semantic relatedness. Pylkkänen et al (2002b), as discussed in §2.1.2.3, shows that neurally as well, morphological priming effects cannot be predicted by summing semantic and phonological priming effects.

The current experiment 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.

6.6 Issues in Long Distance Priming

The failure to find a consistent, general priming effect for the irregular verb pairs in the long lag paradigm is not as surprising as it might at first seem. As we've seen already in the immediate priming experiment reported in chapter 3, not all irregular past tense/stem pairs are associated with a behavioural priming advantage.

The initial hypothesis, formed on the basis of the Allen and Badecker (2002) cross-modal results, was that the failure of an irregular allomorph to prime its stem correlate was due to post access competition between formally similar allomorphs. But in fact this is not what the results of experiments one and two seem to show.

Instead it appears that there is no competition between allomorphs on any formal level that would be analogous to the competition between orthographically similar forms such as *curt* and *cart*. There is no evidence that the high degree of formal similarity between the allomorphs *gave* and *give* has any effect on the processing of these items.

To the extent there is evidence for any kind of interference between various allomorphs of a single root in the recognition process, the evidence seems to be that activation of an irregular rule can interfere with the subsequent recognition of the default allomorph of the shared root.

We have good evidence from other long lag priming experiments discussed in Chapter 2 (Stanners et al, 1979, Marslen-Wilson and Tyler, 1998) that morphological priming persists over many intervening items, just as identity priming does. Since in our model both involve the exact same mechanism, namely reactivation of the same root, this is not surprising.

What we do not know is what the duration of rule activation is. If an irregular rule is activated in the recognition of an irregular allomorph, does the link to that rule stay active as long as the root it is connected to does? Or is the link more like the similarity networks connecting semantic and phonological neighbours, activated briefly and then left to quickly subside to normal resting levels?

Depending on the answer, we might just as easily predict inhibition for irregular allomorph pairs over long lags. In fact, we find a mix of priming and inhibition, with a few cases of null effects.

Clearly these results are inconclusive and suggest the need for further experiments. A long lag MEG priming experiment that included not just the irregular verb pairs, but also the regulars and the +S+O-M pairs (*boil~broil*) would presumably go a long way towards clarifying the reason we find such mixed results for the irregulars in experiment 3.

6.7 The Time Course of Lexical Activation

Ko et al (2004), replicating and expanding on Rastle et al (2000), provide evidence for an early, form based process of affix stripping. The evidence comes from the differential neural and behavioural responses to *brother* and *brothel*. When this system encounters a word that contains substrings that are often distinct morphemes in the language, those possible morphemes are in some sense stripped off the putative stem.

Though this mechanism would clearly result in errors in cases like *brother* where the resemblance to morphologically complex words is accidental, it is easy to see how it would be a very useful mechanism in most cases. If the early visual processing component can successfully strip off affixes from stems, prior to lexical access, the process of identifying the stored root is much simpler.

The different effects of orthographic overlap between past tense and stem forms for irregular and regular verbs are consistent with this kind of form based stripping mechanism.

Allen and Badecker (2002), and experiment one, reported in §3, show that irregular allomorphs can interfere with the processing advantage otherwise conferred by morphological priming. Yet although *walked* has roughly the same degree of formal overlap with *walk* that *kept* does with *keep*, there is no evidence that orthographic similarity is ever a factor in regular verb priming experiments.

The form based affix stripping mechanism provides an explanation for this. The past tense morpheme in *walked* is easily recognizable as the past tense and easily dissociable from the stem *walk*. By the time initial lexical activation occurs, *walked* has already been broken into its constituent pieces. The stem form *walk* easily activates its root WALK, and the past tense allomorph –*ed* easily activates its lexical entry as well.

6.8 Conclusions

The introduction to this dissertation began with articulation of a single goal: to provide support for full, across the board morphological decomposition, irrespective of irregular allomorphy. This goal has been achieved. The two immediate priming experiments 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, the experiments reported here, taken together with a wide range of other experiments investigating the psychological status of morphological relationships, provide a number of interesting starting points for further research.

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. As discussed in §6.5, 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 'stems' 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, and in fact pattern with the regulars and repetition priming pairs, the dual mechanism model is not supported by the experiments in this dissertation.

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 in this dissertation 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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Appendix 1: Stimuli for Experiments 1 & 3.

Condition	Unrelated Prime	Related Prime	Target
Irregular + Overlap	beach	bit	bite
Irregular + Overlap	daily	bled	bleed
Irregular + Overlap	fate	chose	choose
Irregular + Overlap	faith	came	come
Irregular + Overlap	blood	dealt	deal
Irregular + Overlap	fault	dug	dig
Irregular + Overlap	dozen	drew	draw
Irregular + Overlap	luck	drove	drive
Irregular + Overlap	north	fed	feed
Irregular + Overlap	note	gave	give
Irregular + Overlap	fall	grew	grow
Irregular + Overlap	gift	hung	hang
Irregular + Overlap	holy	heard	hear
Irregular + Overlap	fear	held	hold
Irregular +Overlap	dance	met	meet
Irregular + Overlap	front	rang	ring
Irregular + Overlap	block	ran	run
Irregular + Overlap	lower	sent	send
Irregular + Overlap	hope	shot	shoot
Irregular + Overlap	large	sang	sing
Irregular + Overlap	crime	sank	sink
Irregular + Overlap	home	sat	sit
Irregular + Overlap	far	slid	slide
Irregular + Overlap	nose	spat	spit
Irregular + Overlap	fruit	swung	swing
Irregular + Overlap	daisy	woke	wake
Irregular + 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
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
Ortho Overlap	tone	stoop	stop
Ortho Overlap	cost	stew	stow
Ortho Overlap	rule	stroke	strike
Irregular - Overlap	cause	bound	bind
Irregular - Overlap	start	broke	break
Irregular - Overlap	press	brought	bring
Irregular - Overlap	fill	bought	buy
Irregular - Overlap	turn	caught	catch
Irregular - Overlap	tempt	did	do
Irregular - Overlap	walk	fought	fight
Irregular - Overlap	try	found	find
Irregular - Overlap	move	froze	freeze
Irregular - Overlap	boil	went	go
Irregular - Overlap	keep	lay	lie
Irregular - Overlap	need	lit	light
Irregular - Overlap	shrug	paid	pay
Irregular - Overlap	wait	said	say
Irregular - Overlap	thank	sought	seek
Irregular - Overlap	want	sold	sell
Irregular - Overlap	dare	slew	slay
Irregular - Overlap	kill	spoke	speak
Irregular - Overlap	length	stood	stand
Irregular - Overlap	pack	stole	steal

Irregular - Overlap	crawl	struck	strike
Irregular - Overlap	look	swore	swear
Irregular - Overlap	spare	took	take
Irregular - Overlap	call	taught	teach
Irregular - Overlap	push	told	tell
Irregular - Overlap	save	thought	think
Irregular - Overlap	fail	wove	weave

Appendix 2: Stimuli for Experiment 2

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

Irregular - Overlap	save	think	thought
Irregular - 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 + Overlap	beach	bit	bite
Irregular + Overlap	daily	bled	bleed
Irregular + Overlap	fate	chose	choose
Irregular + Overlap	faith	came	come
Irregular + Overlap	blood	dealt	deal
Irregular + Overlap	fault	dug	dig
Irregular + Overlap	dozen	drew	draw
Irregular + Overlap	luck	drove	drive
Irregular + Overlap	north	fed	feed
Irregular + Overlap	note	gave	give
Irregular + Overlap	fall	grew	grow
Irregular + Overlap	gift	hung	hang
Irregular + Overlap	holy	heard	hear
Irregular + Overlap	fear	held	hold
Irregular + Overlap	dance	met	meet
Irregular + Overlap	front	rang	ring
Irregular + Overlap	block	ran	run
Irregular + Overlap	lower	sent	send
Irregular + Overlap	hope	shot	shoot
Irregular + Overlap	large	sang	sing
Irregular + Overlap	crime	sank	sink
Irregular + Overlap	home	sat	sit
Irregular + Overlap	far	slid	slide
Irregular + Overlap	nose	spat	spit

Irregular + Overlap	fruit	swung	swing
Irregular + Overlap	daisy	woke	wake
Irregular + Overlap	food	wrote	write