Testing models of English past-tense inflectional morphology: Semiregular patterns

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Abstract

Surprisingly little research in the debate over the English past tense has focused on the regularity among irregular verbs (semiregularity; e.g., *keep-kept*, *weep-wept*). While previous experiments have shown that the presence of semiregular phonological neighbors can slow down production time for regular verbs (Seidenberg & Bruck 1990), little is known about the effect of regular neighbors on semiregulars. In this experiment, subjects completed a stem-inflection task by inflecting 81 randomly ordered verbs while RTs and errors were recorded. Both regular and irregular verbs were used, with varying degrees of individual frequency, family frequency, and family regularity. Linear regressions showed that both regulars and irregulars were subject to frequency as well as family regularity factors. The effect of family regularity was strongest when individual and family frequencies were low. These family regularity effects for irregulars are not consistent with dual-mechanism models like Words-and-Rules which claim that the presence of regular neighbors has no effect on irregular inflection. These results lend credence to the view that regulars, semiregulars, and pure irregulars are not processed independently, but fall along a continuum of regularity, which is consistent with single-mechanism Connectionist models.

1. Introduction[1]

1.1 Motivation and intent

For various historical and theoretical reasons, one of the fiercest battles between Classical computation and Connectionist association has been fought over the English past tense: “The significance of the English verb is that its procedures for forming the past tense offer an unusually sharp contrast, within the same cognitive domain, between a *highly regular procedure* and a *highly irregular and idiosyncratic set of exceptions*” (Marslen-Wilson & Tyler 1998, emphasis mine). It is widely held that the English past tense is not very important *per se* but is a very convenient, straightforward microcosm of a larger theoretical debate about how language works. By contrast, the English progressive is fully regular (all progressive verbs end in *-ing*) and thus is an uninteresting research topic. In essence, the obvious quasiregularity (presence of both regular and irregular inflections in the same domain) of the past tense has made it a well-trodden battleground for rule-based and analogy-based theories that seek to explain the presence of both ‘regular’ and ‘irregular’ transformations in the past tense, though it should be added that the disproportionate interest in the English past tense should not diminish the importance of studying other inflectional morphologies in other languages.

In this thesis, I will outline the nature and importance of the past-tense debate, explain two popular models and their strengths and weaknesses, examine behavioral and neuropsychological data, and finally, advance the topic of semiregulars in the debate. Semiregulars are so-called ‘irregular’ verbs that exhibit internal regularity (i.e., make similar irregular transformations, such as *keep-kept* and *weep-wept*). I will review the literature on

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[1] I am indebted to Robert Thornton, Jay Atlas, and the rest of Pomona College Department of Linguistics and Cognitive Science for their help and support. Additional thanks are due to the 20 experiment participants.

semiregularity and the predictions of the models, as well as present an original experiment designed to find what effects (if any) the presence of regular and semiregular phonological neighbors have on each other.

The two essential questions I seek to answer are (1) Are regular and irregular verbs *categorically distinct* or merely different ends of a *spectrum*? and (2) How well do single- and dual-mechanism models of the past tense *fit the data*? I believe that a focus on semiregular forms can shed new light on the answers to both questions. First, semiregulars can be thought of as somewhere on a continuum between regulars and pure irregulars (e.g., the suppletive *go-went*), but it remains an empirical matter whether they actually pattern with regulars, irregulars, or in between. Second, semiregulars are handled differently by single- and dual-mechanism models, and detailed research on semiregularity may yield results which are better accommodated by one model than the other.

The past-tense debate erupted when Rumelhart and McClelland (1986) attempted to show that 'rules' were unnecessary for quasiregular domains such as the past tense. The aim of this thesis is not to do away with rules, however, nor is it to highlight their necessity. Rather, it is to try to understand the vast landscape of research on the past tense, what each model contributes, where each is lacking, and ultimately, where this debate should be headed. It seems that many researchers on both sides of the debate have become too entrenched in it to see the forest for the trees anymore. Though considerable progress has been made in our understanding of the inflectional morphology of the English past tense, the two leading models (Connectionist and Words-and-Rules) are both supported by much of the data. Hopefully, this examination of semiregulars will contribute to our understanding of inflectional morphology, help make clear which model (if any) works best, and guide future research in the area.

1.2 Why model?

It is instructive to consider why any kind of computational model should even be considered. Obviously, there are important limitations and caveats to be had with any type of modeling. But it is important to note that models are not just idle toys—they can actively test and inform specific theories about how the brain can accomplish various tasks. Seidenberg and Zevin (2006) elaborate:

> Behavioral experiments can tell us what the effects of stimulus and task manipulations are on overt responses. Imaging can tell us what brain regions and circuits are involved in processing. There is a further need for computational models that explain how brain mechanisms give rise to behavior. Otherwise the behavioral work is isolated from the brain and the neuroimaging has an atheoretical, descriptive character.

Indeed, models can be *informative* and *instructive* for our theories of the mind and brain. By allowing for empirical experimentation in ways unavailable to mere observational science, models give researchers the chance to try to match the performance of observed subjects, and then determine what aspects (if any) of the model can be extrapolated to theories of language and cognition. Simulating actual computations can "enforce a rigor on our hypotheses which would be difficult to achieve with mere verbal description" (Elman et al. 1996). Models allow for tinkering and manipulating structure and data, while simultaneously providing access to their internal representations. To be sure, cognition and mentation are highly complex processes, and models necessarily simplify these processes to some extent; but "complex processes require an understanding of nonlinear interactions among a large number of components, and properties that emerge in systems as a result of such interactions. Models are essential for exploring this kind of complexity" (Munakata & McClelland 2003).

1.3 Caveats

We should not proceed in any discussion of computational modeling without keeping in mind that like Camelot in *Monty Python*, it is *only a model!* Models simulate, approximate, and estimate, but they do not *replicate* in any strict sense of the term. Hardly anyone would claim that a model of language acquisition actually *knows* anything about language or the world. Yet models' value as theory-testers cannot be overlooked.

Further, in regard to the debate over 'rules', it should be noted that the question at hand is whether rules are explicitly used *by the brain* in the process of inflecting regular past-tense verbs. This is not a debate about whether there is a general, descriptive morphophonological rule about the *language*. With these caveats in mind, let us begin.

2. The past tense debate

2.1 Why the past tense?

The regular past tense inflection of *-ed* applies to 86% of the 1000 most common verbs (Pinker 1999). Irregular forms tend to be high-frequency, and high-frequency verbs tend to be irregular. This is often explained by noting that only high-frequency words could remain irregular without being subsumed by the regular rule (Pinker 1999). Other explanations include the idea that high-frequency verbs *become* irregular due to frequent production costs which may lead to irregularly abbreviating past tense forms (Lupyan & McClelland 2003). Regardless, it is clear that there are at least two different ‘types’ of verb inflection; what remains highly contended is whether or not these types are categorically distinct or merely two ends of a spectrum. The debate is largely fought by proponents of two competing theories of the past tense: single- and dual-mechanism models. While other types of models exist,[2] the focus of this paper is on these two leading models.

As previously mentioned, the English past tense has become a battleground for a larger theoretical war (Rumelhart & McClelland 1986; Fodor & Pylyshyn 1988; Elman et al. 1997; Pinker 1999; Marcus 2001). The debate focuses on the core mechanisms responsible for language and cognition: are they rule-based (Classical) or analogy-based (Connectionist or otherwise non-Classical)? While it is not always clear how much can be extrapolated from the tiny sliver of language phenomena that is the English past tense, when compared contextually with other inflectional morphologies in other languages, it is hoped that overarching themes will emerge. Thus, the English past-tense, while relatively uninteresting in and of itself, has become an unavoidable microcosm of a long-standing debate.

2.2 The dual-mechanism theory: Words-and-Rules

Throughout the past two decades, Pinker and his colleagues (Pinker & Prince 1988; Marcus et al. 1992; Prasada & Pinker 1993; Ullman et al. 1997; Pinker 1999; Pinker & Ullman 2002) have outlined a dual-mechanism approach, the Words-and-Rules theory (WR). Building on the traditionally recognized dichotomy between lexicon and grammar, WR claims that irregular

[2] For example, Chomsky & Halle (1968) claim that inflected (e.g., past-tense) forms are created by the carrying out of productive rules inherent in the inner structure of the word’s representation in the mind. While these theories explain well the large swaths of regularity and consistency among verbs (e.g., all ‘regular’ -*ed* forms and ‘semiregular’ forms like *sweep*-*swept*, *keep*-*kept*), they posit “implausibly abstract underlying representations (e.g. *rin* for *run*, which allows the verb to undergo the same rules as *sing*-*sang*-*sung*)” (Pinker & Ullman 2002) to handle counterexamples.

forms are stored in the lexicon (declarative memory) while regular forms are produced on-the-fly by a combinatorial operation (procedural rule) appending the suffix *-ed* as a rule. Thus, regular past-tense forms are not stored in the lexicon but produced on-line, whereas irregulars are retrieved solely from lexical memory. More specifically, WR claims that all verbs enter two different routes, and the route that finishes first 'wins out'. The rule mechanism begins to add the *-ed* suffix to the stem while the memory system performs a lookup for any stored forms in the lexicon. In the model the lookup is quicker than the rule application, and if a stored irregular form is found, it inhibits the rule mechanism and outputs the irregular; if the lookup fails because no form is found, the rule system will continue unabated and produce the regular form. This satisfies the pre-theoretic intuition (see English lessons in grade school) that there is a general rule for forming past-tense verbs and a list of exceptions that just have to be memorized.

Indeed, the role of the *rule* in dual-mechanism models is critical. Thus it deserves clarification as to what exactly is meant by a 'rule'. Firstly, WR claims that the rule is *not* merely descriptive, but is actually a mechanism *employed by the brain* in language processing. An example of a descriptive-only 'rule' would be something like "the sun rises every morning". Though the rule may always be true descriptively, nothing about the rule is involved in the actual process of making the sun rise (or seem to rise from our vantage point). By contrast, the rule *itself* is proposed to be involved in the actual inflection of regulars in WR. This actually posits something about the *brain*, not something about the *language*. In other words, the debate comes down to whether the brain has explicit rules or merely analogical systems which produce rule-like behavior.

In later versions of WR, modifications have been made to accommodate certain empirical findings. For instance, WR now allows that regular verbs can be stored in the memory as well as produced by rule. This overcomes the problem of verbs that can be inflected either regularly or irregularly (such as *dived/dove*), because anytime an irregular is found in the memory system, it inhibits the rule process (as per WR), and thus forms like *dived* wouldn't be likely, given the presence of *dove*. Clearly the evolution and devolution of irregular verbs throughout the history of English shows that multiple forms can be present simultaneously in the language. Unfortunately, there is no specific account of which regulars would or would not be stored in the lexicon in WR, but it seems that the vast majority of regulars are *not* stored in the lexicon. Additionally, while the earliest WR theories proposed that the lexicon is served by a standard lookup procedure, it has been accepted that within the memory mechanism there may be an associative system, not unlike a Connectionist network, but that "lexical entries have structured semantic, morphological, phonological and syntactic representations of a kind not currently implemented in pattern associators [Connectionist networks]" (Pinker & Ullman 2002).

Pinker, Prince, and others have positioned the dual-mechanism as a sort of hybrid compromise between generative phonology's combinatorial capacity and Connectionism's associative memory, though they clearly envision something more complex than just a rule system strapped onto a pattern associator. To some extent, WR can be seen as a "best of both worlds" type of scenario, maintaining that the past tense system arises as an epiphenomenon of two distinct linguistic faculties (lexicon and grammar), which rely on each other to produce systematic language in the first place (Pinker & Ullman 2002). Furthermore, lexicon and grammar are parallel to the well-known dichotomies in other domains such as the distinction between declarative and procedural memory (Cohen & Squire 1980; Ullman 2001).[3]

One criticism of this model is its "inability to generalize to multiple paradigms cleanly. A word may be irregular (and thus a memorized exception) with respect to one syntactic form but others—'go' takes an irregular past tense, but its plural is the regular 'goes' instead of *'wents' ... These variations cannot be explained without resorting to further rules and a detailed (and complex) theory of the timing of rule application" (Plunkett & Juola 1999). Thus, while WR seems a clean, straightforward theory when applied to only one morphology, trying to expand it to other morphologies at the same time makes obvious its complications with handling different complex inflectional systems.

2.3 The single-mechanism theory: Connectionist networks

The most popular instantiation of a single-mechanism theory for past-tense inflection is the Connectionist network, although other kinds of single-mechanism models exist (Eddington 2000; Albright & Hayes 2003). Rumelhart and McClelland (1986) challenged Classical views by illustrating how a Connectionist network could learn both regular and irregular forms of past tense in English within the same 'mechanism'. Many newer Connectionist models have improved upon the original model by extending it to the acquisition of past tense (Plunkett & Marchman 1993) as well as patient data (Joanisse & Seidenberg 1999).

The primary difference between Connectionist approaches and WR (besides the number of mechanisms) is that the former eschew explicit symbolic rules for associative, analogical

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[3] Similar distinctions are seen in the dichotomies of explicit and implicit memory and knowing *that* vs. knowing *how*.

pattern matching. Connectionist models of the past tense tend to use distributed representation, which means that individual words are not assigned uniquely to certain nodes but rather share activation space with related words. Thus, phonologically or semantically similar words are expected to overlap to some degree in their representation. Usually models of the past tense will create an overall bias for regular inflection because it is statistically speaking the most common inflection and is applied in the same way regardless of the sound of the stem. Repeated activation of specific words increases the strength of their representation in the network. This explains frequency effects for irregulars, as they must be high in frequency to overcome the network's general bias toward regularization.

The critiques of Connectionist accounts of past-tense verb formation center around the models' lack of *rules* and what behaviors are seen as unfortunate consequences of this fact (i.e., the models lack traditional properties like compositionality and systematicity—see below). While it's true that at the micro level, Connectionist models are built on rules (algorithms), the point is that there is no explicit rule in the network akin to "add *-ed* to verb stem *v*". This is exactly what McClelland and Rumelhart (1986) intended to show was unnecessary. Critics of Connectionism counter that it is essential to have the algebraic compositional power to cleanly inflect many regular verbs, because regular inflection is said to be insensitive to phonology, semantics, or any statistical measures, and words are proposed to have symbolic representational structures that cannot be implemented outside of Classical models (Fodor & Pylyshyn 1988; Ling 1994).

Pinker (1999) claims that "A pattern associator's ineptitude with novel combinations appears to be deeply rooted in its design" and "When it comes to generalizing regular inflection to novel verbs, pattern associators are simply the wrong tool for the job. The problem is that a single mechanism is being asked to do several jobs with contradictory demands." But it certainly does not follow that Connectionist models are limited because they have only *one* mechanism. Even Marcus (2001) admits that "The sheer number [of mechanisms] tells us little." So it's not at all clear that the cardinality of mechanisms matters much, so long as the mechanism(s) can handle "several jobs with contradictory demands."

Marcus (2001) outlines three criteria for a Connectionist model to succeed: it must be able to freely add -*ed* to novel words, it must add -*ed* to novel words that are unusual or formed from nouns regardless of their *frequency*, and it must always add -*ed* to a verb's stem rather than the inflected form (i.e., no blends). In principle, most researchers would agree with the first criterion because it should be possible to inflect any word with an -*ed*, as we would expect it to be theoretically possible for speakers to overregularize any irregular. The second criterion is clearly built on the assumptions that frequency effects do not obtain for regulars and that denominal and unusual novel verbs are always regular (the former assumption is challenged below; the latter is far from empirically certain). As far as the third criterion, it is clear that children do produce blends (e.g., *ated*), although rarely (Marcus 2001); presumably any successful model must be able to produce blends, but not do so often.

Marcus (2001) claims that the most successful Connectionist models have been the ones to implement an explicit rule-based system (and thus aren't fully Connectionist). Short of that, he says, "no one has yet proposed a comprehensive single-mechanism model" (Marcus 2001). He argues that the models that are reported to successfully avoid rules actually sneak in a rule system, like Hare, Elman, and Daugherty's (1995) hybrid model which uses a "Clean-up

Network". Thus he concludes that Connectionist models cannot produce accurate verbal behavior without a rule apparatus to apply in certain cases.

2.4 Architectural differences between models

The more obvious differences between Connectionist and Classical (e.g., WR) accounts of any mental process are a direct consequence of their divergent architectural structures. Classical models are based on Turing or Von Neumann machines, whereby symbols cause the system to undergo certain syntactic manipulations of representational variables. Connectionist models are more analog in nature; rather than discrete symbols, content in a neural net is represented *approximately* by the multidimensional vector specified by patterns of node activation. It should be apparent that the Classical view builds into its architecture an inherent sense of precision, systematicity, and rule-following. Connectionist models, if they are to display such traits, must be examined at a more abstract level.

The harshest opponents of Connectionism (Fodor & Pylyshyn 1988; Pinker & Prince 1988; Fodor & McLaughlin 1990) claim that the models fail to capture the requisite combinatorial compositionality, systematicity, and symbolic representation to explain the infinite capacities and productivity of the human mind, in particular language. These critiques carry with them the momentum of the Chomskian cognitive revolution and have caused a backlash against what is seen as an associationist rehashing of behaviorist desires to circumvent cognitive complexity.

A primary attack employed by Fodor and Pylyshyn (1988) to discredit Connectionism centers around the notion of *compositionality*. They take it to be a hallmark of the human mind that complex expressions are syntactically structured like a molecule of atomic concepts, so that productive inferences can be made quickly and efficiently. This is easily accomplished by Classical computational theory because such computation is nothing if not explicit manipulation of symbols—and, as in Formal Logic, symbolic representations are readily compounded into more complex structures by use of conjunctive operators like AND.

Yet other notions of compositionality exist. Van Gelder (1990) defines compositionality as *any* general, effective, and reliable process for producing an expression given its constituents and decomposing the expression back into the constituents. He agrees that any sophisticated system must be able to represent complex structured items, but he argues that Fodor and Pylyshyn make the further assumption that a compositional structure must *literally contain* the physical token of each of the expression's constituents, the way that the atomic symbol 'Mary' is *literally* a part of the complex molecular symbol 'John loves Mary', which is how composition has traditionally been viewed in Classical computation. This type of compositionality, which van Gelder terms "concatenative", usually is realized by spatial or temporal juxtaposition, but it must exhibit, at a minimum, "linking or ordering successive constituents *without altering them* in any way as it forms the compound expression" (van Gelder 1990, emphasis mine). By contrast, in *functional* compositionality, all that matters is that there be *systematic methods* for "generating tokens of compound expressions, given their constituents, and for decomposing them back into those constituents again." Representations in Connectionist networks are vectors in a high-dimensional space realized by activation levels over a set of units, and van Gelder states that such vectors "stand in similarity relations by virtue of their internal configuration, relations that can be measured using standard vector comparison methods." He adds that these spatial similarities may underlie the systematic generation and decomposition of representations. Van Gelder (1990) concludes that Connectionist networks must enable "processes that are causally sensitive to, and hence constrained by, *the systematic structural similarities among the representations themselves*, so that the overall system exhibits the right kinds of systematic behaviors" (emphasis mine).

But this is unlikely to persuade Fodor and Pylyshyn of anything. They are committed to the notion that there is *literal* syntactic representation of compositionality, to the extreme that "the symbol structures in a Classical model are assumed to correspond to *real physical structures* in the brain and the combinatorial structure of a representation is supposed to have a counterpart in structural relations among physical properties of the brain" (1988, emphasis mine). This is an incredibly bold statement—one that seems very much empirical in nature, despite their theoretical attempts to back it up.

Another property that Fodor and Pylyshyn (1988) claim is lacking in Connectionist models but present in Classical models is *systematicity*, which depends in part on compositionality. Connectionist networks are said to exhibit problems with systematicity in their tendency to generalize systematically only about items within their training data. When tested on novel items (e.g., nonce verbs), many Connectionist networks cannot display the type of generalized systematic processing we know humans are capable of. For example, in Marcus' discussion (2001) of Hinton's family-tree learning model, he points out that the model doesn't learn the syntax of a generalization like *sibling-of*, but merely the generalization about variables it has been trained on. Though humans know that *sibling-of* is a symmetrical relation (if Amy is the sibling of Bob, then Bob is also the sibling of Amy) the network can only know that relation if it has been trained specifically on Amy and Bob, not just any sibling pairs. While Marcus claims that this deficiency is inherent in the structure of Connectionist networks, it is not clear that this must be the case.

This is a problem of *inductive learning* (a notoriously difficult philosophical and computational problem given the fact that there are an infinite amount of functions to fit any data points). Though it is obvious that Connectionist networks are capable of inductive learning, it is not clear that the inductions they make are consistent with the inductions humans are capable of making. As Marcus (2001) points out, "in each domain in which there is generalization, it is an empirical question whether the generalization is restricted to items that closely resemble training items or whether the generalization can be freely extended to all novel items within some class." He believes that Connectionist networks cannot in principle handle free generalization, though humans seem to be able to.

Matthews (1994) argues that Connectionists who seek to meet Fodor's and others' demands are unlikely to meet their "challenges to provide an explanation of systematicity, not because systematicity does not admit of a connectionist explanation, but rather because [Fodor, Pylyshyn, and McLaughlin] are prepared to admit as explanatory, accounts that only classical models can provide. If they are to win, connectionists are going to have to insist on their right to change what counts as an explanation of systematicity" (1994). In other words, Fodor and Pylyshyn expect a successful Connectionist network to do exactly what the Classical model already does—employ rules.

2.5 Where the debate stands

Many researchers on both sides of the argument have noted that both the single- and dual-mechanism models "explain the qualitative and quantitative properties of the acquisition of the past tense by the human child" (Marslen-Wilson & Tyler 1998) and "most of the behavioral data can be accommodated by both theories" (Joanisse & Seidenberg 1999). Others argue that neither model works (Eddington 2000). It is clear that the debate is far from settled.

In a sense, single- and dual-mechanism proponents cannot see eye to eye because they are coming from opposite sides but can't meet in the middle. Because dual-mechanism models presuppose the existence of a rule-following and a memory system, their proponents tend to focus on the end-state—the 'adult' stage of inflection. In a way, this is a top-down model: start with the presupposition of the end-product and work out the details based on its perceived mechanisms and properties. By contrast, Connectionist models are driven by data to produce a dynamic pattern associator, while presupposing a minimalist architecture (relative to Classical machinery).[4] In this sense, it's a bottom-up model.

Marcus (2001) notes that the question posed originally by McClelland and Rumelhart has been "twice corrupted":

> The original question was "Does the mind have rules in anything more than a descriptive sense?" From there, the question shifted to the less insightful "Are there two processes or one?" and finally to the very uninformative "Can we build a connectionist model of the past tense?" The "two processes or one?" question is less insightful because the *nature* of processes—not the sheer number of processes—is important...The sheer number tells us little, and it distracts attention from Rumelhart and McClelland's original question of whether (algebraic) rules are implicated in cognition...The "Can we build a

[4] "The strict modular separation of form and semantics espoused by the dual-route tradition is *not a starting point* for most connectionist researchers. For them, the question of whether form and meaning interact is an *empirical* question that requires detailed examination on a case by case basis." (Baayen & Moscoso del Prado Martín 2005, emphasis mine)

> connectionist model of the past tense?" question is even worse, for it entirely ignores the underlying question about the status of mental rules...many connectionist models implement rules, sometimes inadvertently. (pp. 81-83)

It is definitely true that the original question of "Do we have rules?" is the deepest and most meaningful. And it is also may be the case that some Connectionist models have implemented rules inadvertently. However, it does not follow that a successful Connectionist model would tell us nothing (and I believe Marcus would agree here) about past-tense formation. It is (theoretically) possible that Connectionist models can be created that produce the same rule-like effects of Classical models without the explicit manipulation of symbols via algebraic rules. While Connectionist models don't perfectly match behavioral data, there is an elegance in the way that they capture statistical regularities that is much more difficult for Classical models. The ugly fact of the matter is that each account has its strengths. In order to determine which model is ultimately stronger, we must look at the problem in new ways (such as examining in more detail the effects of semiregularity; see sections 4 and 5).

3. Verbal, behavioral, and neuropsychological data

Various kinds of data and techniques are employed to test the models. Over the course of two decades, experiments for past-tense inflection have run the gamut from observation of children's acquisition, inflection tasks for words and non-words, priming experiments, functional neuroimaging, neuropsychological studies of aphasic patients, and applications to other languages. In this section, the results of these various types of methods are summarized and compared.

3.1 Observations from acquisition

One interesting phenomenon found in the acquisition of the English past tense and other quasiregular domains is the characteristic U-shaped learning profile (Berko 1958; Brown 1973; Marcus et al. 1992). First children learn the irregulars, then as they begin to pick up on the pattern found in regular forms, they *unlearn* (or otherwise inhibit) the memorized irregulars and start to *over*regularize them (e.g., *eated* instead of *ate*). Finally, they *relearn* (or otherwise reengage) the irregular forms while maintaining the ability to form regular conjugations as well. This unintuitive process is a hallmark of quasiregularity and an important benchmark for any model to explain.

One of the most compelling aspects of Connectionist models of past tense is that the networks display the same learning profile (as inferred from patterns in how errors change over time in number and kind) as children do in experimental studies. There is an attractive pull to the fact that even a (relatively) simple model can replicate seemingly complex and unexpected learning patterns consistent with evidence from children.

A notable weakness of WR is in explaining the U-shaped learning profile observed in quasiregular domains such as the past tense. Dual-mechanism theories have a much more hand-waving, less cohesive explanation of the progression of errors a child produces. The theory does not propose that the 'add -*ed*' rule is innate (clearly speakers of other languages don't have this rule), and therefore it must be learned at some point. The assumption is that the rule is reached by an epiphany of sorts, and is thought to be marked by the first overregularizations. This realization comes after the child has memorized the high-frequency irregulars, but then the new rule becomes over-applied to irregular stems (e.g., *eated*), before the two systems are finally mediated by some equilibrium between the two mechanisms. Proponents of symbolic rules claim that a child's first overregularization is evidence that the rule has been deduced. Accordingly, they predict a sudden onset of regularization starting around the time of the first overregularization, and show data which support this (Marcus et al. 1992). Not surprisingly, Connectionists have cast doubt on those same data by claiming that regularization is not sudden, but gradual (McClelland & Patterson 2002b). It is clear that for WR to succeed, it must show that it naturally produces a U-shaped learning curve like Connectionist networks do. Unfortunately, no actual computational models of WR exist to carry out direct comparisons with the performance of Connectionist networks.

Overregularization errors are commonly used to infer the progress that a child has made in learning the past tense. Dual-mechanism theorists like Marcus, Pinker, and others have claimed that predominantly low overregularization errors are indicative of occasional misapplication of a rule in a dual-mechanism system that normally functions effectively in acquisition (Marcus et al. 1992; Marcus 1995; Pinker 1999). Marcus et al. (1992) claimed that data from the CHILDES database (MacWhinney 2000) support these low error rates. Additionally, Marcus (1995) extends this account to English noun plurals, arguing that there was no substantive difference between overregularization rates for irregular verbs and irregular nouns, despite the fact that nouns have far fewer irregular forms (and thus one would expect different overregularization rates). This is important because if inflection is analogy-based, then because English nouns are more routinely regular in plural form than verbs are in past-tense form, then one would expect more overregularizations for nouns than verbs (due to the increased bias for regular inflection). In response, Marchman, Plunkett, and Goodman (1995) show evidence that irregular nouns did see significantly higher overregularization rates in children than irregular verbs (what a Connectionist model would predict) as overregularization errors become significantly more frequent. Additionally, a detailed corpus presented by Maslen et al. (2004) reaffirms these trends.

Meta-analyses of children's speech have led to research on other error types as well. For instance, dual-mechanism proponents claim that because Connectionist networks lack explicit algebraic rules, they end up producing far more errors (relative to a child learning English), like blends—when an already inflected verb gets an *-ed* stuck on the end (e.g., *ated*, *broked*, or even *jumpeded*). Because the WR account has two separate pathways and claims that regular and irregular verbs are treated in *qualitatively* different ways (Marcus 2001), blends would be exceedingly rare, if not impossible. But Connectionist models of the past tense do not have access to the phonotactics of English, which may well account for the general lack of blends in speakers.

Interestingly, Stemberger (1993) found that overregularizations were more common in certain phonetic environments. Specifically, children are more likely to overregularize a vowel-change irregular when the base form vowel is dominant than when the past-tense form vowel is dominant. This may explain why verbs like *blow*, *throw*, and *know* are often overregularized (base vowel /oʊ/ is dominant over past vowel /u/), but verbs like *see* are not (past vowel /ɔ/ is dominant over base vowel /i/). This suggests that phonological information can affect performance on irregulars.

In an interesting study, Shirai and Andersen (1995) present evidence that the *aspect* of a verb may influence early learning in children. Specifically, an analysis of parental dialogue with children suggests that the past tense is used most heavily with children in cases where the aspect is telic, punctual, and resultant-state. Congruently, children first use past-tense forms in contexts that match those aspectual elements, predominantly with achievement and accomplishment verbs. They later expand usage to verbs whose aspect differs semantically from the prototype of 'pastness'. This gradual expansion of the boundary for past-tense inflection eventually leads to the mature adult state of being able to inflect any verb. This evidence strongly favors the prototype structure of analogy-based models.

3.2 Past-tense inflection tasks

Probably the most popular method for testing past-tense inflection is the stem-inflection task (SIT). In a typical SIT, participants are set up in front of a computer screen which displays a verb stem (e.g., *eat*) and they are instructed to say out loud the correct past-tense form of the verb (e.g., *ate*) as quickly and accurately as possible. While these tasks are unlike inflection in natural speech, they are assumed to tap the same resources. This allows for detailed measurements of reaction time (RT) and error rates.

Typically, results from a normal SIT show a frequency by regularity interaction (common in quasiregular domains) whereby irregular verb inflection is inhibited by low stimulus frequency, but the same trend is not found in regular verbs (Prasada, Pinker, & Snyder 1990; Marcus et al. 1992). WR enthusiasts take this dissociation between regulars and irregulars to be indicative of a categorical distinction between the two forms and the two mechanisms used to handle them. However, it has been shown that frequency by regularity effects can also be displayed naturally in Connectionist networks (Daugherty & Seidenberg 1992), not as a product of separate mechanisms, but by the fact that the network tends to have an overall bias toward regular *-ed* inflection, which can only be overcome by high-frequency verbs (higher frequencies mean more activation in the network). Thus, irregulars have to be high-frequency to override regularization tendencies, while regulars can be any frequency and still be inflected correctly.

One of the bigger difficulties for Connectionist models is extrapolating to unusual-sounding novel words (i.e., words not in the training set that don't resemble English phonology; see section 2.4). Researchers often perform '*wug* tests' on native speakers to find out how nonce verbs (i.e., non-word verbs that are made up purely for experimentation) are inflected (Berko 1958; Prasada & Pinker 1993). One interesting finding is that people consistently inflect the nonce verb *plip* into *plipped,* yet usually inflect *spling* into *splung* (Prasada & Pinker 1993; Xu & Pinker 1995); Connectionist networks readily make these generalizations, because they are trained on pairs like *flip-flipped* and *spring-sprung*. In fact, the tendency to naturally make the *spling-splung* inflection is a strength over the dual-mechanism model (which has to use pseudo-Connectionist associative properties in the lexicon to explain irregular inflection for nonce verbs since no possible irregular form could be stored). However, when faced with a word like *ploamph*, which does not phonologically resemble anything the model is trained on, Pinker and colleagues claim Connectionist models have trouble applying the "default" *-ed* rule (which is what English speakers regularly perform to unusual sounding verbs), whereas the rule mechanism in the WR model easily accomplishes this task because any verb stem can be substituted for the variable *v* in an operation such as *v* +'*ed*' (Prasada & Pinker 1993; Xu & Pinker 1995; Pinker 1999). Prasada and Pinker (1993) say that because of this distinction, "similarity-driven and rule-based models would appear to differ in their predictions about humans' ability to inflect verbs with very novel sound patterns." However, McClelland and Patterson disagree with these conclusions (2002b). Ultimately, this tradeoff between the Connectionist network's ease with generalizing from neighbors and the dual-mechanism model's ability to systematically apply a rule is what makes the debate such a back-and-forth tug-of-war.

3.3 Priming experiments

As in other domains, it has been argued that "Both dual- and single-mechanism approaches can account for differences in regular and irregular priming results" (Kieler, Joanisse, & Hare 2008). Because phonological priming and semantic priming have measurably different effects, priming experiments have become an important way to examine the interaction (if there is any) between semantic and phonological information in past-tense formation. In later Connectionist models, researchers have looked at the relationship between semantic and phonological contributions (Joanisse & Seidenberg 1999). It is proposed that regulars may rely more heavily on phonological analogies whereas irregulars may utilize more semantic information.

In an interesting study, Stemberger (2004) found phonological priming for overregularization errors for vowel-change irregulars in sentences where the vowel from the stem or inflected form is used in the subject noun. For example, subjects were more likely to overregularize *freeze* as *freezed* in the past tense inflection of the sentence "The cream *freeze*" or "The chrome *freeze*" (cf. *froze*) vs. the neutral vowel "The slot *freeze*". He posits that for stem-form conditions, the prior vowel serves as a facilitatory prime, and in the past-form conditions, the vowel is inhibitory. He then argues that irregular forms are not produced in a specialized subnetwork but are produced "in the general lexical system simultaneous with general phonological processing."

Kieler, Joanisse, and Hare (2008) found that priming for regulars and suffixed irregulars (e.g., *keep-kept*, which ends in the same alveolar stop used as a regular ending) was similarly strong, but that weaker effects were found for vowel change irregulars (e.g., *take-took*). This is "clearly incompatible with any account [e.g., WR] that draws a categorical distinction between regulars and irregulars." In other words, dual-mechanism accounts posit that all irregulars should pattern differently than regulars, because they are processed by different systems. Results that suggest gradations of regularity among irregulars contradict this prediction.

Interestingly the same study found that in an experiment with a 500ms delay between stimuli (used because studies have shown orthographic/phonological formal overlap effects decrease during longer processing times, while semantic effects increase), "there is no priming when the overlap is purely formal ... or purely semantic. Instead priming is found for all and only those conditions in which *a semantic relationship correlates with a formal one*" (Kieler et al. 2008, emphasis mine). They conclude that morphological priming is produced by the interaction of semantic factors with orthographic/phonological factors, "and is thus best seen as emergent from the systematicity of the mapping among different types of linguistic information" and "priming occurs because the prime and target are related both with respect to form (orthography, phonology) *and* meaning (semantics)." Similarly, Braber et al. (2005) conclude that "Much of what is needed for past tense generation can be captured by the interaction between semantics and phonology." At this point it is too early to say for sure, but it seems clear that priming experiments may contribute important data to the debate which may help settle the respective roles of phonological and semantic information.

3.4 Semantic contributions to inflection

While the earliest models of Connectionist past-tense inflection were solely based on phonological input-output profiles (Rumelhart & McClelland 1986), the last decade has seen a newfound interest in harnessing semantic information in addition to phonology to model inflection. For obvious reasons, the real mechanism(s) involved in the inflection have to be more than just phonological (there are clear cases of homophonous verbs that undergo different changes, e.g., *bear-bore* and *bare-bared*; see below). Because there should be highly consistent overlap between semantic representations for a stem and its inflected form (the assumption is that a past-tense form for a verb shares its semantic content in addition to some marking that the action happened in the past), Connectionists in particular are happy to accommodate semantic data as well. By involving semantics, the network can be strongly activated to add -*ed* to any stem but irregular verbs can overcome that initial tendency by stronger semantic overlap activation. In essence, phonology and semantics working together can allow the Connectionist network to overcome the homophone problem. As such, nonce words will be inflected irregularly only when there is strong phonological and/or semantic overlap with similar irregular forms.

One common critique of Connectionist models is that they cannot explain how homophones can get inflected differently (e.g., *break-broke* vs. *brake-braked*, *let-let* vs. *let-letted*). This is because the original models were built only on phonological input-output (specifically, Wickelfeatures; Rumelhart & McClelland 1986). However, if semantic information is put into the model along with phonological, there's no reason why the networks couldn't correctly handle these separate cases, as homophone pairs are always at least somewhat semantically different. In fact, for any kind of model to differentiate homophones it is requisite that more than phonological information inform the process, or else all homophones would be inflected the same way. So it is certainly important to consider whether semantic information is involved in inflecting verbs.

Pinker and Ullman, however, are skeptical that including semantic information will help improve a Connectionist network's performance: "One [connectionist explanation for systematic regularization] is that if a pattern associator had semantic as well as phonological input units, a complex word with an altered meaning would dilute the associations to irregular forms, favoring the competing regular...[but] experiments have shown that just changing the meaning of an irregular verb does not cause people to switch to the regular" (2002).

A series of clever experiments by Ramscar (2002) illustrate that speakers' intuitions for inflecting nonce verbs are not as straightforward as Pinker (1999) suggests. In particular, the surrounding semantic context in which the nonce word is introduced can have strong effects on how the word is inflected. Ramscar (2002) used nonce verbs *frink* and *sprink* in the clause "the patients all *frink* in" and embedded into one of three contexts meant to prime the semantics of *drink* (consumption of vodka), the semantics of *wink/blink* (eyelid movement), or the neutral case, the semantics of *meditate*. He found that when subjects were asked to produce the past-tense form of the nonce verb, *sprank* and *frank* were three times as likely to be produced in the *drink* context than the regular forms, whereas *sprinked* and *frinked* were almost three times as likely in the *wink/blink* context than the irregular forms. The neutral *meditate* context was close to three times as likely to be inflected as *sprinked* or *frinked*. This is an interesting finding because in a separate experiment Ramscar (2002) found that in a purely non-contextual prompt, people opted for the irregular *sprank* and *frank* 85% and 60% of the time, respectively (this is likely because the irregular *drink* occurs far more frequently in English than the regulars *wink* and *blink*). In other words, something about the semantic context in the 'neutral' *meditate* context caused the nonces to be regularized.

The most natural explanation, given that the results for the *wink/blink* context and the *meditate* context were statistically equivalent, is that using the nonce sententially in a specific context that is not semantically related to a high-frequency irregular is enough to overcome the natural phonological tendency to match the dominant sound pattern of *drink-drank*. It is only when the nonce is presented without specific context or in a context semantically consistent with the irregular that the phonological analogy proceeds unheeded. This strongly suggests that semantic information can be crucial in morphophonological inflection. And when Connectionist models of past tense are trained on phonological and semantic input, they learn to differentiate between phonologically similar verbs based on meaning. In essence, two prominent criticisms of 'rule-less' models—the notion that they can't distinguish between homophones or extrapolate the regular ending to novel words—are cast in significant doubt by these results.

Pushing the issue even further, Ramscar (2002) tested a specific prediction made by Pinker (1999). Pinker claims that denominal verbs (verbs formed from nouns) systematically receive regular inflection; a prime example given of this is the term “flied out” in baseball (not “flew out”). Because the term “fly” (in noun form) came to be identified with a ball hit into the air, it is a supposedly headless noun (i.e., is not connected to the *fly-flew* pattern) and therefore the past-tense form became "flied". Ramscar (2002) tested a group of Americans and a group of Britons (who significantly lack cultural knowledge of baseball) on their intuitions about the past tense of "fly out". He introduced the term in a passage that made it clear to the subject that the verb was *derived from a noun*, and how it was used normally in the present tense. Yet he found that while two-thirds of Americans inflected the term as *flied out*, over 90% of the British subjects opted for *flew out*. This directly contradicts Pinker's predictions. Ramscar (2002) concludes from these experiments that "In fact, semantic factors appear to be more important in inflection than the grammatical considerations put forward by the dual-route account." A series of experiments by Gordon and Miozzo (2008) replicate Ramscar's results, but in a context that makes more explicit the denominal derivation of the verb; they found that acceptability ratings for regular forms were predicted only by derivational status. Still, it is clear that semantic information can play an important role in inflection (though it may not act alone).

Not only has semantic content been shown to affect speakers' judgments of whether a regular or irregular form should be used, but it has also been found that involving a contextual background (i.e, semantic content) for timed past-tense production experiments dramatically changes the regularity and frequency effects reported in the traditional apparatus of inflection from a visually-presented verb stem. Woollams, Joanisse, and Patterson (in press) have run comparative experiments testing the traditional 'Stem Inflection' experiment standardly used against an arguably more natural paradigm, 'Picture Inflection'. They found that while Stem Inflection showed regularity and frequency effects (as is typically reported), in the Picture Inflection task, there was no reliable effect of regularity or frequency on RTs or errors. They conclude that the results "thus add to mounting evidence that past-tense generation in the standard Stem Inflection task is not a good analogue of past-tense production." They then ran simulations on a Connectionist model (Joanisse and Seidenberg 1999), which illustrated that a single-mechanism model with both phonological and semantic representation could produce the same output as humans in the Picture Inflection task (Woollams, Joanisse, & Patterson, in press).

3.5 Neuropsychological data

Proponents of WR and the related Declarative/Procedural model (DP; Ullman 2001) identify double-dissociations between the 'lexicon' system and the 'grammar' system in neurological patients, suggesting that the neural structures for the lexicon and the grammar are localized in different areas of the brain (Ullman et al. 1997). They find evidence from patients with various neurological disorders and aphasias to support this separation; they also look to functional imaging of the brain to show that activation during the processing of lexical information (irregulars) and grammatical information (regulars) are spatially distinct.

In examining patients with damage to temporal or parietal neocortex, Ullman et al. (1997) found that subjects performed worse on inflecting irregular verbs than regular or novel verbs, and often overregularized. These patients included those with impairments of general declarative memory (Alzheimer's) and specifically lexical memory (posterior aphasia). Conversely, patients with damage to the frontal/basal-ganglia system could form irregulars better than regulars. These patients included those with impairments of general procedural memory (Parkinson's and Huntington's) and specifically grammatical knowledge (anterior aphasia). They conclude that "These results support psycholinguistic theories that emphasize grammar and lexicon as *distinct components* over those that minimize or eliminate either, especially in the treatment of regular and irregular grammatical phenomena" (emphasis mine).

Marslen-Wilson and Tyler (1998) put forth further evidence that regulars and irregulars are localized separately in the brain: "The relationship between the patient data and their neuropathology provides evidence for the role of posterior frontal brain regions in the processing of the regular past tense and of the left ventral temporal lobe in the processing of the irregular past tense." But the mere fact that different neural structures are involved in different aspects of past-tense formation is not enough to prove that they are *separate mechanisms*. As they admit, "the fact of dissociation itself is insufficiently constraining to discriminate among these approaches – there are, for example, developmental connectionist accounts which allow for the possibility that different cortical areas can recruit themselves different aspects of the same processing domain, depending on the kinds of computational resources they require" (Marslen-Wilson & Tyler 1998).

Lambon Ralph et al. (2005) criticize aphasic studies such as Ullman et al., saying they are marred by a confounding variable:

> ...regular past-tense forms, especially in words like 'typed' or 'streaked' which have a long vowel or diphthong followed by a stop consonant followed by an alveolar stop, are unusually difficult both to hear and to say. By contrast, most irregular past tense forms are phonologically simple. For a patient with phonological and articulatory deficits, the speech features of regular past-tense words might be expected to incur performance deficits independent of any morphological factors. (p. 107)

They thus claim that the apparent dissociation in patients between regular and irregular forms can be explained by deficits in phonology and articulation, and by properly matching items for phonological complexity, these effects are eliminated. Their data from a cohort of anterior aphasic patients suggest that "those [patients] with the largest and most consistent advantage for producing the past tense forms of irregular > regular English verbs were also the patients whose word production was most adversely affected by phonological complexity ... and by phonological atypicality" (2005). Other analyses of nonfluent aphasic patients suggest that the apparent disadvantage for regular forms disappears when stimuli are controlled for phonological complexity (Bird et al. 2003).

Similarly, Braber et al. (2005) argue that the apparent double-dissociation in Broca's aphasia patients can be explained by a single-mechanism model which "predicts that poor performance with irregular verbs, especially for lower frequency items, should be associated with semantic impairment, while the relative deficit for regular verbs reported in anterior aphasic patients should be associated with phonological impairment." Joanisse and Seidenberg (1999) conclude that the observed deficits in various aphasic patients are due to "impairments to two types of lexical information, semantic and phonological, rather then [sic] memory systems organized around rules and exceptions."

Even supposing that there are double-dissociations, such results can certainly be taken to support WR, though that is not the only possible conclusion. Joanisse and Seidenberg (2005) found:

> ...one cortical region in R-IFG [right inferior frontal gyrus] showed more activation for word and nonword regulars than for the combined irregulars. This result could be construed as supporting the dual-mechanism theory, which holds that some regions of IFG are specifically involved in processing morphological rules but not in processing exceptions to these rules. However, pseudoregulars [semiregulars] patterned with word and nonword regulars in inferior frontal regions, with all three conditions producing similar levels of activation, all of which differed from the true irregulars. (p. 292)

In other words, averaging across irregulars obfuscates the differences within the group. It is explanatory to treat irregulars as a graded set, not a uniform, qualitatively different type.

3.6 Inflections in other morphologies and other languages

While the overwhelming majority of literature on rule-based vs. Connectionist models has focused on the English past tense, there are plenty of areas in English and other languages that these theories should be tested on if they are to claim any sense of universality. One of the most popular arenas for debate outside of the English past tense has become the German plural system, because its supposed 'default rule' is actually less common than other pluralization forms (Clahsen 1999). This inflection paradigm, along with others such as the Arabic Broken Plural, are considered Minority Default processes, because the putative 'default' inflection is in the minority.[5]

There are two main questions which arise from Minority Default systems: (1) Is it empirically true in the languages that the minority inflection is truly the *default*? and (2) Is it theoretically plausible for Connectionist models to handle Minority Default inflections? As for Question 1, while it was initially claimed that systems such as the German Plural and the Arabic Broken Plural constitute true Minority Default, recent work has suggested that these putative 'defaults' are actually subserved by associative, analogical, and prototype processes (Plunkett & Nakisa 1997; Ravid & Farah 1999; Hahn & Nakisa 2000; Bandelow 2003; McClelland & Patterson 2002b; see also below). In regards to Question 2, many Connectionist theorists have

[5] Interestingly, dual-mechanism theorists often tout that their theory is better in part because it avoids having to store the vast majority of past-tense forms (because they can be produced on-line, thus saving memory resources). This may be an advantage for the English past tense, but it does not remain so for Minority Default processes. Yet the case of German plurals (and other Minority Defaults) is commonly used as an attack on Connectionist models, because they have problems dealing with a 'minority rule'. Thus, there is a tradeoff between saving memory resources and the supposed ability to handle Minority Default cases with better reliability. Dual-mechanism theorists can't have it both ways.

shown that their models can handle Minority Default cases if there is at least some phonological or semantic clustering of the 'default' forms (Hare et al. 1995; Plunkett & Nakisa 1997).

One common claim by Pinker (1999) is that though the -*s* ending is rare in the German plural, it is readily applied to surnames and foreign loan words in pluralization. For instance, he claims that a German who has read two books by Thomas Mann will say he's read two 'Thomas Manns' rather than two 'Thomas Männer', which is the normal plural inflection of 'Mann'. As such, surnames supposedly override general trends to apply a 'rule'. Yet there are multiple reasons why this may be the case (including phonological simplicity—the -*s* suffix is easily added relative to vowel changes or suffixations that alter syllabic structure). Connectionist replies have centered around the notion that calling -*s* the 'default' is just a flat oversimplification of German plural dynamics. McClelland and Patterson (2002b) report that "Surnamehood is an arbitrary property that must be associated with a specific use of an item in context, and assigning +*s* to foreign borrowings ending in full vowels requires sensitivity to phonology and etymology. Such specificity undercuts the notion that the German +*s* plural is in any sense a default. It is not the exception that proves the rule; instead it is another case with the graded, probabilistic, and context-sensitive characteristics seen in connectionist networks." A further complication of Pinker's claim is that many foreign loan words are English, and thus would already have a +*s* plural inflection.

Keuleers et al. (2007) challenge Marcus et al. (1995) by suggesting that Dutch plural formation is also analogy-based, not rule-based. Specifically, they show that non-phonological information (e.g., orthography) significantly improves models' correct plural inflections of Dutch nouns over a model that is purely phonological. Similarly, a study by Ernestus and Baayen

(2004) suggests that in Dutch, "analogical similarity indeed affects past tense production across the board, even when participants produce standard forms, while having all relevant information to apply the rule at their disposal."

Baayen and Moscoso del Prado Martín (2005) examine three Germanic languages (English, German, and Dutch) in various quasiregular inflections. They conclude that "there is a conspiracy of subtle probabilistic (graded) semantic distributional properties that lead to irregulars having somewhat different semantic properties compared to regulars ... irregulars tend to entertain more lexical relations and tend to be more similar to each other in semantic space than is the case for regulars." These tendencies, while not sufficient to guarantee irregularity, are exactly the kind of probabilistic qualities Connectionist networks are good at, and are furthermore inexplicable on a dual-mechanism account.

4. Semiregularity among irregular verbs

Within the 180-odd irregular forms in the English past tense are many families with internal consistency in their inflection. McClelland and Patterson (2002b) collapse the 181 irregular forms identified by Pinker and Prince (1988) into nine closely related groups, which consist of 177 of the 181, and every form ends in /t/ or /d/ (parallel to the regular *-ed* ending which is phonetically realized as /t/, /d/, or /əd/). There are various similarities that cut across the groups. The remaining four irregulars are the only suppletive forms, *be-was* and *go-went*, and the derivatives *forgo* and *undergo*. Because semiregularity runs throughout the vast majority of the irregulars, it is an important issue for single- and dual-mechanism theories to address, although it is certainly underrepresented in the literature. In light of evidence that phonological 'friends' (i.e., verbs in the same phonological neighborhood that make the same transformation) have an effect on error rates in other quasiregular linguistic domains (Stemberger 2004), it is important to examine these effects within the English past tense.

4.1 What is semiregularity? Why is there semiregularity?

It is clear that irregular verbs are not just an arbitrary list of exceptions. While irregulars are not obviously predictable (e.g., *drink-drank* but *think-thought*), they do display a surprising amount of regularity or consistency among themselves. In particular, irregulars that are phonologically similar tend to undergo similar irregular inflections. Though groups of semiregulars can be somewhat large and high-frequency (e.g., *keep-kept*; *sleep*, *sweep*, *weep*, and *creep*), there are always regular exceptions to the pattern (e.g., *seep-seeped*; *reap*, *heap*, *beep*, *peep*, *steep*) and occasionally ambiregulars (e.g., *leap-leapt/leaped*). Semiregulars tend to be high in frequency and clump together, but that is not always the case. Accordingly, neither model considers semiregularity to be rule-driven. However, single-mechanism theorists see semiregularity as evidence that the dichotomy between regulars and irregulars cannot be strict, while dual-mechanism theorists shrug off semiregulars as something to be dealt with only in the associative lexicon.

Lupyan and McClelland (2003) argue that the so-called 'irregular' changes are not all that arbitrary, but instead "result from a combination of factors, the first of which is a pressure to be relatively simple and consistent with the phonology of the language ... So, we have the phonologically regular and reduced *made* instead of the phonologically irregular *maked*, *kept* instead of *keeped*, etc. ... In our view, the pressure for compositionality can be *partially* overcome by frequent words like *make*, but not rarer words like *bake*." These points are interesting (and deserve follow-up) in explaining why semiregulars may be present in the language, but they do not suggest one model over the other.

4.2 Models' treatment of semiregulars

Unfortunately, most research, particularly that of dual-mechanism theorists, treats irregulars as a kitchen-sink, catch-all category wherein all irregulars are *equally unlike regulars*. In reality, there are shades of regularity throughout the irregulars themselves, and ignoring that complexity can hide the subtler differences among various irregular forms.

Single- and dual-mechanism models differ rather drastically in their predictions for semiregularity. As Marchman (1997) summarizes the matter:

> ...both single- and dual-mechanism models suppose that frequency impacts error rates and that phonological features and neighborhood factors influence the production of *irregularization* errors like zero-marking. However, *dual*-mechanism models predict that *regularization* errors should occur *independently of neighborhood similarity*, whereas, as single-mechanism view proposes that similar mechanisms underlie the production of *both* regularization and irregularization errors. Crucially, irregular verbs that are similar to suffixed verbs should be *more vulnerable to regularizations* than those that are not. This latter view further suggests that error patterns will be best captured in terms of the *convergence across sets of item-level predictors*, leading to a characterization of items along a *continuum* of being more or less 'at risk' for erroneous production. (p. 287, emphasis mine)

Thus, single-mechanism models propose that both regular and irregular inflections are driven by the same associative system which incorporates the effects of similar item-level factors. By contrast, dual-mechanism models predict that irregular verbs are subject to item-level factors insofar as they are contained in an associative memory lexicon, but regular verbs are not because they are formed simply by rule.

Dual-mechanism theories are notably weak in explaining semiregulars. Crucially, WR (although this is not necessarily true of all dual-mechanism theories) posits that there is only *one* rule in the English past tense, and it is the *-ed* suffix (which itself has three allomorphs: /t/, /d/, and /əd/). All irregulars, no matter how much internal regularity, are treated as equally irregular. Even though most WR enthusiasts will grant that there is semiregularity (or some sense of internal regularity) within irregulars, all irregular forms are purported to be equally unaffected by the presence of regular neighbors.

In response to Seidenberg and Bruck's (1990) finding that regulars take longer in inflection tasks if they share phonology with the semiregulars, Pinker (1999) gives an explanation that is clumsy at best:

> Word lookup is not instantaneous, and as it proceeds a few irregular verbs in memory might crudely match a regular probe. That could temporarily slow down the rule until the last jots and tittles of the word are properly matched and the false matches have petered out; only then will the rule be allowed to proceed unhindered. *This predicts that regular verbs that are similar to irregulars, inviting temporary false matches, should be slower to produce in the past tense* ... Incidentally, there is *no contradiction* between saying that regular past-tense forms don't depend on their memory entries and that they can be slowed down by temporary false matches with other verbs' memory entries. From your brain's point of view, no verb is either regular or irregular until it has been looked up in memory and discovered to have, or to lack, a special past-tense form. (p. 131, emphasis mine)

Because there is no specific proposal of how all this happens (and thus we can't really test the model), it is difficult to specifically attack Pinker's explanation, although it seems contrived and *ad-hoc*. Interestingly however, the inhibition between the rule mechanism and the memory system in WR is only a one-way street: irregular verbs are "*not attracted* to overregularization by similar-sounding regulars" (Marcus et al. 1992, emphasis mine). In sum, WR predicts that while the presence of semiregular neighbors can slow down the application of a rule for a similar-sounding regular (and thus irregulars can affect regulars), it is not the case that regular neighbors affect the retrieval of similar-sounding irregulars. This provides an easily testable prediction for semiregulars and regulars in the same phonological family on the WR account (see section 5.2 below).

Pinker also goes on to say that "Membership in an irregular family is also *probabilistic* when it comes to people generalizing a pattern to new verbs" (Pinker 1999, emphasis mine). This suggests that semiregularity can be salient even for inflecting nonce verbs (and explains the *spling-splung* inflection from Prasada & Pinker (1993)). These are welcome adjustments to better fit the empirical data, just like the admission that regular forms *can* be stored in the associative memory. But when considering these together, it is even more apparent that the exact relationship between mechanisms is woefully underspecified in the WR account:

> ...in the absence of a precise model this assumption [of which regulars are stored in the lexicon] weakens the DMT [dual-mechanism theory] considerably. If the DMT is conceptualized as an associative memory in which all irregulars and many regulars are stored, and a rule-mechanism that is responsible for inflecting all remaining regular verbs, then it becomes hard to see how this theory could be falsified. Whenever a regular verb is found to display properties that indicate its storage in the lexicon, this verb could be added to the ever growing number of stored regulars. This would reduce the DMT to a post-hoc, descriptive theory of verb inflection. (Westerman & Plunkett 2007, p. 303)

And if regulars can constitute exceptions to the semiregularity found in some irregulars (which supposedly qualifies them for being stored in the lexicon—Pinker & Ullman 2002), then is it really so cut-and-dry what constitutes the rule and what constitutes the exceptions? At the very least, the ambiguity apparent in Pinker's attempts to accommodate data from semiregulars should give us pause to consider what's really left of the 'rule'.

In contrast, single-mechanism models are a good fit for the semiregularity found in irregular verbs. McClelland and Patterson, in examining a Connectionist model of the past tense, note that the 177 out of 181 irregulars which end in an alveolar stop, "exploit to some degree the connection weights that produce regular items. Only the suppletive items fail to make any use of the connections that produce the regular past tense" (2002a). And furthermore, because Connectionist models handle both regulars and irregulars in the same system, it is predicted that their presence will *affect each other*. This is a clean contrast with the predictions of the dual-mechanism theory.

4.3 Experimental data on semiregularity

Though it was reported almost two decades ago (Seidenberg & Bruck 1990) that low-frequency regular verbs with high-frequency semiregular neighbors take longer to produce, surprisingly little research has been performed focusing on the effects of semiregular and regular neighbors; in particular, there is a paucity of research examining how semiregulars are affected by the regularity of their family. Though there have been some studies (mostly performed by Connectionists), their results are not mentioned often in the literature (particularly dual-mechanism literature).

In one of the few WR-driven analyses of family regularity effects, Ullman (1999) found that speakers give higher acceptability ratings to irregular forms with lots of irregular neighbors, but that acceptability ratings for regular forms are unaffected by phonological neighbors. By contrast, Marchman and Callan (1995) found that in addition to item frequency, regularizations for both regulars and irregulars were found to be significantly correlated with phonological attributes: “Crucially, regularization was a function of phonological similarity to frequent suffixed items, especially for irregulars that normally undergo a vowel-change.” Similarly, Marchman (1997) found that for children, the presence of many suffixed (regular) neighbors causes irregulars to be suffixed (overregularized) more often than they would be with fewer regular ‘enemies’, and concludes that “item-level phonologically-based factors impact children’s tendency to produce overregularizations of irregular verbs, as well as work to ensure that regular verbs will be successfully produced in their correct form.” Specifically, both frequency effects and phonological neighbors affected regulars and irregulars. Additionally, zero-marking errors were more common for verbs ending in alveolar stops (which all zero-marked irregulars end in) suggesting that the final consonant is phonologically salient in analogizing regular or irregular past-tense forms (Marchman 1997; Marchman, Wulfeck, & Weismer 1999).

Marchman, Wulfeck, & Weismer (1999) found that in children with Specific Language Impairment and those with Normal Language capabilities, “Neighborhood [family] analyses suggested that children from both groups were sensitive to patterns of phonological similarity across stems and past tense forms. In particular, an *irregular verb's similarity to regular verbs* increased the chances for erroneous suffixation” (emphasis mine). Further, they conclude that “...error patterns suggest that the source of the systematicity derives from surface-level, phonological features of verb stems, driven by similarity to items from a subclass of irregular verbs (i.e., zero-marking verbs).” These points taken together are clearly more compatible with one analogical mechanism handling all verbs.

5. Experiment

As noted in sections 4.2 and 4.3, WR and Connectionist models make different predictions about the effects of semiregulars on inflection. Specifically, Connectionist models handle both regulars and irregulars within the same statistical mechanism, and thus would be inherently sensitive to the relative frequencies of regulars and semi/irregulars; in this paradigm, regulars and irregulars would be subject to the same factors.[6] In contrast, WR posits that effects of frequency are confined to the lexicon, and thus the frequencies of regular verbs in the same phonological family as semiregulars should have no effect on the semiregulars' inflection (though the phonological similarity of the semiregulars to regular probes can supposedly cause the rule mechanism to be slowed down). So both models predict regularity effects on regulars, but only Connectionist models predict regularity effects on the semiregulars.

In order to examine the effects of semiregulars, a stem-inflection task (SIT) is used to measure subjects' RTs and error rates for various regulars and semiregulars. Afterward, data is analyzed to determine whether stimulus frequency, family frequency, or family regularity had any predictive effects on performance. The frequencies and regularity are calculated from an extensive data set of over 500 verbs in almost 50 phonological families. The results are compared to the predictions of the models to determine which best fits the data.

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[6] Errors in the past tense should be less frequent when "there is little competition between a verb's mapping type and similarly sounding 'enemies.' In *contrast* to the dual-mechanism model, *both* regularization and irregularization errors should be *predicted by the same set of factors*" (Marchman, Wulfeck, & Weismer 1999, emphasis mine).

5.1 Method

5.1.1 Participants

Twenty students from the Claremont Colleges in Claremont, California volunteered to participate in a past-tense verb inflection task. All were native English speakers with normal hearing and normal vision.

5.1.2 Stimuli

The stimuli consisted of 81 English verbs, presented in their stem form (see Appendix A). The verbs were chosen from a larger data set collected beforehand. The larger set was generated by taking words from lists of commonly used irregulars and using an online rhyming dictionary to find all other verbs with the same phonological ending. While it has been argued that articulatory constraints at the onset of a verb can influence overregularization,[7] it is generally accepted in the literature that verbs are most generalizable by rhyme (Pinker & Prince 1988; Prasada & Pinker 1993). As such, an assumption was made that the rime (stem-final vowel or vowel-consonant sequence) is more phonologically salient than the onset in analogizing past-tense formation.[8]

Verbs that are polysyllabic in their stem form were included in the list, but only monosyllabic verbs were used in the experiment. In total, almost 50 families with over 500 verbs were gathered. From those verbs, 38 regular, 41 irregular, and 2 'ambiregular' (verbs that

[7] For instance, *snuck*, which entered the American English lexicon as an acceptable irregular form in the last century, must have been formed by analogy to words like strike-struck rather than its irregular neighbors-by-rime, which form either the speak-spoke pattern or the seek-sought pattern. (Pinker 1999)

[8] Note that on the WR account, phonological generalizability exists only in the lexicon, and thus affects only (or primarily) irregulars; on the Connectionist account, all forms are phonologically and/or semantically generalized.

can be regular or irregular—*shine* and *shear*[9]) were presented as stimuli in the experiment. Four of the regular words were controls from three families that always form regular *-ed* endings; the remaining 77 words were culled from 33 families that contained both regular and irregular verbs (the families ranged from mostly regular members to mostly irregular, more specific analysis below). No families contained only irregular verbs, as there are no such families (Pinker 1999). At least one regular and one irregular were used from each family, and an effort was made to ensure that verbs of high, medium, and low individual frequencies were represented. In a few families that have multiple forms of irregularity (e.g., *take-took* and *make-made*), more than one irregular was chosen for comparative purposes. Similarly, in a couple families, an irregular of high frequency and one of low frequency were used, to allow for direct comparisons.

5.1.3 Procedure

Subjects sat in front of a computer screen running a PsyScope (Cohen et al. 1993) script for the duration of the experiment. They wore a headset with a microphone, which acted as a voice trigger key for the program. They first read brief instructions, informing them to say out loud the past tense form of the presented verb stem as *quickly and accurately* as possible. They were asked to speak loudly and clearly and to avoid mumbling (e.g., "um") which would prematurely trigger the microphone. Five practice trials were run before the 81 test verbs were presented.

For each stimulus, a focal + sign was displayed in the center of the screen before a verb stem would appear. The subject would say out loud the past tense form of the verb. As soon as the microphone registered the onset of speech, the word would disappear from the screen. This

[9] The ambiregular verbs were not used in the analysis below but merely for the purpose of more detailed analysis in the future.

was done to try to eliminate dependence on the written form (which could likely cause a bias toward regularization, since regular verbs on average preserve more of the original form). The experimenter checked off verbs on a list that were correctly produced, and if a subject produced anything else, the experimenter transcribed the word or utterance as best as possible for later coding and analysis. If the subject made a correction, their first completed word was used for analysis, and not their correction. Each of the 20 subjects were exposed to all 81 stimuli, but in a different, randomized order (in an attempt to even out priming effects).

5.1.4 Analysis

There are three critical variables to consider for each verb: how often it is used in the vernacular (stimulus frequency), how often verbs in its family are used (family frequency), and what proportion of the verb's family is regular vis-à-vis irregular (family regularity ratio). The frequencies of the verbs were looked up in the Kuçera-Francis corpus (1967), and only the verb instances of the words were counted, to avoid words like *mine* (which occur far more frequently as non-verbs) from inflating their group's frequency ratios.

The family frequency was determined by summing the frequencies of the whole family, but there were many words that did not appear in the Kuçera-Francis corpus (1967). In order to avoid the odd claim that the verbs have 0 frequency (and to assist in data analysis), the 'add one smoothing' (Jurafsky & Martin 2000) approach was adopted, such that every verb's frequency was increased by one (this has the added bonus of giving the total family frequency a net addition equal to the cardinality of the total family, which may be a relevant factor for generalization). Because the distribution for family frequency was skewed by very high-frequency outliers, the additional step of computing the logarithm of the frequencies was used for the actual analysis. The logarithms were then centered around the mean.

The regularity ratio for each family was quantified as the sum of the frequency of all of the regular verbs divided by the sum of the frequency for all of the verbs in the family. For these purposes, ambiregular frequencies were divided in two and each half was added to regular and irregular tallies (consistent with Marchman 1997). As such, regularity ratios range between 0 and 1, and a ratio above .5 indicates a relatively regular family, while a ratio below .5 indicates a relatively irregular family.[10] For the regressions, these ratios were centered around .5, such that any negative value would indicate a relatively irregular family and any positive value a relatively regular family.

5.2 Results

For full results from the SIT broken down by verb, see Appendix A.

Four 1-way, 2-way, and 3-way interaction linear regressions were run on regulars and irregulars for both RT and proportion correct (PC). The contribution of three independent variables were compared: centered logarithm of stimulus frequency (CLSF), centered logarithm of family frequency (CLFF), and centered family regularity (CFR). For full results from the linear regressions, see Appendix B.

The most significant dependent variable measure for regulars was RT. Mean RTs for regulars ranged from 699.29 to 1520.82. SF for regulars ranged from 1 to 821 (N=38, M=69.5,

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[10] Specifically, a family with a regularity ratio of 0.2, for example, would mean that approximately 20% of the time speakers use a verb in that family the regular inflection is used, while approximately 80% of the time an irregular inflection is used. Thus, if regular and irregular forms affect each other, we would expect performance on semiregulars in this family to be good, and performance on regulars to be bad, relative to semiregulars and regulars in a family with a regularity ratio of 0.8, *ceteris paribus*.

SD=164.0). FR ranged from .00457 to 1.0 (N=38, M=.48573, SD=.33629). FF ranged from 38 to 3545 (N=38, M=796.03, SD=761.71). 1-way and 2-way interaction linear regressions were significant for predicting RT for regular verbs (1-way: $r = .623$, R^2 change = .388, $p = .001$; 2-way: $r = .738$, R^2 change = .157, $p < .05$), while the 3-way interaction did not add anything to the model (R^2 change = .000). The strongest predictor in the 2-way model was the interaction between CLFF and CFR ($B = 412.156$, $SE_B = 147.167$, $p < .01$). CLSF was the strongest individual predictor of RT and highly significant ($B = -194.159$, $SE_B = 34.165$, $p < .001$). CFR was the second strongest individual predictor of RT but did not quite reach significance ($B = 191.129$, $SE_B = 105.679$, $p = .08$).

The most significant dependent variable measure for irregulars was PC. PC for irregulars ranged from 0.16 to 1.0 (N = 41, M = 0.8817, SD = 0.17086). SF for irregulars ranged from 5 to 1889 (N = 41, M = 318.02, SD = 433.98). FF ranged from 38 to 3545 (N = 41, M = 1017.34, SD = 922.71). FR ranged from 0.00457 to 0.86124 (N = 41, M = .36572, SD = .30356). 1-way, 2-way, and 3-way interaction linear regressions were all significant for predicting PC for irregular verbs (1-way: $r = .508$, R^2 change = .258, $p < .05$; 2-way: $r = .655$, R^2 change = .171, $p < .05$; 3-way: $r = .744$, R^2 change = .125, $p = .005$). The strongest predictor in the 3-way model was the interaction between CLSF, CLFF, and CFR ($B = -1.182$, $SE_B = .388$, $p = .005$). Also significant was the interaction between CLSF and CFR ($B = .448$, $SE_B = .173$, $p < .05$). CLSF was the strongest individual predictor for PC and highly significant in the 3-way ($B = .258$, $SE_B = .066$, $p < .001$). CLFF was the second strongest individual predictor of PC ($B = -.163$, $SE_B =$

.078, $p < .05$). The overall stimulus and family frequency effects for irregulars (while family regularity is held constant at 0.5) can be seen in Figure 1 (Appendix C). The effect of FR is strongest when family frequency is low (-1 SD): see Figure 2 (Appendix C).

6. General Discussion

6.1 Experiment, semiregulars, and models

Overall, the results suggest that the inflection of *both* regulars and irregulars is affected by at least three independent factors (and their interactions): stimulus frequency, family frequency, and family regularity. Regulars were more affected on RT measures than PC, while irregulars were more affected on PC than RT. Both Connectionist networks and the WR model predict the frequency effects observed for irregulars; but while Connectionist models may or may not predict frequency effects on regulars (depending on training), WR does *not* predict any frequency effects on regulars (Prasada, Pinker, & Snyder 1990; Ullman 1999; Ullman 2001) and thus cannot explain the effects of stimulus and family frequency for regulars. Family regularity's effect on regular verbs is predicted by both models, but only the Connectionist networks predict family regularity's effect on irregular verbs. These data strongly support the analogical-based nature of Connectionist models over the strict dichotomy of WR.

The observation that the most significant effects on regulars were present in RTs, but PCs for irregulars is somewhat intuitive (if one accepts that regulars and irregulars can affect each other): the presence of irregular neighbors cause regular formation to slow down, but does not typically overpower the regular inflection itself; on the other hand, the presence of regular neighbors is likely to reinforce the existing bias for regular inflection, and thus may cause more overregularization errors than delays. Still, this split should be further investigated.

The stimulus and family frequency effects seen on regular verbs suggest that the frequency by regularity interaction may not be present.[11] However, taking into account the effects on family regularity, it is evident that a verb's consistency with its phonological neighbors *is* an important factor which can override frequency effects to some extent. Perhaps then, what is really present is a frequency by subregularity interaction, where 'subregularity' refers to internal regularity *within a phonological family*.

On the WR account, irregular inflection is sensitive to phonological patterns in families because the lexicon is posited to have associative properties (Marcus et al. 1992; Pinker 1999), but regular inflection is not sensitive to its phonological neighbors because it's subserved by a non-statistical, symbolic rule mechanism.[12] This contrasts with the single-mechanism model, and the different predictions of the two models are the main motivation for this experiment. As predicted, family regularity affected both regulars and irregulars, although not as strongly as frequency effects. This finding is consistent with the way both regulars and irregulars are handled statistically in a Connectionist network, yet does not square with the predictions of WR. We can further conclude that the data suggest that regulars, semiregulars, and irregulars are not categorically different, but merely fall along a continuum; this conclusion defies the strict dichotomy of WR.

[11] This is likely due to the fact that most of the regulars used in the experiment (34/38) had at least one irregular phonological neighbor (while most regulars in the language don't have any). This suggests that excluding factors like family regularity in data analysis may lead to the obfuscation of a real effect. Further analysis of regulars is needed to make any conclusive judgment, however.

[12] "Verbs are protected from overregularization by similar-sounding irregulars, but they are not attracted to overregularization by similar-sounding regulars, suggesting that irregular patterns are stored in an associative memory with connectionist properties, but that regulars are not." (Marcus et al. 1992)

It remains to be seen how WR theorists could try to explain these results. Perhaps more modifications to the theory are in order (such as the adoption of associative properties in the lexicon and the admission of regular forms into the lexicon). However, it's unclear what modifications could be made that wouldn't undermine the very foundation of the WR model itself. One possible route is to suggest that because regular forms *can* be stored in the associative lexical memory, regular forms that are phonologically similar to stored irregulars will become stored in the lexicon as well, presumably to counteract the inhibition of the rule application that is purportedly caused by "temporary false matches" (Pinker 1999). If this proposal is made, it would be very difficult to tell what's really left of the rule mechanism. In order to best analyze what the rule contributes to the functioning of the theory, it would be beneficial to have an actual WR computational model to test. Unfortunately, while there is a plethora of Connectionist models of the past-tense, there is a dearth of actually testable WR models.

It is still too early to tell what will happen next, but complications like semiregularity need to be addressed in any paper dealing with the topic. Hopefully more research like this will encourage increased attention to these issues. One thing is clear: researchers on both sides of the debate cannot continue to lump all irregulars in the same boat. Additionally, future research on semiregulars should examine more specific ways to measure phonological similarity, and additional analysis of the commonalities between regulars and semiregulars, in the vein of McClelland and Patterson (2002a), is desperately needed. Other ways of measuring regularity ratios are possible, and those should be explored. Further, different types of inflection tasks (ones that more closely replicate natural speech, such as inflection from pictures (Woollams, Joanisse, & Patterson, in press)) should be looked at for comparison.

6.2 Quantities and qualities of mechanisms

It is common for dual-mechanism theorists to claim that the apparent complexity of inflectional morphology is evidence that any theory with only one 'mechanism' is insufficient: "Any theory that has one mechanism doing all the work is proposing a kind of crippleware that the human brain is bound to outperform" (Pinker 1999). Yet this construal of 'one mechanism' is rather like 'one function'. Single-mechanism theories are only 'single' in contrast to the *categorical distinctness* of dual-mechanism lexicon/grammar theories. Beyond Pinker, Marslen-Wilson and Tyler even ponder a poly-mechanism theory: "It is becoming clear, both functionally and neurologically, that at least two, if not more, separable systems are involved" (1998).

Pinker's characterization of 'one mechanism' oversimplifies what is really meant by single-mechanism theories. If a 'one mechanism' past-tense inflection model is construed as being nothing more than a subsystem of a broader network of general semantic, syntactic, and phonological processes (as Connectionist networks are typically posited to be), calling it 'crippleware' just because it doesn't embody multiple functionally separable systems is misleading. Artificial neural net models are tinker toys compared to biological neural networks. If Connectionist models were meant to correspond to a functionally isolated system, then Pinker's diagnosis would be dead-on. As it stands, his criticism has its merit—Connectionist models *per se* are in a very real sense crippleware—but it ultimately misses the point. The models are 'single'-mechanism because rather than positing two discrete systems, they posit a system more broadly construed, which handles both regular and irregular forms on a graded prototype continuum as an integrated system of phonological, semantic, syntactic, and morphological processes. Yet as quoted above, Marcus claims that "The sheer number [of mechanisms] tells us little, and it distracts attention from Rumelhart and McClelland's original question of whether (algebraic) rules are implicated in cognition" (2001). This is a valid point, and I would argue that the burden of proof is on those who claim extra mechanisms are necessary. At any rate, criticizing a theory simply for its number of mechanisms seems vacuous. The 'mechanism' envisioned in single-mechanism accounts may be much broader, and the contrasts less stark, than how mechanisms are traditionally perceived in the dual-mechanism frame of view.

6.3 Criticism of stem-inflection tasks

In the process of running subjects for the experiment, I came to a number of realizations. Primarily, my overall impression from observing the participants was that the way in which the task was oriented seemed wholly unlike the process of forming past-tense verbs in realtime speech. One very obvious indicator of this fact is the vastly higher error rate observed in inflection-from-verb-stem tasks, not just in this experiment, but as reported in others (Woollams, Joanisse, & Patterson, in press). While it could be argued that the increased prevalence of errors is a natural artifact of the pressures of the laboratory setting, and not indicative of a difference in the process of past-tense formation, there is no reason that this must be the case.

Rather, it is fairly clear that there is a distinctly unnatural character to these types of experiments. There is simply very little of regular speech that corresponds to forming a past-tense verb from the visual presentation of its verb stem form. While the same could be argued of other psycholinguistic laboratory experiments, there seems to be a much starker contrast between the isolated task of inflection-from-verb-stem and the how verbs are used in fluid, everyday speech. Stem-inflection tasks make the subject far more cognizant of the relationship between the stem and past forms than they would be in any everyday utterance. Not only does the apparatus force the past form to come directly in response to the stem form, but it even makes it explicit to some extent in the mind of the subject. Furthermore, the repetition of the process for dozens of verbs in a row only reinforces the connection between forms.

Proponents of both dual-mechanism and single-mechanism theories overlook this complication. Pinker explicitly claims of the inflection-from-verb-stem task that it causes people to have to "cough up past-tense forms under time pressure, as they do in rapid conversation" (1999). While this similarity is true, he overlooks the parts of the experiment that are largely incongruent with past-tense formation in rapid conversation. For one thing, past-tense formation is usually triggered conceptually or semantically, not from the presentation of the verb stem. In other words, as a speaker talks, if the verb form is triggered semantically (from the content of the sentence being spoken) and the speaker has some inclination of pastness, there is no reason why they would need explicit priming from the verb stem itself to produce the form. There is no theoretical obstacle to forming a past-tense verb without ever specifically accessing its stem form. This is very similar to the notion of non-concatenative compositionality (van Gelder 1990) discussed above. Unless it is proven that we must form a past-tense verb from its stem form, we cannot assume that an inflection-from-verb-stem task accurately recreates the natural past-tense formation process we always undergo in regular fluent speech.

What's most informative to the issue of past-tense formation is how speakers of the language produce or retrieve or otherwise procure the inflected verb *as they actually do in everyday, on-the-fly speech.* Of course, it's near impossible to measure truly on-the-fly speech in any great detail. It is the researcher's task to come up with the best possible approximation of normal speech behavior that allows for the control of some independent variable such that its effects can be measured in some depth. It's entirely plausible that the human mind possesses the ability to produce past-tense verb forms via several different pathways (superpositionality), though they may overlap to some degree. This is just to say that researchers must go to great lengths to ensure that their experiment is as close an approximation of the process typically implemented in on-the-fly speech. To assume that the visual presentation of verb stems to a subject instructed to produce its past-tense form is a close enough approximation of typical human speech is just silly. While no experimental apparatus is perfect, it is surprising that this task has remained the status quo for so long when there are better alternatives. Ideally, many types of tasks should be studied in detail to allow for comparisons across situations with different demands. If certain tasks produce significantly different effects from others, it is an indication that something different is going on in the process.

More research in this vein is desperately warranted. Future experiments must address whether inflection is "obligatorily preceded by retrieval of the verb stem" (Woollams, Joanisse, & Patterson, in press). They surmise that "conclusions concerning the mechanisms involved in inflectional morphology drawn from performance in standard form based elicitation tasks do not necessarily generalise to the processes underlying past-tense generation from meaning, which seem more akin to those supporting spontaneous speech." These possibilities cannot be ignored anymore in the future.

7. Conclusion

In light of all things considered herein, it's safe to say that after two decades of continuous research on the English past tense, the issue is far from settled. In large part, this is due to the fact that the two most popular models both fit the data fairly well. While there is a long way still to go in the debate, I believe that a stronger focus on semiregularity can change the trajectory of the debate for the better.

The results of this experiment suggest that the interactions between regular and irregular verbs are more intricate than the current literature takes them to be. The relative frequencies of semiregulars and regulars can affect processing times and error rates, and the overall regularity of a phonological family may be an important factor. Interestingly, the 2- and 3-way linear regression models show that this relationship is complex, and is in need of further research.

Given all of this data, it is fairly clear that regular and irregular verbs are not categorically distinct, but seem to be two ends of a continuum. Moreover, semiregulars seem to fall somewhere between these two ends. In consideration of these observations, it is evident that analogy-based systems like single-mechanism Connectionist networks, which exploit the patterns in regular *and* semiregular inflections, better approximate the inflectional morphology of the English past tense than the dual-mechanism Words-and-Rules theory.

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Appendix A

#	Stim.	Fam	Reg	Irr	SF	FF	FamReg	RT	%Corr
1	seep	1	0	0	5	621	0.053945	966.20	93%
2	keep	1	1	3	428	621	0.053945	712.45	100%
3	need	2	0	0	347	1062	0.521657	808.26	100%
4	heed	2	0	0	9	1062	0.521657	906.58	100%
5	feed	2	1	2	96	1062	0.521657	904.00	100%
6	fold	3	0	0	12	463	0.073434	796.30	95%
7	hold	3	1	2	404	463	0.073434	765.55	100%
8	ding	4	0	0	1	657	0.004566	1241.17	89%
9	sting	4	1	2	5	657	0.004566	911.50	95%
10	bring	4	1	3	410	657	0.004566	745.05	100%
11	link	5	0	0	20	984	0.046748	737.20	100%
12	sink	5	1	2	36	984	0.046748	1071.20	90%
13	think	5	1	3	844	984	0.046748	743.75	100%
14	whine	6	0	0	4	455	0.982418	792.42	100%
16	scoot	7	0	0	5	182	0.593407	982.21	89%
17	shoot	7	1	2	74	182	0.593407	929.15	90%
18	grin	8	0	0	31	328	0.152439	833.55	100%
19	spin	8	1	2	21	328	0.152439	836.25	90%
20	cite	9	0	0	32	724	0.212707	961.16	95%
21	bite	9	1	2	19	724	0.212707	1128.45	70%
22	write	9	1	2	434	724	0.212707	882.94	89%
23	blind	10	0	0	6	1099	0.084622	880.11	100%
24	find	10	1	2	930	1099	0.084622	957.80	100%
25	strand	11	0	0	8	739	0.282815	874.68	100%

Notes: ambireg. verbs 15 & 46 (*shine* & *shear*) not analyzed.
Fam: phonological family number. **Reg** (regularity): 0=regular, 1=irregular.
Irr (type of irreg.): 0=reg, 1=suffix, 2=vowel change, 3=suff & vc, 4=zero-mark, 5=suppletive.
SF: stimulus frequency. **FF**: family frequency. **FamReg**: family regularity ratio (total freq. reg./ total freq. fam.) **RT**: reaction time (msec). **%Corr**: overall % of correct inflections.

#	Stim.	Fam	Reg	Irr	SF	FF	FamReg	RT	%Corr
26	stand	11	1	3	319	739	0.282815	960.89	84%
27	pit	12	0	0	2	755	0.458940	1081.25	75%
28	hit	12	1	4	102	755	0.458940	1035.79	89%
29	pride	13	0	0	2	846	0.816785	1520.82	94%
30	ride	13	1	2	81	846	0.816785	876.60	90%
31	slide	13	1	2	33	846	0.816785	892.79	79%
32	fret	14	0	0	3	2035	0.018919	1020.05	90%
33	let	14	1	4	320	2035	0.018919	1096.69	81%
34	get	14	1	2	1207	2035	0.018919	776.40	100%
35	heave	15	0	0	5	1303	0.588258	946.07	100%
36	leave	15	1	3	526	1303	0.588258	852.05	95%
37	streak	16	0	0	5	393	0.082697	1092.63	74%
38	seek	16	1	3	125	393	0.082697	986.79	79%
39	speak	16	1	2	227	393	0.082697	1101.50	90%
40	reach	17	0	0	261	375	0.757333	794.00	100%
41	teach	17	1	3	91	375	0.757333	701.21	100%
42	yell	18	0	0	26	867	0.110727	707.90	100%
43	sell	18	1	3	87	867	0.110727	875.39	100%
44	fear	19	0	0	41	815	0.514110	884.67	100%
45	hear	19	1	3	392	815	0.514110	820.10	95%
47	peel	20	0	0	8	826	0.194915	827.39	100%
48	kneel	20	1	3	14	826	0.194915	820.82	41%
49	bake	21	0	0	8	3545	0.010437	736.06	100%
50	shake	21	1	2	80	3545	0.010437	980.00	74%
51	make	21	1	1	1889	3545	0.010437	930.06	100%
52	scare	22	0	0	20	753	0.656042	942.40	100%
53	swear	22	1	2	30	753	0.656042	906.80	85%
54	glow	23	0	0	9	3371	0.127855	996.25	75%

#	Stim.	Fam	Reg	Irr	SF	FF	FamReg	RT	%Corr
55	know	23	1	2	1316	3371	0.127855	1071.28	89%
56	go	23	1	5	1291	3371	0.127855	1183.56	94%
57	call	24	0	0	528	836	0.781100	719.30	100%
58	fall	24	1	2	183	836	0.781100	798.70	100%
59	end	25	0	0	98	835	0.483832	741.30	100%
60	lend	25	1	1	19	835	0.483832	1005.84	58%
61	match	26	0	0	43	280	0.510714	876.94	100%
62	catch	26	1	3	137	280	0.510714	791.95	100%
63	heat	27	0	0	19	804	0.490050	873.20	100%
64	meet	27	1	2	271	804	0.490050	764.90	100%
65	squeeze	28	0	0	26	209	0.861244	917.39	89%
66	freeze	28	1	2	29	209	0.861244	849.00	78%
67	use	29	0	0	821	1359	0.720383	699.29	100%
68	choose	29	1	2	156	1359	0.720383	958.50	100%
69	lose	29	1	3	224	1359	0.720383	1066.95	90%
70	size	30	0	0	8	377	0.586207	1014.28	100%
71	rise	30	1	2	115	377	0.586207	778.25	100%
72	pick	31	0	0	128	227	0.832599	737.80	100%
73	stick	31	1	2	38	227	0.832599	927.21	84%
74	trim	32	0	0	12	38	0.526316	884.61	94%
75	swim	32	1	2	18	38	0.526316	737.40	100%
76	trust	33	0	0	32	89	0.797753	797.20	100%
77	thrust	33	1	4	18	89	0.797753	950.11	16%
78	crank	34	0	0	1	58	1.000000	811.32	100%
79	rank	34	0	0	4	58	1.000000	946.15	100%
80	tire	35	0	0	32	625	1.000000	854.10	95%
81	pile	36	0	0	19	194	1.000000	712.95	100%

Appendix B

Results of data analysis

Table B-1: Overall Means and SDs for Regulars and Irregulars

		Stim. Freq.		Fam. Freq.		Fam. Reg.		RT		Percent Corr.	
Type	**N**	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
All	79	198.5	353.5	910.9	851.0	0.423	0.323	898.7	142.0	0.919	0.138
Regular	38	69.5	164.0	796.0	761.7	0.486	0.336	892.5	160.4	0.960	0.073
Irregular	41	318.0	434.0	1017.3	922.7	0.366	0.304	904.5	124.3	0.882	0.171

Table B-2: 2-way Interaction Linear Regression
Regular verbs—Reaction Time

Variable	B	Std. Err.	Beta	Sig.
(Constant)	830.636	27.689		0.000**
Stim. Freq.	-194.159	34.165	-0.850	0.000**
Fam. Freq.	23.752	72.751	0.066	0.746
Fam. Reg.	191.129	105.679	0.401	0.080
SFxFF	-29.837	80.774	-0.078	0.714
SFxFR	120.412	116.580	0.232	0.310
FFxFR	412.156	147.167	0.383	0.009**

Table B-3: 1-way Interaction Linear Regression
Irregular verbs—Reaction Time

Variable	B	Std. Err.	Beta	Sig.
(Constant)	918.504	23.158		0.000**
Stim. Freq.	-61.617	34.585	-0.317	0.083
Fam. Freq.	158.768	55.956	0.519	0.007**
Fam. Reg.	-24.936	66.765	-0.061	0.711

Table B-4: 1-way Interaction Linear Regression
Regulars verbs—Proportion Correct

Variable	B	Std. Err.	Beta	Sig.
(Constant)	0.977	0.014		0.000**
Stim. Freq.	0.036	0.017	0.343	0.044*
Fam. Freq.	-0.009	0.031	-0.054	0.776
Fam. Reg.	0.040	0.042	0.186	0.337

Table B-5: 3-way Interaction Linear Regression
Irregular verbs—Proportion Correct

Variable	B	Std. Err.	Beta	Sig.
(Constant)	0.836	0.030		0.000**
Stim. Freq.	0.258	0.066	0.966	0.000**
Fam. Freq.	-0.163	0.078	-0.388	0.043*
Fam. Reg.	-0.082	0.088	-0.145	0.358
SFxFF	-0.232	0.139	-0.448	0.104
SFxFR	0.448	0.173	0.717	0.014*
FFxFR	0.523	0.270	0.380	0.062
SFxFFxFR	-1.182	0.388	-0.992	0.005**

Appendix C

Figure 1. Effects of SF and FF on PC for Irregulars

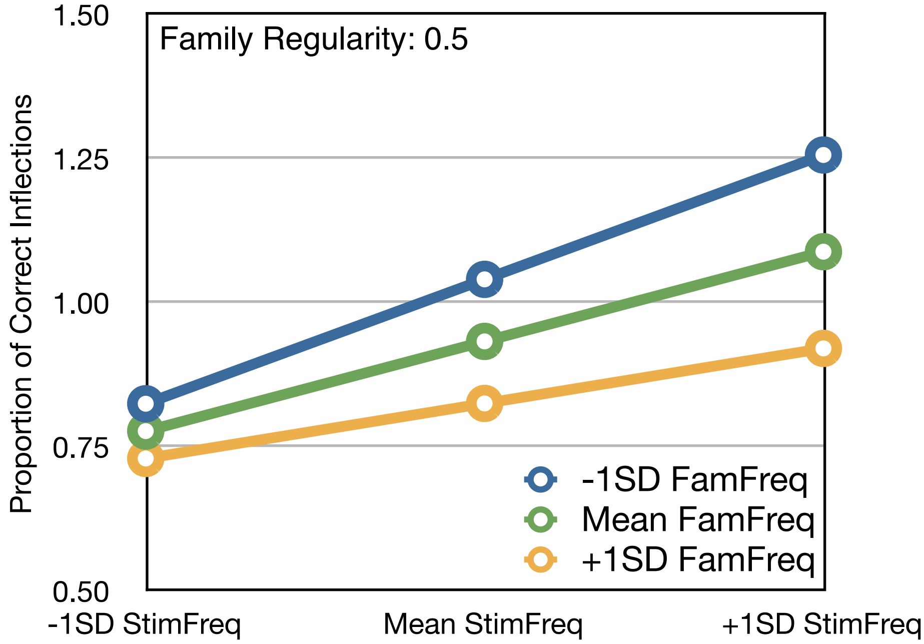
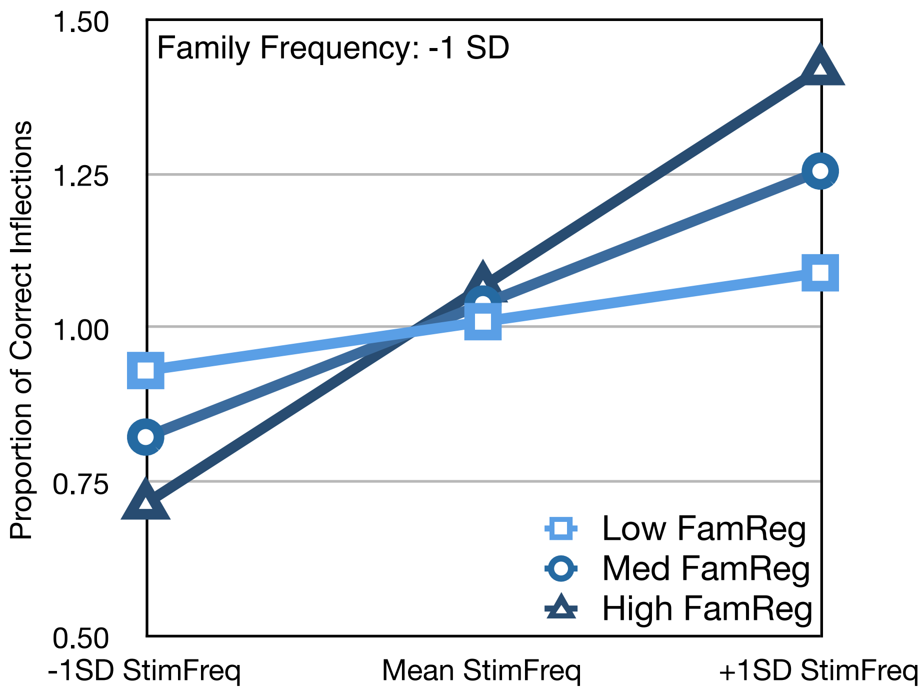


Figure 2. Effects of SF and FR on PC for Irregulars



Note:
These graphs are linear regressions. The Y-axis is the proportion of correct inflections. Because a proportion cannot go above 1.0, the graphs may seem somewhat confusing at first. The values above the 1.0 proportion line are actually impossible because that would mean a stimulus with a higher frequency than its own family. However, because this is a linear regression, the trend line continues linearly. If a nonlinear regression were done, the functions would probably asymptote at 1.0.