

The science of language¹

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Abstract

The study of language is currently fractionated. Theoretical linguistics has largely ignored advances in psycholinguistics, which in turn remains largely unconstrained by advances in neurolinguistics. Moreover, all of these fields generally work in isolation from the study of other cognitive functions. This fractionation has resulted in an enormous loss of useful information, seriously impeding progress in the study of language. To achieve a fully coherent explanation of the representational, processing and biological bases of language, a true science of language will consider and integrate theories and methods from all disciplines of the mind and brain. Here we explore in some detail the utility of this approach in the study of the linguistic distinction between storage and computation, and demonstrate its effectiveness not only in elucidating previously unresolved problems, but also in generating new approaches and insights in the study of language.

1. The study of language

The cognitive revolution that began about 50 years ago called for a synergistic integration of the various disciplines that examine the mind and brain, including psychology, neuroscience, theoretical linguistics, computer science, and philosophy (e.g., see Gardner 1985). Since then, enormous progress has been

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made in the study of the mind and brain. Language has certainly been among the beneficiaries of this new science of the mind. Numerous empirical discoveries and theoretical insights have been achieved within each of the disciplines investigating language, ranging from theoretical linguistics to cognitive psychology (psycholinguistics) to cognitive neuroscience (neurolinguistics).

Nevertheless, what has *not* emerged is a true science of language. First, each discipline has largely focused on those particular issues that it has considered to be both theoretically relevant and methodologically tractable. Second, where there have been interactions between the disciplines, a striking asymmetry has emerged. Linguistic theory has almost exclusively examined issues pertaining to the underlying architecture of language, and has largely disregarded psychological and neural theories and evidence. Psycholinguistics has focused on real-time processing, and to a lesser extent on representation. While psycholinguistic theories have attempted to explain psycholinguistic phenomena within the constraints of both psychological and linguistic principles, they have largely ignored constraints from neuroscience. Neurolinguistics, meanwhile, has traditionally examined problems from both theoretical linguistics and psycholinguistics in the context of issues such as neuroanatomical localization. This asymmetry among the three disciplines has led to an important loss of information in the study of language, with crucial theoretical and empirical findings failing to constrain our broader understanding of this cognitive capacity.

This disciplinary asymmetry has to a large extent been justified in terms of another tenet of the cognitive revolution, namely the importance of *levels of explanation* or representation. On this view, a given phenomenon is best accounted for at a particular level of explanation that is largely independent from other levels. For example, representational accounts of language should not “care” how language is processed in the mind, or how it is instantiated in the brain. Conversely, the brain is not taken to seriously constrain representational or even processing accounts.

We believe that this separatist approach has significantly stymied advances in our understanding of language, and that a new conception in the study of this cognitive capacity is called for. Language should be investigated not so much as an interdisciplinary exercise, but rather as a single enterprise that incorporates theoretical and methodological approaches both *across and within* disciplines, including neuroscience, psychology, and theoretical linguistics.

First, theories and data from *across* all of these disciplines must be taken into account. Most issues – even if they are primarily concerned with representation, or with processing or neural correlates – can and should be informed by data obtained with methodologies from across theoretical linguistics, cognitive psychology and cognitive neuroscience. All such data must moreover be interpreted in light of all relevant language theories from *all* of these disciplines,

each of which is likely to crucially inform the issue at hand, albeit potentially in different ways. The scientific method of hypothesis testing, in the context of competing theories of language, with the potential for falsification, is critical. Note that we are *not* suggesting that all aspects of representation, processing, and neural correlates can be reduced to a single level of explanation. Although one *can* examine these independently, doing so excludes information that is likely to provide important constraints on our understanding of language.

Second, wide-ranging contributions from *within* disciplines, in particular neuroscience and psychology, are also critical. Partially due to the widely-held assumption that language is subserved by domain-specific cognitive and neural mechanisms, it has been investigated largely in a vacuum. Researchers of language have generally not attempted to examine implications for language from data and theories taken from other cognitive domains. However, increasing evidence from cognitive psychology and especially from neuroscience suggests the existence of shared neurocognitive correlates for language and non-language functions, including memory, attention, motor function and even vision (Gathercole and Baddeley 1993; Ullman et al. 1997; Ullman 2001c; Friederici 2002; Hauser et al. 2002; Hickok and Poeppel 2004; Ullman 2004).

Importantly, the acknowledgement of such shared neurocognitive substrates is expected to lead to entirely new directions in the study of language. Theories and data from other cognitive domains are likely to generate *novel* predictions about language that would be far less likely to be entertained in the isolated study of language alone. Because neurocognitive substrates often work similarly across the different domains they subserve (Gathercole and Baddeley 1993; Ullman et al. 1997; Middleton and Strick 2000; Friederici 2002; Hickok and Poeppel 2004; Ullman 2004), discoveries in one domain may very well be applicable in another. Importantly, unlike language, other domains are routinely investigated not only in humans, but also in animal models. Animal research allows for highly invasive techniques that have led to a far deeper understanding of particular aspects of non-language domains than has been possible in language. Thus our knowledge of the genetic, molecular, pharmacological, endocrine, cellular and anatomical bases of a number of non-language functions far outstrips our knowledge of these aspects of language. Of course, as in all work with animal models, it is always necessary for animal research to be followed up with human research. In the case of language, this would presumably take place in two steps, with predictions from animal models examined first in humans in the same non-language domain, and then in the language functions hypothesized to depend on the same neurocognitive substrates.

2. Storage versus computation

In this section we examine the issues and ideas laid out above, in the specific context of the fundamental distinction in language between storage and computation. First, we provide a brief overview of this distinction in contemporary *theoretical linguistics*. We compare the perspectives of a number of competing theoretical frameworks, focusing on one syntactic distinction (control versus raising predicates). We argue that, despite important theoretical linguistic advances in understanding this phenomenon, critical aspects of the distinction remain unsolved, and may crucially benefit from the contributions of neurocognitive theories and data. Second, we present a specific *neurocognitive* theory of the storage/computation distinction, and show how it may bring new insights into this and other issues.

2.1. Storage versus computation in linguistic theory

All linguistic frameworks accept some sort of distinction between storage and computation. However, frameworks vary considerably with respect to the amount of work done by each, with aspects of a particular analysis treated as lexical in one framework but grammatical in another. (Here we use the term “lexical” to indicate storage in the lexicon, and “grammatical” to refer to rule- or constraint-based composition.) In the Minimalist Program and its predecessors the grammar plays a large explanatory role in analysis, with a relatively reduced role for the lexicon (Chomsky 1965, 1981, 1986, 1995). Many other theories, such as Lexical-Functional Grammar (LFG; Bresnan 2001) and Head-driven Phrase Structure Grammar (HPSG; Sag and Wasow 1999), allow for considerably richer lexical representations, with a correspondingly reduced role for grammar. Other theories posit an even greater role for the lexicon. Construction Grammar assumes that the lexicon contains not just arbitrary word-specific knowledge, but also complex linguistic structures (Fillmore et al. 1988; Croft 2001). Cognitive Grammar posits redundant representations, with complex structures capable of being both stored *and* computed (Langacker 1987). Langacker points out, we believe correctly, that one type of representation does not necessarily preclude another. He refers to the common linguistic theoretical assumption that representational types are mutually exclusive as the “exclusionary fallacy” (Langacker 1987).

Cross-framework differences in the division of labor between lexicon and grammar can be seen in the contrast between infinitives that are arguments of either (1) control predicates (e.g., *try*), or (2) raising predicates (e.g., *chance*).

- (1) *The nurse tried to win the lottery.*

(2) *The nurse chanced to win the lottery.*

The linguistic evidence distinguishing these constructions is well known (Rosenbaum 1967; Postal 1974; Rudanko 1989; Walenski 2002), and boils down to the generalization that a control verb like *try* assigns a semantic role² to its grammatical subject (*nurse*), while a raising verb like *chance* does not. Thus the basic difference between control and raising predicates can be described as an argument structure difference, or alternatively in terms of semantic differences between verbs (Langacker 1995). All of the frameworks mentioned above encode this distinction in the lexicon. However, the *selection* of the logical subject of the infinitive (hereafter referred to as the *controller*;³ e.g., in the examples above, the potential or actual entity that does the winning) is treated quite differently in different frameworks, with a bias towards a dependence on either the grammar or the lexicon.

Perhaps the best-known grammar-biased approach is that of Principles and Parameters theory, which claims that there are different types of empty category in a subordinate subject position (Chomsky 1981, 1986). On this view, the infinitive is treated as either an IP (following a raising verb), with NP-trace in the subordinate subject position ([spec, IP]), or as a CP (following a control verb), with PRO in the subordinate subject position. In both cases, the empty category (NP-trace, PRO) is co-indexed with the controller (e.g., *nurse*). These indices receive their values on the basis of movement operations for raising, and from the putative control module for control. Thus there are structural differences (IP vs. CP; NP-trace vs. PRO; co-indexation mechanism) in addition to (and motivated by) the lexical argument structure difference.

Within the Minimalist program (Chomsky 1995), a more recent grammar-biased approach argues that the lexically based argument structure difference between control and raising verbs results in a distinct number of θ -role features that need to be checked (via movement) for the two constructions (Hornstein 1999). On this view, the identity of the controller depends on which NP moves to check the features of the infinitive, and is thus a function of the grammar.

Approaches biased towards the lexicon include both LFG and HPSG. In LFG, both a verb's argument structure *and* a rule identifying the controller are stored in that verb's lexical entry, though the controller is actually linked to the external argument of the infinitive at an abstract level of grammatical structure (F-structure) (Bresnan 1982). In HPSG, the determination of the controller is a function of lexically defined predicate types that feed into grammat-

2. The characterization of semantic role assignment in this statement is intended to be theory-neutral, without supporting any particular view of semantic or thematic roles.

3. *Controller* is chosen as a convenient cover term for the logical subject of the infinitive in both raising and control constructions, and is not meant to imply any theoretical claim or to endorse any particular analysis.

ical processes of feature unification (Sag and Wasow 1999). Thus, as in LFG, controller selection is lexically determined, while the process of linking the controller to the infinitive is a function of the grammar. (For a fuller treatment of each of these analyses, also see Walenski 2002).

Thus all of these linguistic accounts of control and raising (and presumably any other accounts as well) posit *both* a lexically-based distinction between different types of verbs (i.e., in terms of argument structure or semantics) *and* a grammatical process of linking the controller to the external argument of the infinitive. These properties of control and raising clearly follow from the linguistic evidence (see Walenski 2002). Although the particular details of these processes differ across frameworks (e.g., co-indexation, movement, application of lexical rule at F-structure, or unification), such particulars depend largely on theory-internal assumptions, and may be at least partially reducible to notational variants. In contrast, the mechanisms by which the controller is selected vary *substantively* among frameworks. In a particular framework, these mechanisms are treated as either lexical (lexical rules, lexical types) or grammatical (co-indexation, movement, feature-checking), but not both. Therefore, whereas the different theoretical frameworks largely converge with respect to both the linking process and the lexical distinction between verbs, there has been a clear lack of agreement regarding the processes underlying controller selection. This suggests that the problem of controller selection might not be resolvable on linguistic grounds alone, and thus may benefit particularly from other disciplines.

We believe that neurocognitive theory and evidence are likely to elucidate this issue. Although psycholinguistic and neurolinguistic studies of control and raising are still in their infancy, they have already provided evidence for distinct lexical (argument structure) and grammatical (linking the infinitive to its controller) processes during real-time comprehension (Featherston et al. 1998; Walenski 2002), consistent with the fundamental distinctions and processes agreed upon on linguistic grounds. With respect to controller selection, psycholinguistic studies suggest *redundant* strategies, with both a grammatical default (i.e., choose the direct object as controller) and verb-specific lexical information (i.e., whether a verb is subject control or object control) contributing to the identification of a controller (Sakamoto 1996; Sakamoto and Walenski 1998). The data suggest that the default operates in the absence of information from the lexicon, and is either overridden or confirmed when this information becomes available. This may be consistent with a form of the Elsewhere principle; for additional discussion, see below.

The distinction between control and raising predicates is only one instance of an unresolved issue in the study of language that is likely to benefit greatly from neurocognitive theory and data. Our understanding of a wide range of problems, from phonology to morphology to syntax, has profited from neural and cognitive studies (Gathercole and Baddeley 1993; Ullman 2001c; Friederici

2002; Hickok and Poeppel 2004; Ullman 2004). For example, the last decade or so has witnessed the emergence of a true synergistic integrative research program in the investigation of certain aspects of morphology, which have been increasingly elucidated by studies of their representational, computational, processing, anatomical, electrophysiological, endocrine, and genetic bases, as well as by a wide range of studies of developmental and adult-onset brain disorders and of second language (Ullman et al. 1997; Marslen-Wilson and Tyler 1998; Clahsen 1999; Pinker 1999; Ganger et al. 2000; Broveto and Ullman 2001; Ullman 2001c; Estabrooke et al. 2002; McClelland and Patterson 2002; Pinker and Ullman 2002; Ullman et al. 2002; Bird et al. 2003; Estabrooke et al. 2004; Ullman 2004; Clahsen and Felser in press; Ullman et al. in press). Below we discuss some of these data and their implications for our understanding of language.

2.2. *A neurocognitive perspective of storage and computation*

Neurocognitive studies of language suggest that this capacity is subserved by multiple functionally and biologically distinct memory systems in the brain that also subserve non-linguistic functions and processing (Gathercole and Baddeley 1993; Ullman 2001c, 2004). Here we focus on two memory systems: *declarative* and *procedural* memory. Evidence suggests that these two systems underlie lexicon and grammar, respectively (Ullman et al. 1997; Ullman 2001a, 2001c, 2004). The inter-disciplinary study of both the language and non-language functions of these memory systems has provided and is likely to continue to provide important data and theoretical explanations that inform and constrain our understanding of language (Ullman 2004). The major characteristics of these memory systems are summarized in Table 1.

The declarative memory system subserves the learning, representation, and use of knowledge about facts (“semantic memory”; e.g., *Paris is the capital of France*), and personal, contextually bound events (“episodic memory”; e.g., *I had fish for dinner last night*) (Squire 1994; Eichenbaum and Cohen 2001). Declarative memory is particularly important for the contextual/associative binding of arbitrarily related pieces of information, and allows for the rapid learning of new associations. Knowledge learned in declarative memory seems to be generally, but not necessarily, retrieved explicitly, i.e., “consciously” (Chun 2000; Tulving 2000). Learning in declarative memory depends primarily on the hippocampus and surrounding medial temporal lobe structures. These are connected extensively to temporal and parietal neocortical regions, where declarative knowledge eventually comes to largely reside (Suzuki and Amaral 1994; Damasio et al. 1996; Martin et al. 2000; Eichenbaum and Cohen 2001). Declarative memory seems to be modulated by estrogen, and depends particu-

Table 1. Overview of the functional and biological bases of the declarative and procedural memory systems.

	Memory systems	
	Declarative memory	Procedural memory
Specialized for learning:	Arbitrary associations	Sequences
Learning speed:	Fast	Gradual, incremental
Learned knowledge is consciously accessible?	Typically, but not necessarily	No
Non-language functions:	Learning and use of fact and event knowledge	Learning and use of motor and cognitive skills
Language functions:	Acquisition, representation and processing of lexical knowledge, including memorized complex forms; conceptual semantics	Acquisition, representation and processing of complex structures, across syntax, morphology, and possibly phonology and compositional semantics
Important brain structures:		
Subcortical/Medial:	Hippocampus	Basal ganglia
Neocortical:	Mainly temporal lobe regions	Mainly frontal lobe regions, especially premotor and associated cortex, including posterior Broca's area
Hormones and neurotransmitters:	Estrogen; Acetylcholine	Dopamine

larly on the neurotransmitter acetylcholine (Sherwin 1988; Packard 1998; Ullman 2004).

In the domain of language, declarative memory underlies the lexicon (Ullman et al. 1997; Ullman 2001c, 2004). Lexical/declarative memory contains all idiosyncratic word-specific information, as in traditional linguistic approaches (Bloomfield 1933; Chomsky 1965). It also contains representations of complex structured expressions with non-transparent meanings, such as idioms

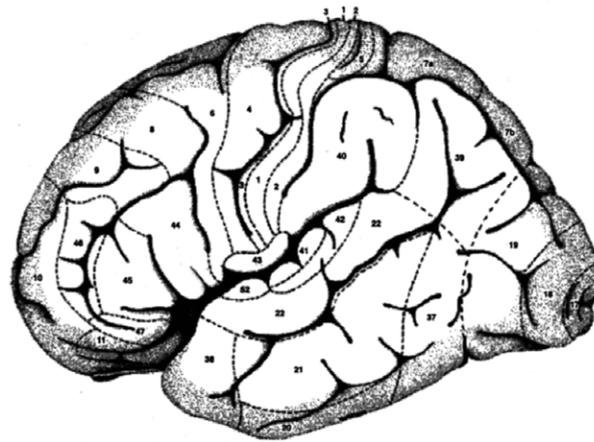
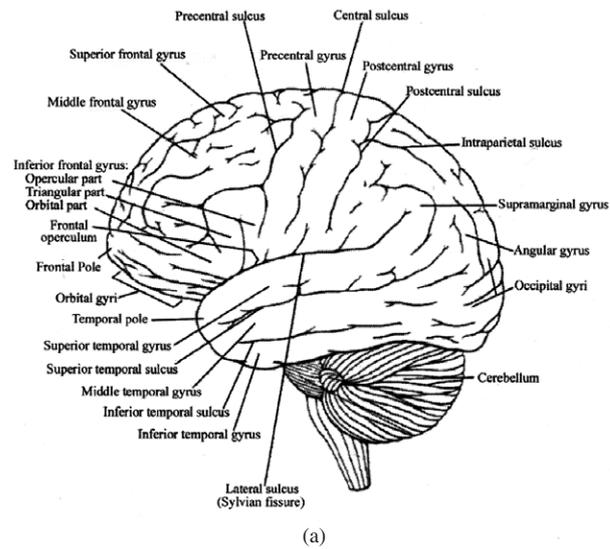


Figure 1. Regions and structures of the brain: (a) Cortical regions, including gyri and sulci. The frontal lobe lies anterior to the central sulcus, above the lateral sulcus. The temporal lobe lies below the lateral sulcus, going back to the occipital lobe at the back of the brain. The parietal lobe lies behind the central sulcus above the temporal lobe. (b) Brodmann's areas, which correspond to areas with different cellular architecture (eg, different cell types and densities).

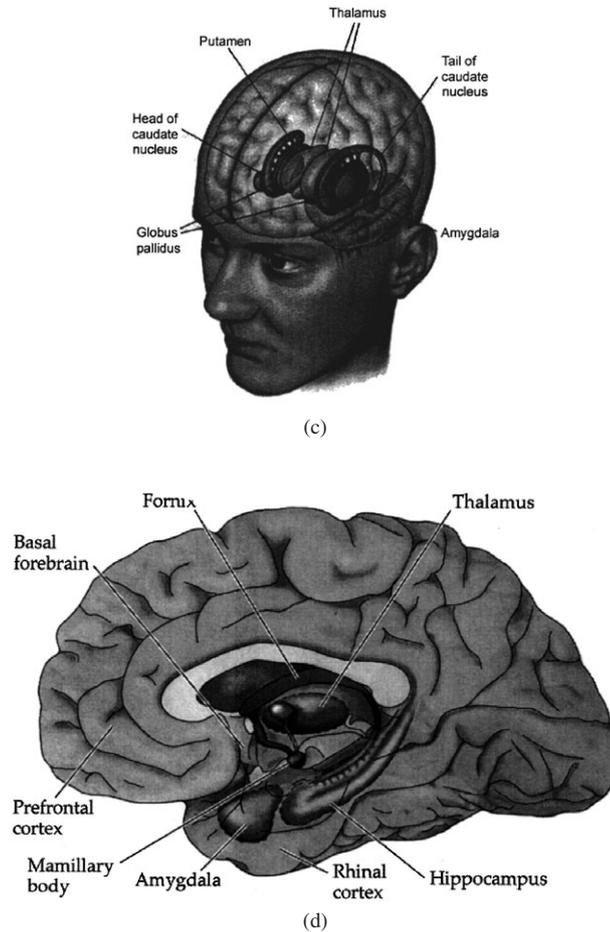


Figure 1 cont. (c) The basal ganglia, which consist of several structures, of which the caudate, putamen, and globus pallidus are indicated here. (d) The hippocampus, together with other structures it is closely connected to.

(Pinker and Ullman 2002; Ullman and Walenski 2005). In addition, transparent and predictably structured complex forms (e.g., *walked, the cat*) that might be expected to be a function solely of morphological or syntactic computation (at least in certain linguistic approaches), can *also* be memorized in the lexicon (potentially with specification of their internal structure), resulting in the possibility for redundant (stored versus computed) representations for certain forms. This is in essence somewhat similar to suggestions that the output of

word formation rules in morphology are stored in the lexicon (Aronoff 1976). However, studies of inflectional morphology have found that the memorization of such complex forms is not all or nothing. The reliance on memorized versus computed representations seems to depend on multiple item-, task- and subject-specific factors, including the forms' frequency of use, whether the language was learned in childhood or after puberty, and even an individual's sex or current hormonal status (Alegre and Gordon 1999; Ullman 2001b; Pinker and Ullman 2002; Estabrooke et al. 2004; Ullman 2004, in press; Ullman et al. 2003). It is not yet clear what the limitations are on the size or complexity of these complex linguistic "chunks", or precisely how their internal structure may be represented (i.e., similar to what has been proposed in various linguistic accounts, or something else entirely).

In addition to these purely storage-related functions, evidence suggests that the lexicon subserves a limited amount of associative-based computation (Pinker 1999; Pinker and Ullman 2002). Novel forms can be computed by generalizing patterns on the basis of already-memorized forms. For example, *splang* can be generated as the past-tense of the novel verb *spling* by generalizing over memory traces of the previously-learned *sing-sang*, *spring-sprang*, and *ring-rang* (Bybee and Slobin 1982; Prasada and Pinker 1993; Pinker 1999; Pinker and Ullman 2002). It is not clear to what extent this associative generalization may also subserve the creation of other complex forms, such as over-regularizations like *digged* (Hartshorne and Ullman 2004) or even syntactic structures (Ullman in press). Note however that any such computation in lexical/declarative memory is a qualitatively different beast from the compositional computations that are subserved by the grammatical/procedural system, and are likely to be inadequate for important aspects of grammar (see below and Ullman in press, to appear). This issue awaits further study.

The procedural memory system subserves the learning and control of motor and cognitive "skills" or "habits" (Squire 1994; Eichenbaum and Cohen 2001), and may be particularly important for acquiring and performing skills involving sequences (Graybiel 1995; Willingham 1998). Learning in procedural memory appears to be gradual and incremental, and not well-suited to the sudden acquisition of novel associations (Squire 1994; Knowlton et al. 1996). Once learned, procedures generally apply rapidly and automatically. Procedural memory is considered to be an "implicit" memory system, as learned procedural knowledge does not appear to be available to conscious access (Tulving 2000). The procedural memory system is especially dependent upon frontal/basal ganglia circuits, particularly the caudate nucleus in the basal ganglia, and premotor and associated cortex (including the posterior portion of Broca's area, corresponding to the pars opercularis, or Brodmann's area 44) in the frontal lobes (Graybiel 1995; Eichenbaum and Cohen 2001; Ullman 2004). The system also involves other areas of the brain, including portions of superior temporal and

inferior parietal cortex (Ullman 2004). Finally, the neurotransmitter dopamine plays a particularly important role in aspects of procedural learning and processing (Harrington et al. 1990; Nakahara et al. 2001; Goerendt et al. 2003).

In the domain of language, evidence suggests that the procedural memory system subserves the acquisition, knowledge and processing of aspects of grammar – in particular those concerned with the rule-governed combination of morphemes, words, and phrases into more complex sequentially and hierarchically structured units (Ullman et al. 1997; Ullman 2001c, 2004). No principled distinction is made between morphological and syntactic computation. Rather, composition in these sub-domains (and potentially others, including phonology and compositional semantics Ullman 2004) is posited to depend on the same underlying system, somewhat akin to certain linguistic accounts of grammar (Langacker 1987; Lieber 1992). This neurocognitive perspective does *not* deny the possibility of functional segregation among these sub-domains, as has been posited in numerous other linguistic accounts – e.g., word formation rules that do not appear to have any analogue in syntax, or syntactic rules that cannot “see inside” complex words (Chomsky 1970; Selkirk 1982; Di Sciullo and Williams 1987). Indeed, the functional neuroanatomical organization of frontal/basal-ganglia circuits seem to be consistent with such segregation (Ullman 2004).

The declarative and procedural memory systems interact in a number of ways. Together, the systems form a dynamically interacting network that yields both cooperative and competitive learning and processing, such that memory functions may be optimized (Poldrack and Packard 2003; Ullman 2004). First of all, the two systems can interact cooperatively to learn a given task (Willingham 1998). The declarative memory system may acquire knowledge early, thanks to its rapid learning abilities, while the procedural system gradually learns the same or analogous knowledge (Packard and McGaugh 1996; Poldrack and Packard 2003). Interestingly, the time-course of the learning in and eventual dependence on the two memory systems can be modulated pharmacologically (Packard 1999).

Second, animal and human studies suggest that the two systems also interact competitively (for reviews, see Packard and Knowlton 2002; Poldrack and Packard 2003; Ullman 2004). This leads to a “see-saw effect” (Ullman 2004), such that a dysfunction of one system results in enhanced learning in the other, or that learning in one system depresses the functionality of the other (Packard et al. 1989; Poldrack and Packard 2003; Ullman 2004). The see-saw effect may be explained by a number of factors, including direct anatomical projections between the two systems (Sorensen and Witter 1983), and roles for both estrogen and acetylcholine (Ullman 2004). For example, acetylcholine may not only serve to enhance declarative memory functions, but might also play an inhibitory role in brain structures underlying procedural memory (Calabresi et al. 2000).

These cooperative and competitive interactions between the memory systems lead to specific predictions for language. For example, very young children should (rapidly) memorize complex forms (e.g., *walked*) in lexical/declarative memory before grammatical rules are (gradually) abstracted in procedural memory (Ullman in press). Evidence seems to support this view (Marcus et al. 1992). Even when the grammatical system is eventually able to compute a particular type of representation, the same representation may *also* be memorized in the lexicon, although presumably with lower probability than before, given competition between the systems. Indeed, learning in one system is expected to inhibit learning in the other. Thus evidence suggesting that the ability to learn in declarative memory improves over the course of childhood, with a plateau in adolescence (Kail and Hagen 1977; Ornstein 1978; Di Giulio et al. 1994) leads to two predictions. First, one should find a similar developmental pattern of improvements in lexical acquisition. This may indeed be the case (Bloom 2000). Second, one should also observe a concomitant decrement in learning abilities in grammar over the course of childhood, with particular problems after puberty. Evidence from both first and second language acquisition supports this view (Curtiss 1977, 1989; Johnson and Newport 1989; Weber-Fox and Neville 1996; DeKeyser 2000).

The perspective that declarative and procedural memory respectively subserve lexicon and grammar is supported by multiple lines of converging evidence, from computational, anatomical, electrophysiological, and endocrine studies, as well as from a wide range of studies of developmental and adult-onset brain disorders. These studies suggest that the language and non-language functions subserved by these systems pattern together (Ullman et al. 1997; Ullman 2001a, 2001c, 2004; Ullman and Pierpont 2005). For example, the same brain structures are activated in functional neuroimaging studies of both lexical and declarative memory, while damage to these brain structures impairs both of these functions.

Here we present two inter-related phenomena that demonstrate how the study of these memory systems can lead to specific predictions for the representation of language. A large body of evidence has shown that certain declarative memory abilities are enhanced in females relative to males, and that estrogen improves declarative memory in both sexes (Kramer et al. 1997; McEwen et al. 1998; Miles et al. 1998; Woolley and Schwartzkroin 1998; Kimura 1999; Halpern 2000; Maki and Resnick 2000). Similar sex and hormonal effects are therefore predicted for lexical abilities (Ullman et al. 2002; Ullman 2004, in press). Early evidence from patient, electrophysiological, psycholinguistic and developmental studies supports these predictions, and suggests that women and girls are significantly more likely than men and boys to memorize rather than compute complex representations such as regular inflected forms (e.g., *walked*) (Steinhauer and Ullman 2002; Ullman et al. 2002; Ullman and Estabrooke

2004; Hartshorne and Ullman 2004; Ullman et al. 2003; Ullman et al. 2004). Moreover, hormone studies in both sexes suggest that estrogen improves aspects of lexical processing, and apparently increases reliance on stored (e.g., *walked*) as opposed to computed (e.g., *walk + -ed*) complex forms (Estabrooke et al. 2002, 2004; Ullman et al. 2002). Thus sex differences (between subjects) and changes in estrogen levels (within subjects) both result in differences in the relative reliance on distinct – stored versus computed – representations of regular inflected forms. This has the important representational consequence that *both* types of representations must co-exist, within as well as between individuals (Ullman et al. 2002, 2003; Ullman 2004, in press).

As discussed briefly above, numerous other factors also affect the relative dependence on redundant stored versus computed representations – including the frequency of the form (high frequency forms are more likely to be memorized), the age of acquisition of the language (late learned second language relies more on memorization), and the dysfunction of one or the other memory system (e.g., individuals with Specific Language Impairment, who suffer from impairments of the grammatical/procedural system, compensate by memorizing many complex forms) (Alegre and Gordon 1999; Ullman and Gopnik 1999; Ullman 2001b; van der Lely and Ullman 2001; Ullman 2004, in press; Ullman et al. 2003). Importantly, even though these redundant representations are indistinguishable in form and presumably in distribution, and thus are difficult if not impossible to tease apart on linguistic grounds, they can be empirically distinguished using a wide range of neurocognitive methods (Ullman and Pierpont in press; Ullman et al. 2003).

It should be emphasized that there appear to be many ways by which the lexical/declarative memory system can learn and process complex structures that are also computable by the grammatical/procedural system. In addition to memorizing chunks (see above), individuals may depend on stored schemas or constructions (e.g., of the sort proposed by Construction grammar; Fillmore et al. 1988; also see Wray and Perkins 2000; Dobbins et al. 2003). Additionally, transition probabilities between words may be memorized, particularly when adjacent words co-occur frequently in the same syntactic frame (Ullman to appear). Productivity may result from associative generalization over similar forms or structures stored in lexical memory (see above); the integration of conceptual-semantic relations among items; or the use of prescriptive-type “rules” learned in declarative memory (Ullman 2001b; Clahsen and Felser in press; Ullman in press, to appear).

We must emphasize that it is surely *not* the case that any complex structure computed by the grammatical system can *also* be memorized in, or otherwise depend on, lexical/declarative memory. For example, structures that involve long-distance dependencies may cause particular difficulties for this system (Ullman in press). Likewise, the grammatical/procedural system is also con-

strained. For example, truly arbitrary sound-meaning pairings are very unlikely to be learned by this system. Whether a particular representation is a function of one or the other system, or could be redundantly represented in both systems, depends on multiple factors that must be independently assessed.

Crucially, the two systems also *interact* in certain ways that have important consequences for the relative dependence on redundant and competing lexical and grammatical representations. As we have seen above, learning in one system may inhibit learning in the other, decreasing the likelihood of co-existing representations. Additionally, evidence suggests a processing primacy for lexical/declarative representations, which appear to supercede (i.e., block) representations computed by the grammatical/procedural system. For example, the presence of a memorized irregular past tense (*dug*) blocks the grammatical computation of the corresponding over-regularization (*digged*) (Marcus et al. 1992; Pinker 1999; Pinker and Ullman 2002). Similarly, the availability of a memorized regular past tense form (*played*) seems to block the grammatical computation of the *same* form. Thus improvements in lexical/declarative memory, as a function of sex or estrogen levels, increase the likelihood of using stored regular forms, at the expense of computed ones (see above). This primacy of lexical over grammatical representations is highly reminiscent of the Elsewhere principle and related hypotheses in morphology and syntax (Aronoff 1976; Wexler and Culicover 1980; Kiparsky 1982; Pinker 1984). These state that a more restrictive rule or representation blocks a more general one. On the neurocognitive perspective described here, this principle might instead be characterized (at least in some if not all cases) as “lexicon blocks grammar”. Such blocking effects are expected in any situation where a given type of representation could be computed by either system (Pinker 1999; Pinker and Ullman 2002; Ullman 2004), not only in morphology, but also in syntax (e.g., as suggested above for the case of controller selection).

3. Summary and conclusion

We have argued for a true science of language. This science seeks to consider and integrate all theoretical perspectives and methodological approaches, across and within disciplines, extending to the study of non-language functions and even to animal models. No one theoretical or empirical approach is in principle relied on more than others. Thus the scientific method is rigorously applied, with all theories, assumptions and hypotheses subjected to testing and potential falsification, using all available methods.

We have discussed in some detail how such a science can contribute to our understanding of a specific issue in the study of language, namely the nature of the distinction between storage and computation. While existing theoretic-

cal linguistic frameworks have provided important representational insights in this area, at least some (and probably many) aspects of this issue are unlikely to be resolved on purely linguistic grounds. Theories and methods from cognitive psychology and cognitive neuroscience, broadly defined, have not only shed light on a number of problems in this and other areas left unresolved by theoretical linguistics, but have also led the way to completely new realms of investigation in the study of language. Thus the neurocognitive relation between lexicon/grammar and declarative/procedural memory (the “Declarative/Procedural” theory, e.g., Ullman et al. 1997; Ullman 2001c, 2004) has demonstrated the relevance of a range of issues and problems not traditionally examined in the study of language, including the importance of non-language functions, animal models, subject variability, and redundant competing representations.

In conclusion, we would like to emphasize that, like any other cognitive function, language is rooted in the biology of the mind, and therefore *must* be investigated as a biological function. The science of language suggested here explicitly acknowledges this fact, and attempts to explain all aspects of language in its biological context as a function of the human mind and brain.

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References

- Alegre, Maria and Peter Gordon (1999). Frequency effects and the representational status of regular inflections. *Journal of Memory and Language* 40: 41–61.
- Aronoff, Mark (1976). *Word Formation in Generative Grammar*. Cambridge, MA: The MIT Press.
- Bird, Helen, Matthew A. Lambon Ralph, Mark S. Seidenberg, James L. McClelland and Karalyn Patterson (2003). Deficits in phonology and past tense morphology: What’s the connection? *Journal of Memory and Language* 48 (3): 502–526.
- Bloom, Paul (2000). *How Children Learn The Meanings Of Words*. Cambridge, MA: The MIT Press.
- Bloomfield, Leonard (1933). *Language*. Chicago: The University of Chicago Press.
- Bresnan, Joan (1982). Control and complementation. In *The Mental Representation of Grammatical Relations*, Joan Bresnan (ed.), 282–390. Cambridge, MA: The MIT Press.
- (2001). *Lexical-Functional Syntax*. Oxford: Blackwell Publishers.
- Brovetto, Claudia, and Michael T. Ullman (2001). First vs. second language: A differential reliance on grammatical computations and lexical memory. CUNY 2001 Conference on Sentence Processing, Philadelphia, PA.
- Bybee, Joan L. and Dan I. Slobin (1982). Rules and schemas in the development and use of the English past tense. *Language* 58 (2): 265–289.
- Calabresi, Paolo, Diego Centonze, Paolo Gubellini, Girolama A. Marfia, Antonio Pisani, Giuseppe Sancesario and Giorgio Bernardi (2000). Synaptic transmission in the striatum: From plasticity to neurodegeneration. *Progress in Neurobiology* 61: 231–265.
- Chomsky, Noam (1965). *Aspects of the Theory of Syntax*. Cambridge, MA: The MIT Press.
- (1970). Remarks on nominalization. In *Readings in English Transformational Grammar*, Roderick Jacobs and Peter Rosenbaum (eds.), 184–221. Waltham, MA: Ginn.

- (1981). *Lectures on Government and Binding*. Dordrecht: Foris.
- (1986). *Knowledge of Language: Its Nature, Origin and Use*. New York: Praeger.
- (1995). *The Minimalist Program*. Cambridge, MA: The MIT Press.
- Chun, Marvin M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Sciences* 4 (5): 170–178.
- Clahsen, Harald (1999). Lexical entries and rules of language: A multidisciplinary study of German inflection. *Behavioral and Brain Sciences* 22 (6): 991–1060.
- Clahsen, Harald and Claudia Felser (in press). Grammatical processing in language learners. *Applied Psycholinguistics*.
- Croft, William (2001). *Radical Construction Grammar: Syntactic Theory in Typological Perspective*. New York: Oxford University Press.
- Curtiss, Susan (1977). *Genie: A Psycholinguistic Study of a Modern-Day "Wild Child"*. New York: Academic Press.
- (1989). The case of Chelsea: A new test case of the critical period for language acquisition. University of California, Los Angeles. Ms.
- Damasio, Hanna, Thomas Grabowski, Daniel Tranel, Richard Hichwa and Antonio Damasio (1996). A neural basis for lexical retrieval. *Nature* 380 (6574): 499–505.
- DeKeyser, Robert M. (2000). The robustness of critical period effects in second language acquisition. *Studies in Second Language Acquisition* 22: 499–533.
- Di Giulio, Diane V., Michael Seidenberg, Daniel S. O'Leary and Naftali Raz (1994). Procedural and declarative memory: A developmental study. *Brain and Cognition* 25 (1): 79–91.
- Di Sciullo, Anna Maria and Edwin Williams (1987). *On the Definition of Word*. Cambridge, MA: The MIT Press.
- Dobbinson, Sushie, Mick Perkins and Jill Boucher (2003). The interactional significance of formulas in autistic language. *Clinical Linguistics and Phonetics* 17 (4–5): 299–307.
- Eichenbaum, Howard and Neal J. Cohen (2001). *From Conditioning to Conscious Recollection: Memory Systems of the Brain*. New York: Oxford University Press.
- Estabrooke, Ivy V., Kristen Mordecai, Pauline M. Maki and Michael T. Ullman (2002). The effect of sex hormones on language processing. *Brain and Language* 83: 143–146.
- (2004). Endogenous and exogenous estrogen influences language processing in healthy young women. *Journal of Cognitive Neuroscience Supplement*: 34.
- Featherston, Samuel, Matthias Gross, Thomas F. Münte and Harald Clahsen (1998). Brain potentials in the processing of complex sentences: An ERP study of control and raising constructions. *Essex Research Reports in Linguistics* 23:38–76.
- Fillmore, Charles J., Paul Kay and Catherine O'Connor (1988). Regularity and idiomacity in grammatical constructions: The case of *let alone*. *Language* 64: 501–538.
- Friederici, Angela (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences* 6 (2): 78–84.
- Ganger, Jennifer, Steven Pinker, Allison Baker and Sonia Chawla (2000). The heritability of early language milestones of vocabulary and grammar: A twin study. Paper presented in "The genetics of early language development" symposium. Conference of the International Society of Infant Studies (ISIS), Brighton, U.K.
- Gardner, Howard (1985). *The Mind's New Science: A History of the Cognitive Revolution*. New York: Basic Books.
- Gathercole, Susan E. and Alan D. Baddeley (1993). *Working Memory And Language*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Goerendt, Ines K., Cristina Messa, Andrew D. Lawrence, Paul M. Grasby, Paola Piccini and David J. Brooks (2003). Dopamine release during sequential finger movements in health and Parkinson's disease: A PET study. *Brain* 126: 312–325.
- Graybiel, Ann M. (1995). Building action repertoires: Memory and learning functions of the basal ganglia. *Current Opinion in Neurobiology* 5: 733–741.

- Halpern, Diane F. (2000). *Sex Differences in Cognitive Abilities*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Harrington, Deborah L., Kathleen York Haaland, Ronald A. Yeo and Ellen Marder (1990). Procedural memory in Parkinson's disease: Impaired motor but not visuoperceptual learning. *Journal of Clinical and Experimental Neuropsychology* 12 (2): 323–339.
- Hartshorne, Joshua K. and Michael T. Ullman (2004). Why girls say “holded” more than boys. Ms. Hauser, Marc, Noam Chomsky and William Tecumseh Fitch (2002). The faculty of language: What is it, who has it, and how did it evolve? *Science* 298 (5598): 1569–1579.
- Hickok, Gregory. and David Poeppel (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition* 92 (1–2): 67–99.
- Hornstein, Norbert (1999). Movement and control. *Linguistic Inquiry* 30 (1): 69–96.
- Johnson, Jacqueline S. and Elissa L. Newport (1989). Critical period effects in second language learning: The influence of maturational state on the acquisition of English as a second language. *Cognitive Psychology* 21 (1): 60–99.
- Kail, Robert V. and John W. Hagen (1977). *Perspectives on the Development of Memory and Cognition*. New Jersey: Lawrence Erlbaum.
- Kimura, Doreen (1999). *Sex and Cognition*. Cambridge, MA: The MIT Press.
- Kiparsky, Paul (1982). From cyclic phonology to lexical phonology. In *The Structure of Phonological Representations*, Harry v. d. Hulst and Norval Smith (eds.), 131–175. Dordrecht: Foris.
- Knowlton, Barbara J., Jennifer A. Mangels and Larry R. Squire (1996). A neostriatal habit learning system in humans. *Science* 273: 1399–1402.
- Kramer, Joel H., Dean C. Delis, Edith Kaplan, Louise O'Donnell and Aurelia Prifitera (1997). Developmental sex differences in verbal learning. *Neuropsychology* 11 (4): 577–84.
- Langacker, Ronald W. (1987). *Foundations of Cognitive Grammar Volume 1: Theoretical Prerequisites*. Stanford, California: Stanford University Press.
- (1995). Raising and transparency. *Language* 71 (1): 1–62.
- Lieber, Rochelle (1992). *Deconstructing Morphology: Word Formation in Syntactic Theory*. Chicago: The University of Chicago Press.
- Maki, Pauline M. and Susan M. Resnick (2000). Longitudinal effects of estrogen replacement therapy on pet cerebral blood flow and cognition. *Neurobiology of Aging* 21 (2): 373–83.
- Marcus, Gary F., Steven Pinker, Michael T. Ullman, Michelle Hollander, T. John Rosen and Fei Xu (1992). Overregularization in language acquisition. *Monographs of the Society for Research in Child Development* 57 (4, Serial No. 228): 1–165.
- Marslen-Wilson, William and Lorraine K. Tyler (1998). Rules, representations, and the English past tense. *Trends in Cognitive Sciences* 2 (11): 428–435.
- Martin, Alex, Leslie G. Ungerleider and James V. Haxby (2000). Category specificity and the brain: The sensory/motor model of semantic representations of objects. In *The Cognitive Neurosciences*, Michael S. Gazzaniga (ed.), 1023–1036. Cambridge, MA: The MIT Press.
- McClelland, James L. and Karalyn Patterson (2002). Rules or connections in past-tense inflections: What does the evidence rule out? *Trends in Cognitive Sciences* 6(11): 465–472.
- McEwen, Bruce S., Stephen E. Alves, Karen Bulloch and Nancy G. Weiland (1998). Clinically relevant basic science studies of gender differences and sex hormone effects. *Psychopharmacology Bulletin* 34(3): 251–9.
- Middleton, Frank A. and Peter L. Strick (2000). Basal ganglia and cerebellar loops: Motor and cognitive circuits. *Brain Research Reviews* 31 (2–3): 236–250.
- Miles, C., R. Green, G. Sanders and M. Hines (1998). Estrogen and memory in a transsexual population. *Hormones and Behavior* 34(2): 199–208.
- Nakahara, Hiroyuki, Kenji Doya and Okihide Hikosaka (2001). Parallel cortico-basal ganglia mechanisms for acquisition and execution of visuomotor sequences – a computational approach. *Journal of Cognitive Neuroscience* 13 (5): 626–467.
- Ornstein, Peter A. (1978). *Memory Development in Children*. New Jersey: Lawrence Erlbaum.

- Packard, Mark G. (1998). Posttraining estrogen and memory modulation. *Hormones and Behavior* 34 (2): 126–39.
- (1999). Glutamate infused posttraining into the hippocampus or caudate-putamen differentially strengthens place and response learning. *Proceedings of the National Academy of Sciences of the United States of America* 96 (22): 12881–12886.
- Packard, Mark G., Richard Hirsh and Norman White (1989). Differential effects of fornix and caudate nucleus lesions on two radial maze tasks: Evidence for multiple memory systems. *Journal of Neuroscience* 9 (5): 1465–1472.
- Packard, Mark G. and Barbara J. Knowlton (2002). Learning and memory functions of the basal ganglia. *Annual Review of Neuroscience* 25: 563–593.
- Packard, Mark G. and James L. McGaugh (1996). Inactivation of hippocampus or caudate nucleus with lidocaine differentially affects expression of place and response learning. *Neurobiology of Learning and Memory* 65 (1): 65–72.
- Pinker, Steven (1984). *Language Learnability and Language Development*. Cambridge, MA: Harvard University Press.
- (1999). *Words and Rules: The Ingredients of Language*. New York: Basic Books.
- Pinker, Steven and Michael T. Ullman (2002). The past and future of the past tense. *Trends in Cognitive Sciences* 6 (11): 456–463.
- Poldrack, Russell A. and Mark G. Packard (2003). Competition among multiple memory systems: Converging evidence from animal and human brain studies. *Neuropsychologia* 41 (3): 245–251.
- Postal, Paul M. (1974). *On Raising*. Cambridge, MA: The MIT Press.
- Prasada, Sandeep and Steven Pinker (1993). Generalization of regular and irregular morphological patterns. *Language and Cognitive Processes* 8(1): 1–56.
- Rosenbaum, Peter S. (1967). *The Grammar of English Predicate Complement Constructions*. Cambridge, MA: The MIT Press.
- Rudanko, Juhani (1989). *Complementation and Case Grammar: A Syntactic and Semantic Study of Selected Patterns of Complementation in Present-Day English*. New York: State University of New York Press.
- Sag, Ivan and Thomas Wasow (1999). *Syntactic Theory: A Formal Introduction*. Stanford: CSLI.
- Sakamoto, Tsutomu (1996). *Processing Empty Subjects in Japanese: Implications for the Transparency Hypothesis*. Fukuoka: Kyushu University Press.
- Sakamoto, Tsutomu and Matthew Walenski (1998). The processing of empty subjects in English and Japanese. In *Syntax and Semantics 31: A Cross-Linguistic Perspective*, Dieter Hillert (ed.), 95–112. San Diego: Academic Press.
- Selkirk, Elizabeth O. (1982). *The Syntax Of Words*. Cambridge, MA: The MIT Press.
- Sherwin, Barbara B. (1988). Estrogen and/or androgen replacement therapy and cognitive functioning in surgically menopausal women. *Psychoneuroendocrinology* 13 (4): 345–357.
- Sørensen, K. E. and M. P. Witter (1983). Entorhinal efferents reach the caudato-putamen. *Neuroscience Letters* 35 (3): 259–64.
- Squire, Larry R. (1994). Declarative and nondeclarative memory: Multiple brain systems supporting learning and memory. In *Memory Systems 1994*, Daniel L. Schacter and Endel Tulving (eds.), 407. Cambridge, MA: The MIT Press.
- Steinhauer, Karsten and Michael T. Ullman (2002). Consecutive ERP effects of morpho-phonology and morpho-syntax. *Brain and Language* 83: 62–65.
- Suzuki, Wendy A. and David G. Amaral (1994). Perirhinal and parahippocampal cortices of the macaque monkey: Cortical afferents. *Journal of Comparative Neurology* 350 (4): 497–533.
- Tulving, Endel (2000). Introduction (vi memory). In *The New Cognitive Neurosciences*, Michael S. Gazzaniga (ed.), 727–737. Cambridge, MA: The MIT Press.
- Ullman, Michael T. (2001a). The declarative/procedural model of lexicon and grammar. *Journal of Psycholinguistic Research* 30 (1): 37–69.

- (2001b). The neural basis of lexicon and grammar in first and second language: The declarative/procedural model. *Bilingualism: Language and Cognition* 4 (1): 105–122.
- (2001c). A neurocognitive perspective on language: The declarative/procedural model. *Nature Reviews Neuroscience* 2: 717–726.
- (2004). Contributions of memory circuits to language: The declarative/procedural model. *Cognition* 92 (1–2): 231–270.
- (in press). A cognitive neuroscience perspective on second language acquisition: The declarative/procedural model. In *External and Internal Factors in Adult SLA*, Christina Sanz (ed.). Washington, DC: Georgetown University Press.
- (to appear). The declarative/procedural model and the shallow-structure hypothesis. *Applied Psycholinguistics*.
- Ullman, Michael T., Susanne Corkin, Marie Coppola, Gregory Hickok, John H. Growdon, Walter J. Koroshetz and Steven Pinker (1997). A neural dissociation within language: Evidence that the mental dictionary is part of declarative memory, and that grammatical rules are processed by the procedural system. *Journal of Cognitive Neuroscience* 9 (2): 266–276.
- Ullman, Michael T. and Ivy V. Estabrooke (2004). Grammar, tools and sex. *Journal of Cognitive Neuroscience* Supplement: 67.
- Ullman, Michael T., Ivy V. Estabrooke, Karsten Steinhauer, Claudia Brevetto, Roumyana Pancheva, Kaori Ozawa, Kristen Mordecai and P. Maki (2002). Sex differences in the neurocognition of language. *Brain and Language* 83: 141–143.
- Ullman, Michael T. and Myrna Gopnik (1999). Inflectional morphology in a family with inherited specific language impairment. *Applied Psycholinguistics* 20 (1): 51–117.
- Ullman, Michael T., Joshua K. Hartshorne, Ivy V. Estabrooke, Claudia Brevetto and Matthew Walenski (2003). Sex, regularity, frequency and consistency: A study of factors predicting the storage of inflected forms. Ms.
- Ullman, Michael T., Roumyana Izvorski, Tracy Love, Eiling Yee, David Swinney and Gregory Hickok (2005). Neural correlates of lexicon and grammar: Evidence from the production, reading, and judgment of inflection in aphasia. *Brain and Language* 93: 185–238.
- Ullman, Michael T. and Elizabeth I. Pierpont (2005). Specific language impairment is not specific to language: The procedural deficit hypothesis. *Cortex* 41: 399–433.
- Ullman, Michael T., Matthew Walenski, Elizabeth Prado, Kaori Ozawa and Karsten Steinhauer (2004). The real-time composition of complex forms. Ms.
- Ullman, Michael T. and Matthew Walenski (2005). Moving past the past tense. *Brain and Language* 93: 248–252.
- van der Lely, Heather K. J. and Michael T. Ullman (2001). Past tense morphology in specifically language impaired and normally developing children. *Language and Cognitive Processes* 16 (2): 177–217.
- Walenski, Matthew (2002). Relating parsers and grammars: On the structure and real-time comprehension of English infinitival complements. PhD dissertation. University of California, San Diego.
- Weber-Fox, Christine M. and Helen J. Neville (1996). Maturation constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience* 8 (3): 231–256.
- Wexler, Kenneth and Peter W. Culicover (1980). *Formal Principles of Language Acquisition*. Cambridge, MA: The MIT Press.
- Willingham, Daniel B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review* 105 (3): 558–584.
- Woolley, Catherine S. and Philip A. Schwartzkroin (1998). Hormonal effects on the brain. *Epilepsia* 39 (8): S2–8.
- Wray, Alison and Michael R. Perkins (2000). The functions of formulaic language: An integrated model. *Language and Communication* 20: 1–28.