# The Declarative/Procedural Model of Lexicon and Grammar

**Michael T. Ullman[1]**

*Our use of language depends upon two capacities: a mental lexicon of memorized words and a mental grammar of rules that underlie the sequential and hierarchical composition of lexical forms into predictably structured larger words, phrases, and sentences. The declarative/procedural model posits that the lexicon/grammar distinction in language is tied to the distinction between two well-studied brain memory systems. On this view, the memorization and use of at least simple words (those with noncompositional, that is, arbitrary form-meaning pairings) depends upon an associative memory of distributed representations that is subserved by temporal-lobe circuits previously implicated in the learning and use of fact and event knowledge. This "declarative memory" system appears to be specialized for learning arbitrarily related information (i.e., for associative binding). In contrast, the acquisition and use of grammatical rules that underlie symbol manipulation is subserved by frontal/basal-ganglia circuits previously implicated in the implicit (nonconscious) learning and expression of motor and cognitive "skills" and "habits" (e.g., from simple motor acts to skilled game playing). This "procedural" system may be specialized for computing sequences. This novel view of lexicon and grammar offers an alternative to the two main competing theoretical frameworks. It shares the perspective of traditional dual-mechanism theories in positing that the mental lexicon and a symbol-manipulating mental grammar are subserved by distinct computational components that may be linked to distinct brain structures. However, it diverges from these theories where they assume components dedicated to each of the two language capacities (that is, domain-specific) and in their common assumption that lexical memory is a rote list of items. Conversely, while it shares with single-mechanism theories the perspective that the two capacities are subserved by domain-independent computational mechanisms, it diverges from them where they link both capacities to a single associative memory system with broad anatomic distribution. The declarative/procedural model, but neither traditional dual- nor single-mechanism models, predicts double dissociations between lexicon and grammar, with associations among associative memory properties, memorized words and facts, and temporal-lobe structures, and among symbol-manipulation properties, grammatical rule products, motor skills, and frontal/basal-ganglia structures. In order to contrast lexicon and grammar while holding other factors constant, we have focused our investigations of the declarative/procedural model on morphologically complex word forms.*

[1] Departments of Neuroscience and Linguistics, Georgetown University, Research Building, 3900 Reservoir Road, NW, Washington, DC 20007. email: michael@giccs.georgetown.edu.

*Morphological transformations that are (largely) unproductive (e.g., in* go–went, solemn–solem-nity*) are hypothesized to depend upon declarative memory. These have been contrasted with mor-phological transformations that are fully productive (e.g., in* walk–walked, happy–happiness*), whose computation is posited to be solely dependent upon grammatical rules subserved by the pro-cedural system. Here evidence is presented from studies that use a range of psycholinguistic and neurolinguistic approaches with children and adults. It is argued that converging evidence from these studies supports the declarative/procedural model of lexicon and grammar.*

Language may be defined as a relation between form and meaning. The pre-dictability of this relation varies across linguistic forms. The relations of many forms, and of word "roots" in particular, are entirely idiosyncratic. That is, the meaning of these words cannot be predicted, or derived, from their forms, or vice versa. Thus the relation between the form *cat* and the mean-ing "cat" is entirely arbitrary, and so the pairing must be memorized. The set of memorized form–meaning pairings may be defined as the mental lexicon. In contrast, the meaning of other linguistic forms is entirely predictable (derivable), given both the memorized knowledge of the lexical forms from which they are composed, and the grammatical rules (including constraints), which specify their composition. The knowledge of these rules may be defined as the mental grammar. In addition, there are form-meaning pairings that are partially predictable. Although these form–meaning relations may be described by rules, the application of those rules is not entirely predictable, and, therefore, the contexts in which they apply must be memorized.

   Here a mental model of lexicon and grammar is proposed. The model addresses issues of modularity, computation, domain specificity, and neural localization. It is posited that two systems, with distinct computational, psy-chological, and neural bases, play parallel roles in the computation of form–meaning relations. One system is an associative memory of distrib-uted (but structured) representations, over which phonological and concep-tual-semantic mappings are learned, stored, and computed. The other system follows mental rules of grammar in building the sequential and hier-archical structure of complex forms. Although it is posited that this gram-matical system subserves syntactic as well as morphological (and possibly also phonological) computations, here we focus on morphology.

   It is hypothesized that the rule system subserves at least those mor-phological (morphophonological) transformations that are fully productive and that involve only sequencing operations (i.e., in affixation and com-pounding; e.g., *look + -ed → looked, shirt + sleeve → shirt-sleeve*), whereas the memory system underlies at least those morphophonological transfor-mations that do not involve any such sequencing operations (e.g.,

*sing–sang*). For a given morphosyntactic configuration, both systems attempt to compute an appropriate morphologically complex form. If a form is found in memory (*sang*), the rule-based computation is inhibited; otherwise a rule-product (*looked*) is successfully computed. Neither system's role is limited to morphology or even to language. The memory system underlies the learning, representation, and processing of the entire mental lexicon as well as nonlinguistic knowledge about facts and events, such as what a bicycle is and what you ate for lunch yesterday. The rule-subserving system underlies the implicit (nonconscious) learning and expression not only of morphological rules, but also of syntactic (and possibly phonological) rules and of motor and cognitive skills and habits, such as how to ride a bicycle.

The two systems have distinct neural correlates. The memory system is rooted in temporal lobe brain regions, whereas the rule system is rooted in left frontal/basal-ganglia structures. Thus the claim is that morphology itself is modular, and that each of the two principal components underlies the computation of (at least partially) different types of morphological transformations, but that each relies on distinct computational operations and distinct brain structures, and that each component is domain-independent, both within language and, more generally, with respect to other cognitive functions.

This paper is organized as follows. First, some background to different types of morphological transformations is provided. Second, the proposed mental model is described in detail. Third, the two main competing theoretical frameworks are discussed. Fourth, all three competing perspectives are summarized, and competing predictions are made, in terms of the relevant theoretical issues: modularity, computation, domain-specificity/generality, and neuroanatomical localization. Fifth, evidence is presented from psycholinguistic and neurolinguistic studies aimed at probing these theoretical issues and at teasing apart the competing theories.

## MORPHOLOGICAL TRANSFORMATIONS

Within inflectional morphology, words in a given syntactic configuration are associated with one or more morphophonological transformations. Here a morphophonological transformation refers to a phonological mapping between word stems or roots (i.e., bases) and inflected forms for a given (morpho)syntactic configuration. Thus English verbs in the past tense can undergo *-ed* suffixation as well as a variety of other morphophonological transformations (in *bring–brought, sing–sang, keep–kept,* etc.). Similarly, for derivational morphology, words in a given syntactic and semantic configuration may be associated with one or more morphophonological transformations. Thus (at least) *-ity* and *-ness* suffixation underlie the creation of

abstract nouns from adjectives in English. Morphophonological transformations (which I will also refer to as morphological transformations or mappings) can differ along a number of dimensions, across both inflectional and derivational morphology. Here I focus on three dimensions, each of which is relevant to the claims of the proposed model.

First, overt morphophonological mappings are of (at least) two types. Whereas affixation involves the sequencing of morphophonological segments, sequencing may not be evident in other types of mappings. Thus suppletion involves a completely arbitrary relation between base and morphologically complex form (e.g., *go–went*), whereas phonological stem changes involve modification of only particular segments (e.g., *sing–sang*). A given word can undergo none of these types of overt changes (e.g., *hit–hit*), or one or more of them, such as stem changes in addition to affixation (e.g., *break–broken*).

Second, certain morphophonological transformations may have precedence over others in the same syntactic configuration, blocking those with lower precedence. Such precedence is a function of the fact that many morphophonological transformations apply only or primarily under specific conditions. Some apply only to a fixed list of words (e.g., *go–went, bring–brought, teach–taught*), whereas others appear to apply in particular phonological, semantic, and/or morphological conditions. If in a given syntactic (and semantic) configuration two or more morphological transformations have overlapping conditions, and if one of these transformations always applies instead of the others in these overlapping conditions, then it can be said to have strict precedence over the others. For example, in English past tense, the various transformations underlying irregular forms (e.g., *take–took, bring–brought, sing–sang, keep–kept*) take precedence over -*ed* suffixation, thus precluding forms like *taked, bringed,* and *keeped.*

Third, morphological transformations vary widely with respect to their productivity. Here, the level of productivity of a morphological transformation refers to the extent to which it applies to new forms (new words and novel forms) that meet any particular set of conditions, within a given syntactic configuration. *Unproductive* transformations apply only to a fixed list of words (e.g., *go–went*); that is, they apply to no new forms. *Fully productive* transformations apply to every form which meets a necessary and sufficient set of conditions, apart from those forms to which a transformation of higher precedence has applied. For example, the application of the -*ity* suffix to -*able*-suffixed adjectives appears to be fully productive. Such a transformation may be called a *local default,* because it is defaulted to under particular (i.e., local) conditions within a broader syntactic semantic configuration. A fully productive morphological transformation that applies under any phonological, semantic, or morphological conditions, within a given syntactic/

semantic configuration, may be referred to as a *global default*. For example, English past tense *-ed* suffixation is a global default. The necessary and sufficient conditions under which a global default may apply are simply equivalent to its associated configuration. Thus, for a given syntactic/semantic configuration, a local default can apply in a particular subset of the phonological, semantic, or morphological feature space, whereas a global default can apply in the entire feature space.

*Partially productive* transformations apply to some or perhaps many or most, but crucially not to all forms—apart from those forms to which a transformation of higher precedence has applied—that meet any possible set of phonological, semantic, or morphological conditions within a given syntactic/semantic configuration. In other words, there exists no necessary and sufficient set of conditions under which a partially productive transformation can be fully productive. Consequently, there is no strict precedence relationship between a partially productive transformation and the transformation(s) that it can precede: For any set of conditions, a given partially productive transformation will only sometimes precede other transformations. This variable precedence relationship is therefore a key test of partial productivity. For example, the past tense mapping in *feed–fed, lead–led, breed–bred, speed–sped* can apply to new forms (e.g., *cleed–cled*), but does not apply to *heed, seed, need, weed,* which are *-ed* suffixed. Partially productive transformations can range in productivity, and can be found both among stem change and affixal transformations (e.g., German participle *-en* suffixation (Marcus, Brinkmann, Clahsen, Wiese, & Pinker, 1995) and Japanese adjectival past-tense *-katta* suffixation (Fujiwara & Ullman, 1999)).

## THE MENTAL MODEL

A mental model of morphology is presented here. It is similar in certain respects, but crucially different in others, to models that have previously been proposed by my colleagues and myself (Marcus *et al.,* 1992, 1995; Pinker, 1991; Pinker & Prince, 1988, 1991; Prasada & Pinker, 1993; Ullman, 1993, 1999a; Ullman, Corkin *et al.,* 1997).

According to the model (also see Ullman, Corkin *et al.,* 1997; Ullman *et al.,* in press), morphological transformations can be computed by either of two components, which have distinct cognitive, computational, and neural bases.

One component is a memory system. This is not a rote memory containing a list of the morphologically complex forms yielded by morphological transformations. Rather it is an associative memory of distributed representations, over which the transformations' phonological and conceptual–semantic mappings are learned, stored, and computed. The system

learns the mappings of individual morphologically complex forms (e.g., *sing–sang*), learns patterns common to the mappings of different forms (e.g., in *sing–sang, spring–sprang, ring–rang*), and may then generalize these patterns to new forms (e.g., *spling–splang*). Thus, unlike a rote memory, this associative memory is productive, although the extent of its productivity remains unclear. The memory system can be modeled by the sort of connectionist (artificial neural network) systems described below and, in particular, by those whose recurrent connections among units allow for the settling of activity into stable attractor patterns (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996). However, unlike in the models described below, (at least) the phonological representations are posited to be structured, reflecting the morphophonological and phonological structure of stored words (see Pinker, 1999; Pinker & Prince, 1992). Thus a memorized word is represented as a structured assembly of its parts, each of which has a distributed representation, and which presumably include phonemes and syllables, as well as any attached affixes for stored affixed words. Importantly, in this memory system, as in other connectionist models, rules are nothing more than descriptions of patterns in the language.

The other component is a rule system. Its rules, including constraints, are more than descriptions of linguistic patterns. They are represented as mental knowledge and implemented by mental operations. The rules specify any sequential and hierarchical structure of morphologically complex forms. The system computes morphophonological transformations in real-time by symbol manipulation (Newell & Simon, 1981). It concatenates the phonological forms of bases and affixes (e.g., *walk + -ed → walked*; *rat + -s → rats*; *happy + -ness → happiness*; *shirt + sleeve → shirt-sleeve*; *shirt-sleeve + -s → shirt-sleeves*).

The memory system is posited to be the sole computational device underlying phonologically overt morphological transformations that are not explained by affixation. Thus the computation of English irregular past tenses such as *go–went, dig–dug,* and *blow–blew* depends only on the memory system.[2] In contrast, the rule system is posited to subserve at least those morphological transformations that are fully productive (i.e., local or global defaults) and that can be explained in their entirety by affixation rules, such as *-ed* suffixation. Under the assumption that all default transformations can be reduced to affixation processes, the claim can be simplified. The rule system subserves fully productive morphological transformations. Crucially,

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[2] A strong position is not taken on no-change forms, such as the English past tense *hit*. However, a mapping in associative memory between stem and past (*hit–hit*) analogous to that posited for stem-change forms (*dig–dug*) is consistent with the proposed model.

this system is posited to underlie the types of operations that underlie affixation, such as sequencing and concatenation, but not those which underlie non-affixal processes such as phonological stem readjustment. Thus, in the (presumed) absence of a third component, stem-readjustment rules can only be instantiated in the associative memory system and are therefore not mental rules, but only descriptions of patterns in the language.

A strong stance will be taken here on morphological transformations that involve phonologically overt affixation, but are not fully productive (e.g., Japanese adjectival -*katta* suffixation, as in *oishi–oishikatta*). These include transformations that encompass stem changes, in addition to affixation, such as German plural -*er* suffixation (e.g., *Wald–Wälder*). The affixation portion of these unproductive or partially productive transformations could, in principle, be computed by the rule system, or the entire transformation could rely on associative memory, with a structured representation linking distinct representations of base and affix. Here I will take the strong position that only fully productive transformations (i.e., defaults) can be learned and computed by the rule system; morphological transformations that involve overt affixation but are not fully productive are computed solely in a structured associative memory. On this view, the mappings of *oishi–oishikatta, Wald–Wälder,* as well as *keep–kept* and *dig–dug,* are computed in associative memory.

In contrast, it is posited that the morphological transformation underlying *any individual item* can be learned, stored, and computed in associative memory. That is, there is nothing preventing the memorization of any form, or of the between-form mappings that underlie a transformation. Thus, even if a mental rule exists for a given transformation, the form it computes or its morphological mappings, could be learned and subsequently computed in associative memory. In this case, a given form could be computed either in associative memory or by the rule system. The likelihood of the storage and retrieval of a such a form in associative memory increases with various factors, including the form's frequency. Thus low-frequency default forms are particularly likely to be computed by the rule-processing system because they are unlikely to have been memorized.

The computation of a morphologically complex form involves the parallel activation of the two systems, one of which attempts to compute a form in associative memory, while the other attempts to compute a rule product (see Pinker & Prince, 1991). As the memory-based computation proceeds (e.g., during settling into a stable attractor pattern), a continuous signal is sent to the rule-processing system, indicating the probability of the successful computation of a form in (that is, retrieval from) associative memory. It is this signal that inhibits the symbol-manipulating system from carrying out its computation. Thus the computation of *dug* inhibits ("blocks") the com-

putation of *digged.* When a memorized form is not successfully retrieved, the rule may apply, resulting in "overregularization" errors such as *digged* (Marcus *et al.,* 1992; Pinker, 1991; Pinker & Prince, 1991; Ullman, 1993; Ullman, Corkin *et al.,* 1997).[3]

The two components are largely modular, at least with respect to each other. Following Fodor (1983; 1985), the essential property of a module is taken to be informational encapsulation—that the module does not have access to background information. In the proposed mental model of morphology, the two components are largely informationally encapsulated *with respect to each other*: The computation that each component performs does not *require* input from the other. It is not clear whether the memory system even has *access* to information from the rule system; the rule system can only be influenced by the success of the memory system's computation, not by the information used within that computation. The rule system is also posited to be informationally encapsulated in the more general sense, with respect to other mental processes. In contrast, the memory system may be more open to the influence of other processes.

Whereas the Fodorian notion of modularity encompasses domain specificity, the proposed model posits that both systems are domain general. First of all, neither system is dedicated to morphology. The associative memory system underlies the learning, representation, and computation (retrieval) of the sounds and meanings not only of morphologically complex forms, but also of morphologically simple words—that is, words that have not undergone inflectional, derivational or compounding transformations. It is also assumed to contain any word-specific grammatical knowledge, such as grammatical category or subcategorization information. Thus the associative memory system contains the entire mental lexicon. Similarly, the symbol-manipulation system is posited to subserve syntactic (and perhaps phonological) as well as morphological computations. Thus it subserves (at least portions of) the mental grammar. It may play a particularly important role in grammatical structure building—the construction of the sequential and hierarchical structures posited to underlie linguistic forms.

Second, neither is dedicated to language. Each is posited to be a system that has previously been implicated in nonlanguage functions and whose

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[3] Some linguistic theories assume that rule-based computations are carried out internally to the "linguistic" lexicon, even for inflectional morphological transformations such as past-tense computation. According to such theories, both regular and irregular past-tense verbs are formed and stored in the linguistic lexicon and are taken from there for further syntactic composition already inflected. According to the dual-system view, which we will be testing in this paper, the use of irregulars depends upon the mental lexicon, whereas the use of regulars depends upon rule-based operations, irrespective of the extent to which the linguistic lexicon and/or syntax subserve derivational and/or inflectional morphology.

psychological, computational, and neural bases have been intensively investigated. One is a memory system implicated in the learning, representation, and use of knowledge about facts ("semantic knowledge") and events ("episodic knowledge"). The other underlies the learning and expression of motor and cognitive skills and habits. It is argued that the first system's role in facts and events extends to words, whereas the second system's role in skills and habits extends to grammatical rules.

The memory system is often referred to as the "declarative" memory system. It may be particularly important for learning arbitrarily related information—that is, for the associative/contextual binding of information. It is subserved largely by medial temporal lobe structures (the hippocampus and related structures), which are connected largely with temporal and parietal neocortical regions (Suzuki & Amaral, 1994). The medial temporal components underlie the consolidation of memories, which eventually become largely or fully independent of these structures and dependent upon neocortex, particularly in temporal lobe regions. Evidence also suggests that the medial temporal lobe structures may be necessary for the conscious recollection of previously learned information ("explicit memory"). It has been argued that the information learned by this system is not informationally encapsulated, being accessible to multiple response systems (Curran & Schacter, 1997; Graham & Hodges, 1997; Hodges & Patterson, 1997; Schacter & Tulving, 1994; Squire, Knowlton, & Musen, 1993; Squire & Zola, 1996).

Several lines of evidence suggest links between lexical memory and this brain memory system. First, the two overlap in function, as the memory system is thought to underlie semantic knowledge, which is a critical part of lexical memory (word meanings). Moreover, both fact and word knowledge can be arbitrary. Second, neuropsychological evidence suggests that the temporal lobe system may subserve words. Patients with medial temporal lobe amnesia have trouble learning words as well as facts and events (Zola, 1997). "Semantic dementia" is associated with neocortical temporal lobe damage and impairments remembering established facts, events, and words, but with apparent sparing of grammar (Hodges, Patterson, Oxbury, & Funnell, 1992). Posterior (i.e., fluent) aphasia, which occurs with left temporal/temporoparietal damage, is associated not only with word-use deficits, but also with semantic impairments in nonlanguage domains (Alexander, 1997; Farah & Grossman, 1997; Goodglass, 1993). Patients with Alzheimer's disease, whose degeneration severely affects temporal lobe regions (Arnold, Hyman, Flory, Damasio, & Hoesen, 1991), have difficulty learning new, and remembering established, words as well as facts and events (Nebes, 1989). Electrophysiological and neuroimaging studies implicate temporal lobe regions in both lexical and semantic tasks (Barrett & Rugg, 1989, 1990; Martin, Wiggs, Ungeleider, & Haxby, 1996; Nobre, Allison, &

McCarthy, 1994; Simos, Basile, & Papanicolaou, 1997). These data lead to the hypothesis that the temporal lobe system underlies the learning of new, and the use of established, word sounds and meanings, as well as knowledge about facts and events. Thus, the neocortex in temporal and temporoparietal regions may subserve lexical as well as conceptual knowledge.

The other system is often referred to as the "procedural," "skill," or "habit" system. It has been implicated in the learning of new, and the control of long-established, motor and cognitive "skills" or "habits" (e.g., from simple motor acts to riding a bicycle to skilled game playing). Neither the learning nor the remembering of these procedures appear to be accessible to conscious memory—thus the system is often referred to as an "implicit memory" system (Alexander, Crutcher, & DeLong, 1990; De Renzi, 1989; Gabrieli, Corkin, Mickel, & Growdon, 1993; Graybiel, 1995; Mishkin, Malamut, & Bachevalier, 1984; Schacter & Tulving, 1994; Squire *et al.,* 1993; Winocur & Moscovitch, 1990). It has been argued that the procedural system is largely informationally encapsulated, having relatively little access to other response systems (Squire & Zola, 1996). The system may be particularly important for learning and performing skills involving sequences (Graybiel, 1995; Willingham, 1998). Evidence from animal studies suggests that its circuitry may also be critical in the expression of innate behavioral routines (Graybiel, 1995).

The procedural system is rooted in frontal/basal-ganglia structures (De Renzi, 1989; Gabrieli *et al.,* 1993; Graybiel, 1995; Mishkin *et al.,* 1984; Schacter & Tulving, 1994; Squire *et al.,* 1993; Squire & Zola, 1996; Winocur & Moscovitch, 1990). The basal ganglia circuits are connected largely (via the thalamus) with frontal cortex. Importantly, these circuits appear to be parallel and functionally segregated, each receiving projections from a particular set of cortical and subcortical structures, and projecting via the thalamus to a particular cortical region, largely in frontal cortex. Thus a "motor circuit" projects to frontal motor areas, while other circuits project to other frontal areas. The different basal ganglia circuits may have similar synaptic organizations, suggesting that similar neuronal operations might be performed at comparable stages of each circuit (Alexander *et al.,* 1990; Alexander, DeLong, & Strick, 1986). Moreover, it has been independently hypothesized that the frontal lobes may also be organized in such a manner, with distinct topographically organized regions playing the same or similar computational roles in different domains (Roberts, Robbins, & Weiskrantz, 1998; Shimamura, 1995).

Several lines of evidence link grammar to this frontal/basal-ganglia system. First, the two overlap in function, as the control of both skills and grammatical processing presumably requires the coordination of procedures in real time. Second, anterior (i.e., nonfluent) aphasia, which occurs with

left frontal damage, is associated with impairments not only of grammar, but also in the expression of motor skills (ideomotor apraxia) (De Renzi, 1989; Goodglass, 1993). Moreover, Broca's area has been implicated in actual and imagined nonspeech movements (Fox, Mintum, Reiman, & Raichle, 1988), as well as grammatical processing. In nonhuman primates the basal ganglia project to a possible Broca's area homolog (Hoover & Strick, 1993; Preuss, 1995). Patients with Parkinson's disease, whose degeneration strikes frontal/ basal-ganglia structures, may have impairments of grammar use (Illes, 1989; Lieberman *et al.,* 1992) as well as of skill learning and control (Dubois, Boller, Pillon, & Agid, 1991; Harrington, Haaland, Yeo, & Marder, 1990; Saint-Cyr, Taylor, & Lang, 1988; Young & Penney, 1993). These data lead to the hypothesis that the frontal/basal-ganglia system underlies the learning of new, and the expression of established, grammatical rules as well as motor and cognitive skills and habits. Thus it is plausible that one or more particular basal ganglia circuits or subcircuits, projecting to particular frontal region(s), may subserve grammatical processing, and perhaps even finer-grained distinctions, such as morphological vs. syntactic structure building. On this novel view, the frontal/basal-ganglia structures are domain general in that they subserve nonlinguistic as well as linguistic processes, but contain parallel domain-specific circuits.

## Summary

The Declarative/Procedural Model of language can thus be summarized as follows. The declarative memory system is rooted in temporal lobe structures; appears to be specialized for associative binding; might not be informationally encapsulated; and underlies not only the learning and explicit (conscious) use of facts and events, but also of the sounds and meanings of morphologically simple and complex words—that is, the mental lexicon. It may be the case that these processes can be accurately simulated by a (structured) connectionist model. The procedural system is rooted in frontal/basal-ganglia structures; may be specialized for sequences; appears to be largely informationally encapsulated; and underlies the implicit (nonconscious) learning and expression not only of motor and cognitive skills and habits, but also of grammatical rules, in both syntax and morphology. The computation of grammatical rules in this system is best modeled by symbol-manipulation.

Morphological transformations can be learned by and computed over either of the two brain systems. The declarative memory system underlies the learning and computation (i.e., retrieval) of at least those transformations that involve phonologically overt changes, but do not involve any overt morphological sequencing (e.g., *dig–dug*). The procedural system underlies the

learning and computation of at least those transformations that are fully productive (i.e., local or global defaults) and that only involve morphological sequencing (e.g., *walk–walked*). Other transformations that involve sequencing may depend entirely on declarative memory. Any morphologically complex form can be learned in declarative memory, even if it could also be rule computed by the procedural system. The computation of a morphologically complex form involves the parallel activation of both systems; successful retrieval of a form from declarative memory inhibits (blocks) the computation of a rule product in the procedural system.

Thus it is posited that two brain systems, each largely informationally encapsulated from the other, each best explained by distinct computational mechanisms, each having a distinct set of specialized but domain-general functions, and each dependent upon distinct neural structures, play parallel functional roles in the computation of morphological transformations.

It should be noted that in this chapter other language functions, including syntax, are not discussed in any detail in the context of the proposed model. Nonetheless, the general structure of the Principles and Parameters framework, including recent extensions such as Minimalism (Chomsky, 1995), is largely accepted. In particular, the proposed mental model is consistent with the view that the computation of syntactic structures involves the manipulation of bundles of (morpho)syntactic and semantic features and that this manipulation is largely independent of morphophonological processes (Anderson, 1992; Aronoff, 1976; Halle & Marantz, 1993). It should be emphasized that this independence of computation is compatible with the hypothesis discussed above, that the procedural system subserves syntax as well as morphophonology, but that each may depend upon distinct frontal/basal-ganglia circuits.

Finally, it is important to note that the proposed model does not address or preclude the possibility that other neural structures or brain systems, or other cognitive or computational components, may play an important role in the mental grammar or the mental lexicon. These are open questions which must be further investigated.


## TWO COMPETING PERSPECTIVES

The proposed model can be contrasted with two previously posited competing theoretical perspectives. According to what may be termed *traditional dual-mechanism* models, memorized lexical forms are stored in a rote memory (the mental lexicon), whereas grammar is computed in one or more distinct components, each of which relies on symbol manipulation, is

modular (informationally encapsulated), and domain specific to its linguistic functions (Chomsky, 1981, 1995; Fodor, 1983).

In this framework, (at least) suppletive morphologically complex forms (e.g., *go–went*) are stored in and retrieved from the rote memory, whereas default transformations (e.g., *play–played, happy–happiness*) are computed by symbol-manipulation processes (Bybee & Moder, 1983; Bybee & Slobin, 1982; Halle & Marantz, 1993; Halle & Mohanan, 1985; Hoard & Sloat, 1973; Vennemann, 1971). Other types of inflectional and derivational forms, that involve neither suppletive nor default transformations, have been variously posited to be simply stored in rote memory (e.g., for English irregular forms, Bybee & Moder, 1983; Bybee & Slobin, 1982; Vennemann, 1971), computed by (morpho)phonological "stem readjustment rules" (e.g., for forms that undergo stem changes, such as *dig–dug* or *sing–sang;* Halle & Marantz, 1993; Halle & Mohanan, 1985; Hoard & Sloat, 1973), or computed by affixation rules, which are enabled by the memorization of a diacritic on the stem or of a list of stems on the affix (Halle & Marantz, 1993). Moreover, complex words can undergo more than one of these processes. For example, Halle and Marantz (1993) propose that the computation of *kept* is achieved by the *-t* suffixation of the stem *keep* as well as the application of a readjustment rule.

According to *associative memory* theories, all lexical and grammatical knowledge, including knowledge of morphology, is learned by, represented in, and computed over an associative memory. It is generally posited that the associative memory is domain general, in that it also subserves nonlanguage functions, and that it has a relatively broad left hemisphere anatomic distribution (Bates & MacWhinney, 1989; Elman *et al.,* 1996; MacDonald, Pearlmutter, & Seidenberg, 1994; MacWhinney & Bates, 1989; Rumelhart & McClelland, 1986; Seidenberg, 1997). On this view, there is no categorical distinction between noncompositional and compositional forms. There are no mental rules and no distinct system to process rules. Rather, rules are only descriptive entities and the language mechanism gradually learns the entire statistical structure of language, from the arbitrary mappings of noncompositional forms, including morphologically simple items (e.g., *cat*), to the rule-like mappings of compositional forms, including morphologically complex forms. Modern connectionism has offered a computational framework for the single system view. It has been argued that the learning, representation, and processing of grammatical rules as well as lexical items takes place over a large number of interconnected simple processing units. Learning occurs by adjusting weights on connections on the basis of statistical contingencies in the environment (Elman *et al.,* 1996; Seidenberg, 1997). A number of connectionist models have been constructed to simulate the learning and compu-

tation of morphologically complex forms, in particular of inflected forms (Cottrell & Plunkett, 1991; Daugherty & Seidenberg, 1992; Hare & Elman, 1995; Hare, Elman, & Daugherty, 1995; Joanisse & Seidenberg, 1999; MacWhinney & Leinbach, 1991; Marchman, 1993; Plunkett & Marchman, 1991, 1993; Rumelhart & McClelland, 1986; Seidenberg & Daugherty, 1992).

## COMPETING CLAIMS AND PREDICTIONS

The three theoretical perspectives make different claims regarding the four theoretical issues of interest. Different predictions fall out of these claims, enabling one to empirically tease apart the three perspectives.

### Modularity

The proposed model posits intramorphological modularity—that two components play parallel roles in the computation of morphological transformations, and that they subserve at least partially nonoverlapping types of transformations. Therefore psychological and neural dissociations between these types of morphological transformations are predicted. The exact split between different types of transformations is not the same as that posited by traditional dual-mechanism theories (e.g., Halle & Marantz, 1993), which assume more forms dependent upon the rule system. The predicted dissociations can, therefore, be distinguished. In contrast, previously proposed single-system models do not posit any dichotomous split between different types of morphological transformations, and predict no such double dissociations (see Joanisse & Seidenberg, 1999; Ullman *et al.,* in press).

### Computation

The proposed model posits that one component is a (structured) associative memory, which is at least partially productive, and that the other is a symbol-processing system. Thus psychological or neural markers of memory and, in particular of associative memory, should be observed with certain morphologically complex forms, but not with others. In contrast, traditional dual-mechanism theories typically predict memory effects for far fewer morphologically complex forms, and do not expect any associative memory effects at all. Associative memory models predict associative memory effects for all morphological transformations.

## Domain Generality

The proposed model posits that stored morphologically complex forms are memorized, as part of the mental lexicon, by the domain-general declarative memory system, which also subserves the learning and use of fact and event knowledge. In contrast, it is posited that morphologically complex forms that are rule products are subserved by the domain-general procedural system, which is hypothesized to underlie the learning and expression of syntactic and other grammatical knowledge, as well as nonlinguistic cognitive and motor skills and habits. Thus the model predicts double dissociations—with one set of associations among stored complex forms, simple lexical forms, and facts and events; and another set of associations among complex forms that are rule products, syntactic computation, and cognitive and motor skills and habits. The associations between stored complex and simple forms, and between rule-computed complex forms and syntax, are expected by at least some traditional dual-mechanism theories. However, no traditional dual-mechanism theories expect the specific associations with nonlinguistic domains. Associative memory models predict none of the specific associations and dissociations, either within language, or between the particular language and nonlanguage domains.

## Localization

The proposed model posits that distinct brain structures subserve each of the two components, with the associative memory depending largely on temporal and temporoparietal regions that underlie declarative memory, and symbol manipulation depending on frontal/basal-ganglia structures that underlie the procedural system. Thus double dissociations are predicted, with irregulars associated with temporal/temporoparietal regions, and regulars associated with left frontal/basal-ganglia structures. These localization predictions are not made by traditional dual-mechanism theories of morphology, although they are consistent with their broad theoretical perspective. The predictions are not consistent with those of any previously proposed single-system models, which do not predict such double dissociations.

## PSYCHOLINGUISTIC AND NEUROLINGUISTIC EVIDENCE

The three competing perspectives can be investigated using a number of different approaches. Here evidence is described from psycholinguistic and neurolinguistic studies. The focus will be on investigations of inflectional morphology and, in particular, of English past tense, because these transformations have been best studied.

## Psycholinguistic Evidence

*Frequency Effects*

Evidence suggests that the more often a word is encountered, the better it is remembered (e.g., Rubenstein, Garfield, & Milliken, 1970). Memorized morphologically complex forms are expected to be frequency sensitive, with high-frequency forms being remembered better than low-frequency forms. Rule products that are constructed from their bases in real-time should show no such "frequency effects" once one controls for access to their memorized stems, to which affixation rules are applied.

Several studies have found frequency effects for irregular but not regular forms, even when controlling for stem access. Stemberger and MacWhinney (1988) examined errors on intended regular and irregular past tense and perfect forms in spontaneous speech. Inflected form frequencies significantly predicted unmarked-form error rates for irregular, but not for regular forms; note, however, that a measure of stem access, such as stem frequency, was not controlled for. Prasada, Pinker, and Snyder (1990) presented adult subjects with a series of verb stems, and asked them to produce the past tense form of each verb as quickly and accurately as possible. Holding stem frequency constant, subjects took significantly more time to produce low- than high-frequency irregular verbs, whereas no significant difference was found between low- and high-frequency regular verbs. Ullman (1993, 1999a) asked adult subjects to give acceptability ratings of past-tense forms of regular and irregular verbs in past-tense sentence contexts and of their stem forms in present-tense sentence contexts. Acceptability ratings of irregular but not regular past-tense forms correlated positively with their past tense frequencies, partialing out (that is, statistically holding constant) stem ratings. Van der Lely and Ullman (in press) found that for 7 and 8 year old children who were asked to produce past tenses in sentence contexts, irregular but not regular past tense response rates were predicted by their frequencies, even when stem familiarity ratings given by the same children were statistically held constant.

Although frequency effects have also been reported for regulars in healthy adults, these data have been problematic in one or more ways. Stemberger and MacWhinney (1988) gave adult subjects a production task of regular past tense forms and found that their error rates were significantly predicted by their frequencies. However, there was no control for any measure of access to the verb stems, such as stem frequency. Because stem- and inflected-form frequencies are highly correlated, these results could be entirely explained by differences in stem frequency. Similarly, although Marchman (1997) reported frequency effects for both regular and irregular

verbs in a past-tense elicitation task given to children, stem access was not controlled for. Moreover, the children in her study were quite young, ranging as low as 3 years 8 months, with a mean of 7 1/2 years. Because Van der Lely and Ullman (in press) found that 6-year-olds, but not 7- or 8-year-olds, showed frequency effects for regulars, it is not unlikely that the children studied by Marchman showed frequency effects for regulars, in part, simply because they were young and, therefore, still relied to a substantial extent on the memory system (see Marcus *et al.*, 1992).

In addition, the stimuli in both the Stemberger and MacWhinney (1988) and the Marchman (1997) studies consisted almost exclusively of "inconsistent" regulars. That is, regulars whose stems are phonologically similar to the stems of one or more irregulars (e.g., *glide–glided;* c.f., *ride–rode, slide–slid*) and, therefore, they and their similar-sounding neighboring stems do not follow a consistent pattern. According to the proposed model, inconsistent regular past tense forms are likely to be memorized; otherwise generalizations computed in associative memory might lead to nonexistent forms like *glid* or *glode,* which, moreover, could block computation of the regular form *glided* (Ullman, 1993, 1999a, unpublished manuscript). Indeed, in the acceptability ratings study of adults described above, whereas "consistent" regulars, whose stems are not phonologically similar to the stems of irregulars, did not yield any frequency effects, inconsistent regulars did show frequency effects, even with stem ratings partialed out (Ullman, 1993, unpublished manuscript). These results support the proposed mental model's claim that regulars *can* be stored, and are indeed stored under certain conditions. The data also demonstrate that the frequency effects for regulars reported by Stemberger and MacWhinney (1988) and by Marchman (1997) may be explained by the fact that most of their regular verb items were inconsistent regulars.

It has been claimed that, because there are many regular verbs and because regulars (especially consistent regulars) follow a consistent pattern, the contribution of phonologically neighboring regulars to a given regular verb's memory traces may largely overwhelm the contribution of each verb's individual past tense frequency, resulting in weakened past-tense frequency effects for regular verbs (Daugherty & Seidenberg, 1992; Seidenberg, 1992). However, the acceptability ratings study of adults described above found not even weakened past-tense frequency effects for regular verbs, whose correlations between ratings and frequency yielded correlation coefficients that were negative or had $p$ values that were not even approaching significance (e.g., $p$ = .468). Therefore, it is unlikely that such an explanation could account for the data.

Thus results from a number of studies converge to indicate that regular forms are not retrieved from associative memory, but rather are rule-products.

In contrast, the computation of irregulars depends upon memorized representations unique to each past tense form. Note that this does not necessarily preclude traditional dual-mechanism claims that irregulars are rule-products whose computation depends upon memorized information linking stem to rule or affix (e.g., Halle & Marantz, 1993): If this memorized link is unique to each stem-past pair, it could lead to the observed frequency effects for irregulars.

## Neighborhood Effects

Single-mechanism associative memory models expect "phonological neighborhood effects" for all inflected forms. That is, the memory traces representing the distributed phonological stem-past mappings shared among "friendly" neighboring irregulars (e.g., *sing–sang*, *ring–rang*, *spring–sprang*) or regulars (e.g., *slip–slipped*, *clip–clipped*, *trip–tripped*) should be strengthened by the learning of any form with these mappings. Thus hearing *sing–sang* should strengthen not only the memory traces unique to *sing–sang*, but also those shared between *sing–sang*, *ring–rang*, and *spring–sprang*. But it is well known that not all neighbors are friendly. "Enemy" neighbors, which have similar stems but dissimilar past forms and therefore dissimilar mappings, weaken each other (e.g., *sing–sang*, *bring–brought*, *wing–winged*) (Daugherty & Seidenberg, 1992; MacWhinney & Leinbach, 1991; Marchman, 1993, 1997; Plunkett & Marchman, 1991, 1993; Rumelhart & McClelland, 1986; Seidenberg, 1992).

If, as is posited by the proposed model, irregulars are computed in an associative memory with distributed phonological representations, whereas regulars are rule-products, then phonological neighborhood effects should be found for irregular but not regular forms. In contrast, if no past tense forms are computed in associative memory (Halle & Mohanan, 1985; Ling & Marinov, 1993), neither regulars nor irregulars should show phonological neighborhood effects of the sort expected with a distributed associative memory.

Several studies have shown neighborhood effects among irregulars, but have failed to demonstrate them among regulars. This contrast has been shown in novel and real verbs. Bybee and Moder (1983) presented subjects with novel verbs in obligatory past tense sentence contexts. The verb stems varied in phonological proximity to the prototypical pattern, which the authors defined for the *i*-^ (e.g., *string–strung*) group of irregular verbs: sCCV[velar nasal]. They found a continuous effect of similarity as a function of proximity to the prototype: The closer a verb stem was to the prototype, the more likely it was to be inflected to the ^-form. Thus *spling* was more likely to be inflected as *splung* than *vin* was as *vun*. Prasada and

Pinker (1993) replicated this finding, but found that subjects were not significantly more likely to produce regularly-suffixed past tense forms of familiar-sounding novel verbs like *plip* than of odd-sounding novel verbs like *ploamph*—even though the subjects rated the stem *ploamph* to be less acceptable than the stem *plip*. The authors found a similar distinction in an acceptability ratings study of irregular-sounding (*splung*) and *-ed*-suffixed (*plipped*) past tense forms of novel verbs: Subjects gave higher ratings to forms like *splung* than *vun*, whereas forms like *plipped* were not given higher ratings than those like *ploamphed,* once the naturalness of their stems was held constant.

These contrasting neighborhood effects for irregulars and regulars have also been found with real verbs. In the acceptability ratings study described above (Ullman, 1993; Ullman, 1999a), ratings of irregular but not regular verbs correlated, partialing out stem ratings and past tense frequency, with a neighborhood-contribution measure which took into account the number of friends and enemies, the phonological similarity of their stems and past tenses, and their individual form frequencies.

These data, showing neighborhood effects for irregulars but not regulars, with both novel and real verbs, are not consistent with either traditional dual-mechanism or single-mechanism models. Traditional dual-mechanism models are not consistent with the prototype effects found with novel verbs or the frequency- and similarity-sensitive neighborhood effects found with real verbs. In contrast, single-mechanism models have not adequately explained the lack of any regular verb neighborhood effects in all of these studies.

## Neurolinguistic Evidence

### Lesion Studies: Aphasia

Several studies have reported that non-fluent aphasics with left anterior damage and agrammatism (grammatical impairments) are worse at producing (Ullman, Corkin *et al.*, 1997; Ullman *et al.*, 1994; Ullman *et al.*, in press) reading (Badecker & Caramazza, 1987; Badecker & Caramazza, 1991; Marin, Saffran, & Schwartz, 1976; Ullman, Corkin *et al.*, 1997; Ullman, Hickock, & Pinker, 1995; Ullman *et al.*, in press) and judging (Ullman *et al.*, in press) regular than irregular English past tense forms. In contrast, fluent aphasics with left posterior damage and anomia (word-finding problems) have been found to show the opposite pattern in past tense production (Ullman, Corkin *et al.*, 1997; Ullman *et al.*, 1994; Ullman *et al.*, in press), reading (Ullman *et al.*, in press), and judgment (Ullman *et al.*, in press. These double dissociations suggest that regular and irregular past tense computation depend on distinct neural underpinnings. They also link

the computation of regulars to left anterior structures and to grammar, and the computation of irregulars to left posterior regions and to the lexicon.

It has also been shown that whereas some aphasics show priming between past tense and stem forms for regulars (e.g., *jumped* primes *jump*), but not for irregulars (e.g., *gave* does not prime *give*), other aphasics show the opposite pattern (Marslen-Wilson & Tyler, 1997). Although the large lesions in this study preclude making claims about neuroanatomical localization, the results further support the existence of distinct neural underpinnings for the computation of the two past tense types.

## Lesion Studies: Neurodegenerative Disease

Studies of adults with degenerative brain disease have revealed double dissociations between the production of irregularly and regularly inflected forms, and have linked irregulars to memorized words and facts and to temporal lobe regions, and regulars to syntax and motor skill function and to frontal/basal-ganglia structures (Ullman, in press; Ullman, Corkin *et al.,* 1997; Ullman *et al.,* 1993, 1994).

Alzheimer's disease (AD) is associated with severe degeneration of temporal and temporoparietal regions, and relative sparing of the basal ganglia and frontal cortical regions, particularly Broca's area (e.g., see Arnold *et al.,* 1991). The temporal and temporoparietal damage may explain AD impairments at retrieving and recognizing words (Grossman *et al.,* 1998; Nebes, 1989). In contrast, the majority of studies suggest that AD patients are relatively unimpaired at syntactic processing—in spontaneous speech (Appell, Kertesz, & Fisman, 1982; Bayles, 1982; Hier, Hagenlocker, & Shindler, 1985; Kempler, Curtiss, & Jackson, 1987; Murdoch, Chenery, Wilks, & Boyle, 1987; Nicholas, Obler, Albert, & Helm-Estabrooks, 1985; Price *et al.,* 1993), elicited sentence production (Schwartz, Marin, & Saffran, 1979), sentence comprehension (Rochon, Waters, & Caplan, 1994; Schwartz *et al.,* 1979; Waters, Caplan, & Rochon, 1995), and identification or correction of errors (Cushman & Caine, 1987; Whitaker, 1976); similar contrasts have also been shown in French (Irigaray, 1973; see Obler, 1981). AD patients are also relatively spared at performing motor and cognitive skills (Beatty *et al.*, 1988, 1994).

In studies of English regular and irregular past tense, AD patients with severe deficits at object naming or fact retrieval have been shown to make more errors producing past tenses of irregulars than of regulars or -*ed*-suffixed novel verbs. Moreover, across AD patients, error rates at object naming and at fact retrieval correlate with error rates at producing irregular but not regular or -*ed*-suffixed novel past tenses (Ullman, in press; Ullman, Corkin *et al.*, 1997; Ullman *et al.*, 1994; Ullman *et al.*, 1993). Similarly,

Cappa and Ullman (1998) reported that Italian AD patients had more difficulty producing irregular than regular present tense and past participle forms in Italian.

Parkinson's disease (PD) is associated with the degeneration of dopaminergic neurons in the basal ganglia, causing high levels of inhibition in the motor and other frontal cortical areas to which the basal ganglia circuits project. This is thought to explain why PD patients show the suppression of motor activity (hypokinesia) and have difficulty expressing motor sequences (Dubois *et al.,* 1991; Willingham, 1998; Young & Penney, 1993). PD patients may also have difficulty with grammar, both in comprehension (Grossman, Carvell, Gollomp *et al.,* 1993; Grossman *et al.,* 1991; Grossman, Carvell, Stern, Gollomp, & Hurtig, 1992; Lieberman, Friedman, & Feldman, 1990; Lieberman *et al.,* 1992; Natsopoulos *et al.,* 1991) and production (Grossman, Carvell, & Peltzer, 1993; Illes, Metter, Hanson, & Iritani, 1988). In contrast, temporal lobe regions remain relatively undamaged and the recognition of words and facts remains relatively intact in low- or nondemented PD patients (Dubois *et al.,* 1991).

In investigations of the PD production of regular and irregular past-tense forms, it was found that severely hypokinetic PD patients showed a pattern opposite to that found among the AD patients, making more errors producing regular and -*ed*-suffixed novel past-tenses than irregular past-tenses. Moreover, across PD patients, the level of right-side hypokinesia, which reflects left basal ganglia degeneration, correlated with error rates at the production of regular and -*ed*-suffixed novel forms, but not irregular forms. Intriguingly, left-side hypokinesia, which reflects right basal ganglia degeneration, did not show the analogous correlations with error rates in the production of any past-tense type, underscoring the role of left frontal/ basal-ganglia structures in grammatical rule use (Ullman, in press; Ullman, Corkin *et al.,* 1997; Ullman *et al.,* 1993, 1994).

Patients with Huntington's disease (HD) show the opposite pattern to that of PD patients. Although HD is like PD in causing degeneration of the basal ganglia, it strikes different portions of these structures. Unlike in PD, this damage results in the disinhibition of frontal areas receiving basal ganglia projections. This is thought to lead to the unsuppressible movements (chorea, a type of hyperkinesia) found in patients with HD. Patients with HD show the opposite pattern to those with PD, not only in the type of movement impairment (the suppressed movements of hypokinesia vs. the unsuppressed movements of hyperkinesia), but also in the type of errors on -*ed*-suffixed forms (Ullman, in press; Ullman, Corkin, *et al.*, 1997; Ullman *et al.*, 1993, 1994). HD patients produce forms like *walkeded, plaggeded,* and *dugged*—but not analogous errors on irregulars like *keptet,* suggesting that the errors are not attributable to articulatory or motor deficits. Rather

the data suggest unsuppressed *-ed* suffixation. This conclusion is strengthened by the finding that the production rate of these oversuffixed forms correlates with the degree of chorea across patients. These contrasting findings in PD and HD, linking movement and *-ed* suffixation in two distinct types of impairments related to two types of basal ganglia damage, strongly implicate frontal/basal-ganglia structures in *-ed* suffixation. They also support the hypothesis that these structures underlie the expression of grammatical rules as well as movement and suggest that the structures play a similar role in the two domains.

## Developmental Disorders

Specific Language Impairment (SLI) refers to a developmental disorder of language, supposedly in the absence of other cognitive impairments (Bishop, 1992; Leonard, 1998). In recent studies, two groups of subjects with hereditary SLI and with syntactic processing deficits failed to produce novel regular forms and over-regularizations (*plam-plammed, dig-digged*), suggesting that they were unable to use the past tense suffix productively. Intriguingly, they also showed frequency effects for *regular* as well as irregular past tense forms—whereas control subjects yield frequency effects only for irregulars. This suggests that these subjects had difficulty learning grammatical rules, and were therefore forced to memorize regular as well as irregular forms (Ullman & Gopnik, 1994; Ullman & Gopnik, 1999; van der Lely & Ullman, 1996; van der Lely & Ullman, in press). Intriguingly, the subjects in one of the two SLI groups also had motor sequencing impairments (Hurst, Baraister, Auger, Graham, & Norell, 1990; Vargha-Khadem, Watkins, Alcock, Fletcher, & Passingham, 1995) and showed abnormalities in frontal and basal ganglia structures (Vargha-Khadem *et al.*, 1998). These findings have led to the proposal that the impaired members of this group suffer from a procedural system deficit that affects grammatical as well as motor function, but leaves declarative/lexical memory relatively intact (Ullman & Gopnik, 1999).

People with the hereditary developmental disorder of Williams syndrome may have spared syntactic abilities, but abnormal lexical retrieval (Bellugi, Bihrle, Jernigan, Trauner, & Doherty, 1990; Clahsen & Almazan, 1998). It has been shown that children and young adults with the disorder have more difficulty producing irregular than regular past tenses (*dug* vs. *looked*) and plurals (*mice* vs. *rats*), with over-regularizations (*digged*, *mouses*) constituting the majority of their errors (Bromberg et al., 1994; Clahsen & Almazan, 1998). These results dissociate irregulars from regulars, and link irregulars to lexical memory, and regulars to syntactic abilities.

*Electroencephalography*

Two Event-Related Potential (ERP) studies of German inflection and one of Italian inflection have recently been reported (Gross, Say, Kleingers, Münte, & Clahsen, 1998; Penke *et al.,* 1997; Weyerts, Penke, Dohrn, Clahsen, & Münte, 1997). In all three studies, default ("regular") and unproductive nondefault ("irregular") items yielded distinct difference waves for incorrectly versus correctly inflected forms. These results were taken to suggest that affixation and lexically based inflection are subserved by distinct brain structures (Clahsen, 1999). However, this conclusion is problematic in certain respects (see Ullman, 1999b). In two of the studies, of German and Italian past-participle inflection, only the irregulars yielded large difference waves. The absence of substantial difference waves for regulars is consistent not only with dual-mechanism models, but also with single-mechanism models that posit that regulars and irregulars are computed by the same neural processes, but that incorrect irregulars are particularly difficult to process.

The German plural study yielded the most convincing results. Incorrect irregulars yielded a left anterior negativity (LAN), which has independently been linked to grammatical processing and left frontal structure (Friederici, Hahne, & von Cramon, 1998). In contrast, incorrect regulars produced an N400, a central negativity that has independently been linked to lexical-conceptual processing and left temporal lobe structures (see Hagoort & Kutas, 1995). As in the other two ERP studies, the incorrect regulars were irregularized (—*n*-suffixed) forms and the incorrect irregulars were regularized (—*s*-suffixed) forms. Clahsen (1999) suggests that the LAN reflects grammatical processes of affixation, whereas the N400 may be tied to lexical processing. Although this is an exciting possibility, the violations of regulars and irregulars confound lexical and grammatical processes. The presentation of an over-regularization such as *mouses* involves a violation of the lexical expectancy of *mice* as well as an incorrect application of the suffixation rule, making it impossible to link the LAN to either lexical or grammatical processing. Similarly, irregularizations of regulars involve both a grammatical violation—a failure of the rule to apply—and the formation of an unexpected irregular-like novel, again making an unambiguous interpretation of the observed N400 impossible. Thus, this ERP study is important in that it suggests a neurophysiological dissociation between the processing of regulars and irregulars, but stops short of linking either regular or irregular transformations to electrophysiological patterns that are independently associated with grammatical or lexical-semantic processing.

In an ERP study of regular and irregular English past tense morphology, regulars and irregulars were presented in past-tense sentence contexts,

either correctly as past-tense forms (e.g., Yesterday I *dug* a hole), or incorrectly as stem forms (e.g., Yesterday I *walk* after lunch). In comparisons to ERP waves of correctly inflected forms, incorrect regulars (i.e., an illicit absence of past-tense affixation) yielded a LAN, whereas incorrect irregulars (i.e., an illicit absence of a memorized past-tense form) yielded a more central distribution (Newman, Neville, & Ullman, 1998). In a second study, designed to directly compare regular/irregular morphology and syntax/lexical-semantics, subjects viewed sentences with and without violations of syntactic phrase structure and lexical-semantics (after Neville, Nicol, Barss, Foster, & Garrett, 1991), as well as correctly/incorrectly presented regulars and irregulars. Violations of regular verb inflection and syntactic phrase structure yielded LANs, whereas the waveforms yielded by the incorrect irregulars and the lexical-semantic anomalies had more posterior distributions (Newman, Izvorski, Davis, Neville, & Ullman, 1999) that have been argued to be N400s (Ullman, Newman, Izvorski, & Neville, 2000). These results dissociate regular and irregular morphology, link regular morphology to syntax and left frontal structures, and strengthen the ties among irregulars, lexical and conceptual processing, and temporal lobe structures.

## Neuroimaging: PET and fMRI

Jaeger *et al.,* (1996) reported a PET study of English past tense. Healthy English-speaking men were asked to read out loud lists of irregular, regular, and novel verb stems and to produce their past-tense forms. In the comparison between brain activation levels of past-tense production and verb-stem reading, left temporal and temporoparietal regions were associated with greater statistical significance for irregular than regular or novel verbs, whereas a left prefrontal region was associated with greater statistical significance for regular and novel verbs. Unfortunately, this contrast is problematic in several respects. First, the pattern was not found when past-tense production conditions were compared to a rest condition. Second, activation differences found from the comparison of two conditions can result from an increase in one condition or a decrease in the other, compared to a reference condition; in the absence of examination of activation decreases, these cannot be distinguished. Third, the blocking of large numbers of items required by PET might allow subjects to use a strategy to produce the regulars, all of which undergo -*ed* suffixation, but not the irregulars, which require various stem-past transformations. For additional comments on this study, see Seidenberg and Hoeffner (1998).

In a PET study of German verbal inflection, healthy German-speaking subjects were asked to produce past-tense and past-participle forms of regular and irregular German verbs (Indefrey *et al.,* 1997). Sentences requiring

past tenses and those requiring past participles were randomized within scans to avoid response strategies. Between scans, verbs were varied with respect to regularity. In direct comparisons of the regular and irregular conditions, ten cortical areas yielded more signal for irregulars than for regulars, including left and right frontal regions, and left temporal cortex. Two cortical areas showed more signal for regulars than for irregulars: right inferior temporal gyrus and left angular gyrus. Thus different patterns were observed in the irregular and regular verb conditions. The authors concluded that the "stronger cortical activation for irregular verbs and little overlap in activation for regular and irregular verbs are easier to reconcile with dual-process models." Their finding that activation increases in the left dorsolateral prefrontal cortex are more strongly associated with irregular inflection than with regular inflection appears to be at variance with the claims of the declarative/procedural model. However, Indefrey et al. (1997) did not include activation decreases, compared to a reference condition, in their report. As described above, in the absence of an examination of activation decreases, a difference between two task conditions could be attributed to either an increase in one condition or a decrease in the other.

English past tense has also been investigated with fMRI (Bergida, O'Craven, Savoy, & Ullman, 1998; Ullman, Bergida, & O'Craven, 1997). Healthy adults were shown the stems of irregular (e.g., *sleep*) and regular (e.g., *slip*) verbs on a screen and were asked to silently produce their past-tense forms. In left frontal cortex, irregulars yielded a greater activation increase than regulars, whereas regulars yielded a greater decrease, compared to the fixation condition. The opposite pattern was found in left and right temporal lobe regions, where regulars yielded a greater increase than irregulars, while irregulars yielded a greater decrease, compared to fixation. Although the specific causes of these activation changes remain to be investigated, the contrasting patterns of activation suggest that irregulars and regulars have distinct neural underpinnings linked to temporal and frontal regions. Note however, that the blocking (albeit with few items) of regular and irregular verbs suggests caution in interpreting the results.

## *Magnetoencephalography (MEG)*

Magnetoencephalography (MEG) provides a method to investigate the real-time spatiotemporal dynamics associated with the production of regular and irregular past-tense forms. Rhee, Pinker, and Ullman (1999) recorded from a whole-head 64-channel magnetometer while subjects produced past tenses of regular and irregular verbs. Satisfactory solutions to the inverse problem of dipole fitting for data averaged over all subjects were found at a number of 10 msec time slices following stimulus presentation. No right-

hemisphere dipoles were found. Dipoles in both the regular and irregular verb conditions were localized to a single left temporal/parietal region (250 to 310 msec). Dipoles in left frontal regions were found only for regular verbs and only for time slices immediately following the left temporal/parietal dipoles (310–330 msec). The results are consistent with a dual-system model in which temporal/ parietal-based memory is searched for an irregular form, whose successful retrieval blocks the application of a frontal-based suffixation rule (Ullman, Corkin *et al.,* 1997).

## CONCLUSION

The Declarative/Procedural model of lexicon and grammar was presented, and was discussed in detail in the domain of morphology. In this domain, it was compared to the two main competing theoretical frameworks—traditional dual-system and single-system models. Evidence from multiple psycholinguistic and neurolinguistic approaches was examined to tease apart the three models. I have argued that this evidence supports the Declarative/Procedural model of language.

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