

Engines of Linguistic Complexity

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Human language is enormously complex. Some of this complexity is located within individual speakers. Each of us knows tens of thousands of words, and each of these words inhabits its own microworld of complexity. When we put these words together into sentences and discourse, still further complexities arise in the form of collocations, phrases, and grammatical relations. These patterns at the individual level become even more complex when we look at how language varies across social groups and communicative situations.

Fortunately, we are able to use the methods of sociolinguistics, diachronic linguistics, and typological analysis to track this complexity as it arises. Sorting out the patterns is hard work, but the data are rich and we have good methods for conducting this analysis. In theoretical terms, it is also fairly easy to adapt the Darwinian theory of natural selection to apply to the generation of linguistic complexity. In the traditional Darwinian framework, mutations and sexual recombination produce variations in the genotype which then lead to variations in the phenotype. Some of these variations are favored above others. Successful variations thrive and propagate, whereas unsuccessful variations disappear.

Over time, these Darwinian processes have produced enormous complexity in the basic systems supporting life (Tublitz, this volume). Respiration within the mitochondria provides a well-known illustration of this biological complexity. In respiration, glucose is oxidized to carbon dioxide, and adenosine triphosphate (ATP) is produced as a by-product. Through a chain of catalytic reactions, including glycolysis and the Krebs's cycle, one molecule of glucose ends up producing 36 molecules of ATP. The complexity and interlocking balance of the various turns of these catalytic cycles is nothing short of amazing. It is even more amazing to realize that evolution pieced this complex system together, layer by layer, through a blind process of trial and error that extended over hundreds of millions of years.

Linguistic complexity depends upon a neural system whose structure is far more complex than that of respiration. Unlike respiration, linguistic complexity arises from both genetic engines that build complex structures in the human brain and mimetic engines (Mesoudi, Whiten, & Laland, 2006) that codify complex structures from social interaction. Both of these engines depend on variation, adaptation, and selection. For both engines, we are not interested primarily in the initial variation, but in the end structures that result from selection. Of course, we want to understand variation itself as the initial source of complexity, but we do not want to focus on the

complexity involved in the variation, but rather the complexity in the forms that are selected out for further integration into complex neurological and stored structures. In other words, we are talking about the ways in which variations become stabilized and preserved over time during both during child language learning and during the ongoing change of the language itself across time.

The fundamental challenge here is to understand the ways in which the brain provides support for the consolidation of complexity. Once we understand how the core support operates, we can then move on to study how ongoing mimetic processes make use of these core mechanisms to consolidate linguistic complexity. So, let us begin our exploration by considering the neural engines that generate and store complexity. We can begin by recognizing the importance in neural terms of the six fundamental levels of linguistic analysis: auditory phonology, articulatory phonology, lexicon, morphology, syntax, and discourse. The account provided here attributes the consolidation of linguistic complexity to mechanisms operating within each of these six systems. However, before exploring processes and structures operative on each of these six levels, we need to consider some basic issues regarding pseudo-modular organization in the brain.

Modularity and maps

It would be tempting to think of these six levels as computational modules (Fodor, 1983; Levelt, 1989; Pinker, 1997). Indeed, each of these linguistic levels is supported by uniquely adapted processors in localized brain regions. However, thinking of these processors as protected modules like those in a Java program is not in accord with what we know about the brain (Bullinaria, 2007). We know that brain regions are heavily interconnected by asymmetric bidirectional connections. These connections cannot pass symbols, as required by the digital computer. Instead neurons must communicate by depending on isotopic mapping, learned patterns of connectivity, firing synchrony, and modulation through supervisory units. Moreover, except lower organisms or the brainstems of higher organisms, it is seldom the case that a single cell is responsible for a discrete cognitive function. This is certainly true at the level of the cortex, where cells appear to operate in assemblies of thousands of neurons to achieve single cognitive goals.

Brain development in the fetus involves the migration of neurons from the germinal matrix to the periphery. During this migration, cortical areas maintain their connections to the various subcortical areas from which they differentiated. For example, within both the

thalamus and the hippocampus, there are separate nuclei that project to separate cortical areas. Although single axons fire in a directional fashion, these larger sets of connections are bidirectional, thereby providing a system of reentrance or interaction between areas of the brain (Tucker et al, this volume). Within each of these thalamic or hippocampal nuclei there may be additional fine-grained structure that allows the subcortical area to maintain a map of the structure of the cortical area, even after it has migrated to a more distal position. The map-like nature of these connections between cortical and subcortical structures is further supplemented by map-like connections of motor and sensory areas to external sense organs and the body. In motor cortex, there is a somatotopic organization that matches up well with the actual shape of the human body. In sensory areas, cortex is organized to represent the features of the sense. For example, auditory cortex is organized in terms of frequencies, as detected by the cochlea, which is itself organized so that neighboring hair cells respond to similar frequencies. Similarly, the visual cortex is organized in patterns that maintain the position of receptors in the left or right visual field and other peripheral patterns.

This map-like organization of the brain allows areas to communicate with themselves and the body in terms of an embodied neural code that is implicit in the position of a neuron within the map. As processing moves away from the periphery, the blending of these codes increases. However, through reentrance, it is possible for the brain to reground cognitions in terms of these original body maps (Jeannerod, 1997; Schütz-Bosbach & Prinz, 2007; Wilson & Knoblich, 2006). This basic principle of map-like organization across brain areas is further supported by learning methods that function to organize local maps. One powerful way of modeling this local organization relies on the self-organizing feature maps (SOFM) of Kohonen (1990). In this model, neuron-like units are organized in two-dimensional sheets with connections to an array of input and output features. When an input feature vector is activated, units in the map also gain some activation. Through lateral inhibition, the most strongly activated unit will inhibit its neighbors, leading to a winner-take-all effect. This pattern of activity has been well documented for cortical structures. After the initial inhibition, there is then a learning phase in which the connections with the winner and its neighbors are strengthened. As a result of this learning, responses to certain patterns in the input tended to become parceled out across areas of the feature map, with this self-organized differentiation increasing over time. This type of map is a sparse, distributed memory, since there are typically many possible features of which only a few are active for a given input.

The DevLex Model

Li, Zhao, & MacWhinney (2007) have developed a model of lexical learning based on SOFM. This model, called DevLex, uses three separate self-organizing feature maps for auditory phonology, articulatory phonology, and lexical structure. In effect, DevLex provides us with a fully implemented, neurologically grounded, empirically successful account of organization for the first three pseudo-modules in our general account of the origins of linguistic complexity.

Featural organization on the DevLex auditory map relies on the PatPho representational system which parcels out segments into an autosegmental grid. In terms of neural processing, this model assumes that initial auditory processing has yielded a set of perceptual features that are associated with specific syllables, and slots (onset, nucleus, coda) within syllables. This representational system was introduced in MacWhinney & Leinbach (1991) and most subsequent work in neural network modeling of input phonology has used this framework. The activation of segments or syllables in a self-organizing feature map is further controlled through a sequence detection mechanism that expresses the form of a word as a linear trajectory through points in the feature map. Multiple positional variants of a given segment are represented as multiple neighboring nodes in the map. Output phonology is also represented through sequence control units that activate articulatory gestures organized in a second motor feature map. Figure 1 illustrates the overall shape of DevLex.

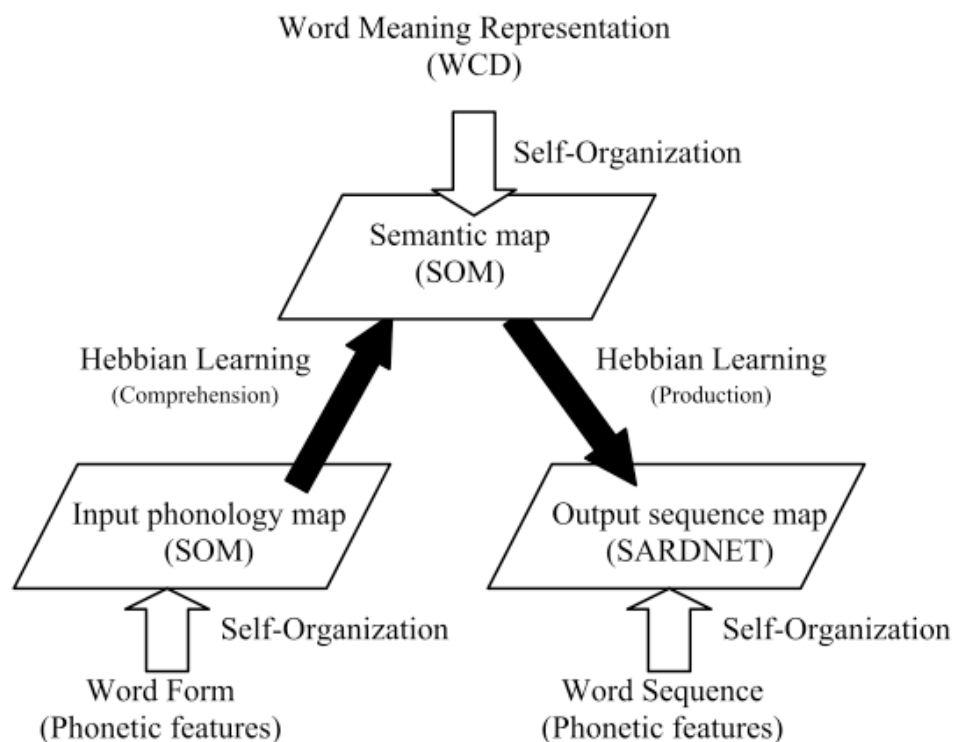


Figure 1: The DevLex Model

The three separate maps of the DevLex model represent three of the six core linguistic modules. These modules are each located in separate brain regions, connected by axonal projections. DevLex trains these connections using Hebbian learning. However, we will see later that there is reason to believe that other processes are involved. Input phonology is in the auditory cortex of the superior temporal sulcus. Output phonology is controlled by some parts of Broca's area, along with motor cortex. The core semantic or lexical map is centered in Wernicke's area, although it is actually far more generally distributed, as we will see later.

Looking first at the control of input phonology, we know that this processing is focused in primary auditory cortex. This area, which spans Brodmann areas 41 and 42, lies in the posterior half of the superior temporal gyrus and the transverse temporal gyri or Heschl's gyri. Within this area, there are in fact multiple tonotopic maps, each of which appears to represent a different view or processing slant on the whole range of the frequency spectrum. Work with rhesus monkeys has shown that the auditory system involves three levels of auditory processing with 15 different tonotopic maps. This pattern of multiple parallel isotopically organized maps is similar to the pattern of

multiple parallel maps found in the motor system. Like many other cortical areas, the auditory cortex is also connected to its own specific thalamic nucleus, the medial geniculate nucleus, from which it receives input.

Human auditory processing is fundamentally similar to that of other mammals and even birds. For example, the human ability to differentiate categorically between syllables with initial voiced stops that have a release time of either more or less than 40 milliseconds after the closure is also found in chinchillas (Kuhl & Miller, 1978) and Japanese quail (Lotto, Kluender, & Holt, 1997). This result and others like it suggests that the basic neural engines for auditory feature detection were consolidated prior to the evolution of hominids. Overall, input phonology functions to reduce the enormous complexity of the auditory world to a much smaller set of contrasts that can link to output phonology and lexical structure. This reduction of complexity is operative in other mammals. However, it is likely that, under the influence of linkage to a lexicon, these processes extend further and occupy additional neural machinery in humans.

In addition to an overall sharpening of the reliance on contrasts, human and primate audition must also differ in the extent to which they must rely on mechanisms for sequence detection. Although syllables can be perceived as wholes, multisyllabic words need to be encoded in ways that associate sounds with syllable position. Prosodic features, such as syllabic stress or moraic timing, can facilitate and sharpen this encoding, but it is still likely that some form of sequence detection is involved in the interfacing of auditory processing with lexical recognition. These sequence detection processes may be present in other mammals, but they are probably elaborated in humans.

Principles of Sequence Detection and Control

There has been extensive work in neuroscience on the study of neural mechanisms for sequence detection and control. Pulvermüller (2003) reviews this literature, including classic models from McCulloch & Pitts (1943), along with some new detailed proposals of his own. The simplest form of sequence detection involves a chain of direct connections. In this scheme, when unit A fires, it primes the next item in the chain, unit B. Unit B will then fire only when it receives input both from unit A and an incoming stimulus. A similar scheme can operate for motor control by allowing actions to trigger one another in sequence, as in the avalanche model of Grossberg (1978).

Although simple chains provide a reliable solution to the sequencing problem, they can lose sensitivity, if the delay between A and B is either less than or more than the natural timing on the synaptic connections between the two neurons. In order to avoid this type of problem, sequence detection can rely on additional mediating elements, configured in various ways. Pulvermüller's version of this mechanism includes bidirectional connections that promote reverberation within the circuit. The fact that forward sequential connections are stronger than backward ones prevents the circuit from firing in the wrong direction. When the first unit fires, it primes the sequence detection unit which then primes the second unit and then reverberation in the whole circuit. At this point, both of the items that have been detected become "visible" which means that they can then pass on information to other processing areas. However, if the second unit fires without being primed, it fails to trigger the sequence unit and activation is then suppressed.

This account applies in a parallel way for the control of output phonology. Here, the relevant mechanism includes components in the cerebellum, motor cortex, and Broca's area. We know that the final stages of speech production involve the control of mouth movements by motor cortex, as modulated by the cerebellum. The motor cortex is directly connected to the spinal cord. As a result, lesions to the motor area inevitably lead to hemiparesis or hemiplegia. The cerebellum retains somewhat more plasticity. Yamamoto et al. (2006) have shown that the cerebellum incorporates two somatotopic systems for control of motor movements of the hand. One of these systems is hard-wired to particular effectors, the second retains full plasticity to allow for the learning of patterns of controlling the first system. It is likely that a similar dual structure also operates for the control of the vocal organs. This system for controlling speech output operates on gestural plans that are unique for each lexical item. As in the case of input phonology, output gestures are triggered by the operation of sequence planning units that trace out trajectories through a feature map space.

Initial Linkage

Having surveyed the three major components of the DevLex model, we can begin to ask how this system becomes consolidated during development in ways that can support a lexical basis for linguistic complexity. First, we can consider how output phonology becomes aligned with input phonology. MacNeilage & Davis (2000) argue that the first stages of babbling are driven by a frame-context CV organization that is parallel to the organization found in the primate

lip-smacking gesture produced by a facial gesture control area in the inferior frontal gyrus. Beginning with such resources, Oller (2000) shows how the child must spend several months organizing laryngeal and oral processes to gain control of phonation. Once phonation is in place, the linkage of input and output phonology deepens through babbling, as modeled by Westermann & Miranda (2004). Patterns arise to produce clear and interesting auditory patterns, including CV and CVCV structures and a range of segment types that the child finds entertaining and rewarding. Up to nine months, this loop between input and output phonology depends little on social input. After that time, as the child pays more attention to the input, the loop becomes further structured to match the input phonology. The complexity arising from these mimetic changes is largely represented in the differences between alternative sound systems. However, the shape of these possible sound systems is still constrained by what children can represent in hearing and reproduce in articulation.

A Distributed Lexicon

Once input and output phonology are coordinated, the child can begin to link these systems to the developing lexicon. In fact, some lexical learning can begin even when only input phonology has been consolidated. However, the presence of a full resonant loop between input and output phonology facilitates the coupling of lexical learning to social interaction. Linkage of these input-output relations to a conceptual structure sets the stage for an enormous burst in linguistic complexity. Although dogs and primates can learn dozens of words, they are unable to link their lexical map to an input-output system. As a result, higher mammals cannot rely on mimetics for organizing and enriching their conceptual lexicon. Humans, on the other hand, are able to acquire a virtually limitless array of words from conversational input.

There is currently no evidence that the brain structures involved in this learning are fundamentally different from those used by the higher mammals. However, in both humans and animals, lexical representations are far more distributed than the representations of input and output phonology. The broad area of cortex at the intersection of the parietal, occipital, and temporal lobes has further access to wide areas of the whole cortex. Unlike the feature maps for input and output phonology, the core conceptual lexicon must make contact with a very diverse set of connections across the brain. Words for tools must make contact with the motor gestures and postures involved in the use of these tools. Words for fruits must make contact

with the visual properties of these flowers, including colors, shapes, and smells. Words for actions must make contact with the motor sequences, perceptual changes, and object affordances involved in these actions. The competition between alternative tools, such as *screwdriver* vs. *drill*, arises at least partly in the motor and parietal areas that control tool usage. However, the competing cell assemblies within the lower level of this hierarchy are then able to transfer activation back to higher level units in the major map that activates phonology. Figure 2 presents a sketch of how this hierarchical organization can operate within a system of self-organizing feature maps (Dittenbach, Rauber, & Merkl, 2002).

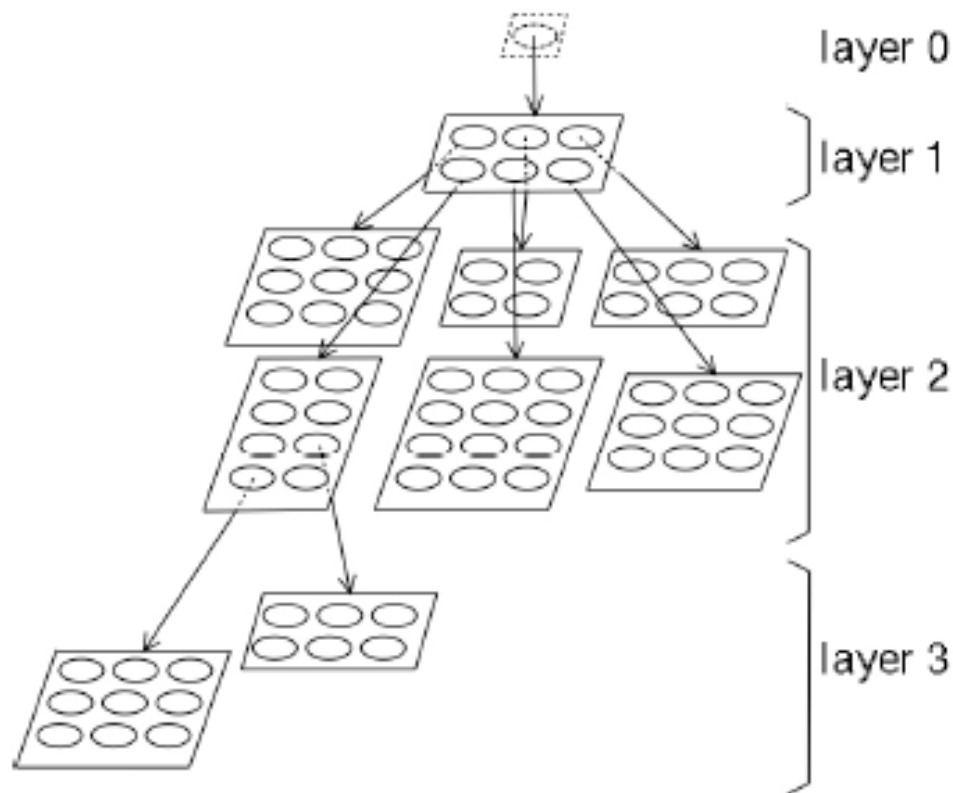


Figure 2: Hierarchical access in self-organizing feature maps

To control this hierarchical access, the brain must rely on long-distance connections between the core lexical areas and areas that flesh out the meanings involved in words. Moreover, these hierarchical connections must be structured in a way that allows for a consistent control of competition at both the local areas and the lexical core.

Consolidation of lexical patterns

This distributed, hierarchical patterning has important consequences for the consolidation of linguistic complexity. Tucker et al. (this volume) argue that ventral stream processing operates upon discrete item-based object representations that are characteristic of processing in temporal cortex. This type of item-based encoding is supported by neostriatal attentional mechanisms and hippocampal reentrant encoding processes. The hippocampus provides a compressed encoding of the distributed patterns related to a word. By maintaining resonant and reentrant reactivation of these patterns, the hippocampus can facilitate the consolidation of these traces into a new cell assembly or lexical pattern. This ventral-hippocampal system provides the basic engine for consolidating and extending linguistic complexity at the lexical level. Here the complexity involves not just the phonological form of the word, but also the diverse connections of the lexical system to many areas of the brain. Because words have become conventionalized mimetic forms, this system then functions to repeatedly consolidate variant meaningful configurations into the same phonological bucket. From this core engine, arise the linguistic complexities of radial semantic structure (Lakoff, 1987), polysemic pathways (MacWhinney, 1989), metonymy, partonomy, and homonymy (Lyons, 1977).

Underneath this linguistic complexity is a further level of psycholinguistic complexity that arises from the fact that words trigger distributed concepts through "resonance". In production, the activation of a distributed meaning pattern triggers activation of the word. In comprehension, activation of a distinct phonology triggers the distributed activation of the concept. A simple word like "hammer" is able to trigger both visual images of a hammer in the ventral "what" stream and functional images of wielding a hammer to hit a nail in the dorsal "how" stream. When we come to more complex words such as "grandfather" or "promise", the meanings involved have to be unpacked in terms of a whole set of embedded predicates, such as "the father of my father, or the father of my mother" or "tell someone that you will perform an action that you would not otherwise have done with the expectation that, if you fail to complete the action, there would be unpleasant social or interpersonal consequences and that you therefore fully intend to complete the action, even if certain barriers arise."

The solidification of complexity at the lexical level relies on this system of distributed resonance. When a complex word like "promise" is produced, it is not necessary that all elements of the chain be fully

activated in working memory. All that is necessary is that enough of the word be activated to guarantee correct lexicalization of this word as opposed to its competitors. In the case of “promise” it may be that all that is necessary is the notion of saying something seriously. The further pragmatic implications involved in serious, focused participation in a conversation may not be available initially in working memory, although there are long-term, distributed links available that can call them up if needed. This is equally true for concrete terms such as “hammer”, since we do not always have to think about using the claw of a hammer to pull out a nail when we hear the word “hammer.” In this way, we can think of words as promissory notes or tokens that are issued in the place of the full set of concepts and stances with which they are linked.

Sequence analysis within the lexicon

In principle, it would be possible to ground a communication system on sentences or propositions compressed into single words. Polysynthetic languages such as Iroquois or Eskimo push hard in this direction with their inclusion of a wide range of moods, persons, surfaces, and aspects into a single verb-based complex. However, languages achieve this compression by relying on an additional morphological engine for the generation of complexity. The engine of morphology rests astride two basic principles in neural organization. Consider the contrast between Hungarian and English in the way they form the phrase meaning “my coat.” In English, the possessive appears as a separate word preceding the noun. Variations in the phonological shape of the following noun have minimal effect on the sound of the possessive pronoun. In Hungarian, on the other hand, the suffix *-om* takes on the shape of either *-am*, *-om*, *-em*, *-öm*, or *-m*, depending on the shape of the stem. Moreover, the stem will also change its shape, depending on the nature of the suffix.

The debate about the cognitive representation of these morphophonological patterns has raged for over three decades in psycholinguistics. The connectionists and analogists view forms such as *kabátom* as produced within the lexicon through interactive activation of analogic patterns. In this model, all lexical forms are produced within the lexicon, without reliance on external routes. The alternative view holds that regular morphological forms are produced by combination between stems and affixes. The third possible formulation is that of MacWhinney (1978, 1982, 1987a, 2005a) which views combinatorial forms as arising through extraction from a core analogic process. Within the framework of self-organizing feature maps, this means that a separate lexical map for affixes emerges from

a process that compares similar morphological formations. For example the comparison of *shoe* with *shoes* will lead to the extract of -s as the initial productive form for the plural. Similarly, the comparison of *kabát* with *kabátom* leads to the extraction of -om as the first person possessive suffix.

This comparison and extraction method is clearly an important additional source of linguistic complexity. This same engine can work within the noun phrase or verb phrase to extract *my* from the combination *my coat*, just as -om is extracted from *kabátom*. Moreover, it is an engine that can work in both both directions. If the pressures of fast speech work to modify combinations such as *going to* into *gonna*, then the latter can be stored as a single form representing what was earlier a syntactic combination.

The extreme analogist view would hold that the neurological basis of complex morphology is completely interwoven with the lexical substrate in Wernicke's area at the juncture of the parietal and temporal lobes. It would view an item such as -om as residing on essentially the same lexical map as an item such as *kabát*. A strength of this approach is that the morphological alterations involved in the relevant combinations would be directly tuned in the connections between these forms and output phonology. However, a weakness in this approach is that it fails to capture the fact that the -om suffix occurs positionally after the stem. To represent this within a single net, sequence detector units would have to be built into the lexical net itself. As an association area, Wernicke's contains few assemblies that could be configured as sequence detectors.

Sequence analysis outside the lexicon

To solve this problem and to boost lexical capacity, evolution shaped a new engine that allowed lexical processing to turn over the control of morpheme combination to other areas. This "offloading" of sequence detection then freed up lexical processing to focus on the basic work of achieving intersection between associations. The modulation of the lexical sequencing was off-loaded to Broca's area in the inferior frontal gyrus (IFG). Among the various cortical areas specialized for sequence processing, this is the area that was closest to the posterior lexical areas. Although this area lies across the Sylvian fissure, it is well connected to the areas back of the Sylvian fissure both in primates (Deacon, 1988) and, presumably, the ancestors of hominids. So, there was no need to establish connectivity between the areas. In this sense, the syntactic engine was not built up from scratch. Rather, like all evolutionary advances, it is a new machine

made up of old parts. Within this new machine, there was a need to make sure that this connectivity supported effective control of lexical activation. To do this, it was important for lexical assemblies in posterior cortex to organize themselves in ways that map up with the already existent connections to IFG. Again, this is not some sudden evolutionary invention, but rather the reshaping of an old machine to serve new functions. The DevLex model shows how this topological structuring of posterior cortex is achieved through movement of lexical forms on the self-organizing feature map.

Figure 3 below illustrates the results of training the DevLex model on parental input derived from the Belfast corpus in CHILDES (MacWhinney, 2000). During this training, words that appear in similar contexts in the parental input self-organize so that they end up being located next to each other in lexical space. In other words, nouns end up next to other nouns and prepositions end up next to other prepositions. This topological self-organization provides support for reliable interactions between IFG and the posterior lexicon. In effect, the topological map is the backbone of a communication protocol between the lexicon and IFG. To understand how this protocol operates to produce complex syntactic structures, we will need to take an excursion into language acquisition theory.

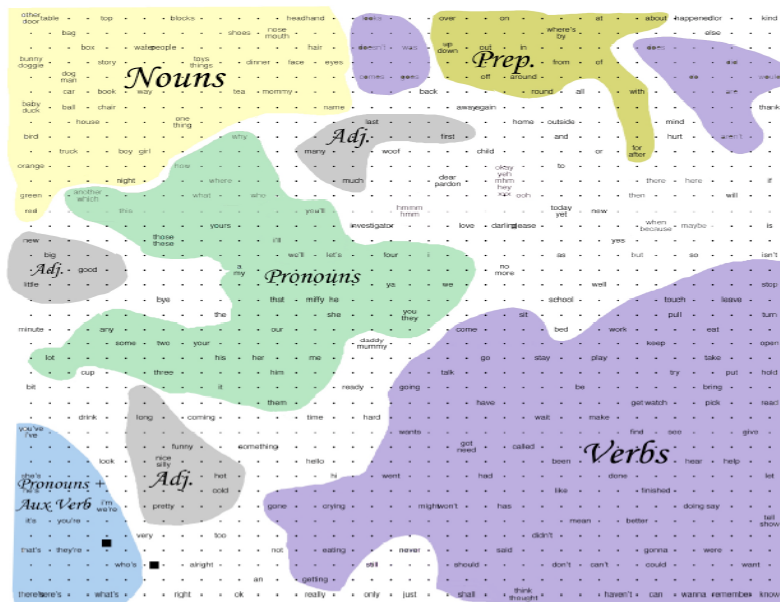


Figure 6. Word representations in GSM from learning the CHILDES parental speech. GSM identifies various grammatical categories (nouns, verbs, prepositions, and pronouns) as well as semantic categories within each of the grammatical categories.

The map presented in Figure 3 is the result of thousands of exposures to each individual word in a thousand word input corpus. During the course of this learning, the shape of the map changes radically, particularly during the first phases of training. Figure 4 shows how the map changes its shape across the first 50, 150, 250, and 500 epochs of training.

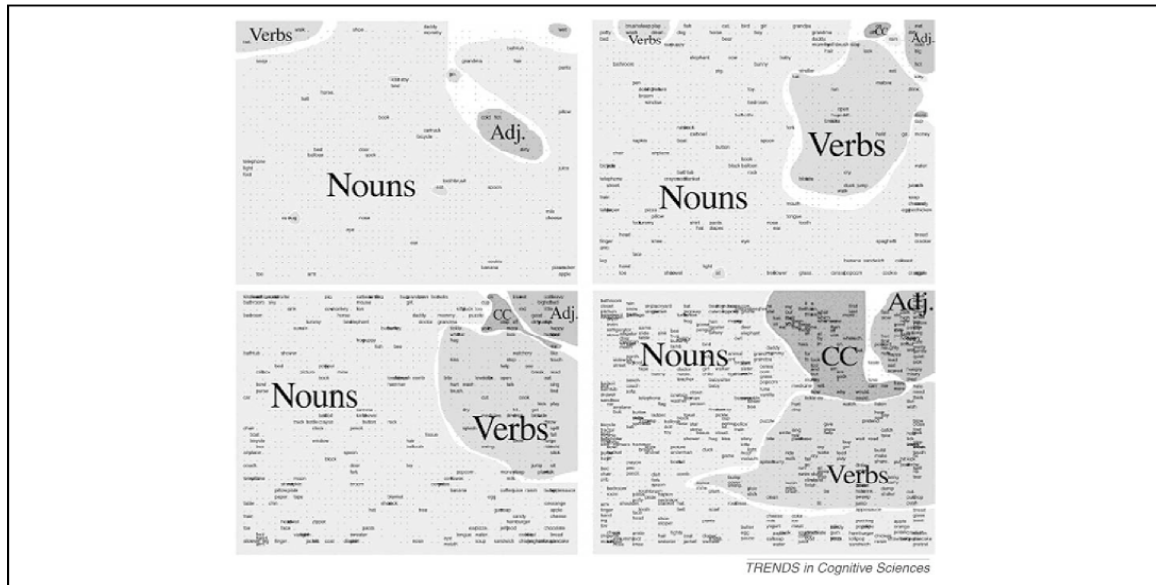


Figure 4: Changes in the DevLex map across the first 100, 150, 250, and 500 epochs.

Item-based Patterns

In the early days of acquisitional theory, Braine (1963, 1971) explored ways of applying learning theory to the study of child language. The formulation he devised focused on the idea that function words tend to appear in fixed positions *vis a vis* content words. For example, *the* appears before nouns and the suffix *-ing* appears after verbs. Like Harris (1951), Braine analyzed these constituent structures in terms of slots that could be filled by items of a certain class. Formulating a set of 12 such rules for a small corpus of child utterances, he referred to his account as a “pivot-open” grammar, since it specified the position of pivot words *vis a vis* the open class. Under the influence of Chomsky’s (1957) ideas about deep

structure, this model was rejected as failing to pay adequate attention to semantic patterning. Later, Braine (1976) revised his account, emphasizing the role of “groping patterns” that established links based not on lexical class, but semantic relations.

Sticking closer to Braine’s original formulations, MacWhinney (1975) introduced the notion of the item-based pattern. Applying this construct to a corpus of Hungarian, MacWhinney examined the word order of 11,077 utterances produced by two Hungarian children between the ages of 17 and 29 months. He found that between 85 and 100% of the utterances in these samples could be generated by a set of 42 item-based patterns. Some examples of these patterns in English translation are: *X + too*, *no + X*, *where + X*, *dirty + X*, and *see + X*. The item-based pattern model was able to achieve a remarkably close match to the child’s output, because it postulates an extremely concrete set of abilities that are directly evidenced in the child’s output.

MacWhinney made no general claims about a pivot or open class, focusing instead on the idea that the first syntactic patterns involve links between individual lexical items and other words with which they are prone to combine. An example of an item-based pattern is the structure *the + X*. This pattern states simply that the word *the* occurs before another word with which it is semantically related. In addition to these positional facts, the item-based pattern encodes the shape of the words that can occupy the slot determined by *X* and the nature of the semantic relation between *the* and *X*. This is to say that an item-based pattern is an predicate-argument¹ relation which encodes:

1. the lexical identity of the predicate,
1. the lexical category of the argument(s),
2. the sequential position of the predicate vis a vis its argument(s), and

¹ This paper uses the predicate-argument relation to describe item-based dependency patterns. This terminology is used to avoid confusions regarding the ways in which clusters inherit head features for X-bar syntax. In the noun phrase, predicates join with their heads to produce new clusters that inherit the features of the head noun. However, in verb phrases and prepositional phrases featural inheritance is driven by the predicate, not the arguments. Because of this, referring to the arguments as the head of a verb phrase would be confusing. The major danger involved in use of predicate-argument terminology for item-based patterns is the possibility that this would be interpreted as applying outside the domain of lexical combinations. Other levels of predicate-argument decomposition and combination exist throughout language and cognition and we are here only focusing on the role of the predicate-argument relation for combinations of words.

3. the semantic relation between the predicate and its argument(s).

The neural architecture that can instantiate this type of pattern is a sequence detector, located in IFG, that maintains explicit bidirectional connections to two other areas. First, the IFG sequence detector must have links to the lexicon. These links have to be directed to both the specific predicate as a lexical item and the argument slot as a general class. Second, the IFG unit must have links to the area performing sentence interpretation and binding together propositions into coherent mental models. Following Tucker et al. (this volume) and the growing theory of embodied cognition, we hypothesize that this processing occurs in the dorsal stream and involves DLPFC, orbital-frontal cortex, the dorsal corticolimbic circuits, and projections to motor and parietal areas.

Returning to the earlier example of English *my coat* and Hungarian *kabátom*, we can trace how these forms are processed in terms of the IFG sequence control mechanism. In English, when the child hears *my coat*, we can imagine that the bare form *coat* has already been learned. The child may see that a person is referring to a coat, but with the additional fact that this is the coat that belongs to that person. According to MacWhinney (1978), the child compares the known and unknown segments of the input *my coat*. In this case, the argument is recognized, but the predicate is new. The child then enters *my* as a new item in the lexicon, in the areas occupied by affixes and other predicates. Linked to this lexical storage is the establishment in IFG of a sequence detector related to *my*. The child's use of this pathway does not preclude storing *my coat* as a full lexical unit or "amalgam". In Hungarian, amalgam processing for *kabátom* is even more likely, but the child can still pull out *-om* as a separate suffix linked to its own IFG sequencing unit.

Generalization and Composition

Initially, the item-based pattern for *my* has a single item as the predicate and a single item as its argument. As the child hears other combinations with either English *my* or Hungarian *-om*, the argument slot begins to generalize. This generalization is supported by the fact that words that can occupy the argument slot are located in the same general area of the lexical map. In this case, the relevant words are all nouns. In fact, in the DevLex model, both positional and semantic features work together to control lexical self-organization. In this sense, feature generalization is an emergent property of growing lexical organization.

Eventually, the process of generalization begins to work on predicates as well as arguments. Because the sequence detectors for *my*, *your*, *his*, and *its* are so closely linked in lexical space, and because they operate on similar argument types, enforce the same positional pattern, and yield the same interpretations to mental models, their operation in IFG becomes more and more overlapping. At this point, we begin to see a merger of item-based patterns into feature-based patterns. What differentiates feature-based patterns from item-based patterns, is that they are no longer linked to specific lexical items, but instead apply to classes of items. In this case, the feature-based pattern is *Possessor + Possession*. In this way, the child slowly pieces together the 23 major grammatical dependency relations of English, as summarized in the work on the GRASP parser (Sagae, Davis, Lavie, MacWhinney, & Wintner, 2007) for the CHILDES database. In this system, predicates can attach to as many as three arguments. Item-based constructions for verbs can also include the verbs of embedded clauses as arguments. And we will see below how item-based constructions for prepositions and auxiliaries include both an endohead and an exohead.

There is a third level of argument generalization, above the levels of the item-based pattern and the feature-based pattern. This is the level of the global construction. Just as feature-based constructions emerge from a process of generalization across item-based patterns, so global constructions emerge from generalization across feature-based constructions. For example, in English, there are literally dozens of verb groups that share a common placement of the subject before the verb. Together, these constructions give support for the SV global construction in English. The SV and VO global patterns of English work together to produce prototypical SVO order (MacWhinney, Bates, & Kliegl, 1984). Other languages promote different combinations of global patterns. In Hungarian and Chinese, for example, SV, OV, and VO orders operate to express alternative varieties of object definiteness, producing SVO and SOV orders. Italian combines SV and VO patterns with secondary, but significant use of VS (Dell'Orletta, Lenci, Montemagni, & Pirrelli, 2005) to produce SVO and VSO orders. Other global patterns control the ordering of topic before comment or the tendency to associate animacy with agency.

In this section, we have discussed four levels of sequence generalization. Beginning with word pairs, the system then extracts item-based patterns, feature-based patterns, and then global patterns. The processing of all of these patterns is supported by the same underlying mechanisms for sequence detection and control. Together, we can refer to all four levels as involving “positional patterns.”

In addition to this process of generalization, positional patterns can be subjected to a process called composition. Composition takes two positional patterns and hooks them up into a single larger sequence. The important consequence of composition is that it increases the proceduralized nature of syntactic processing. For example, it may be that a single complex network, looking very much like a finite state automaton, processes all variants of noun phrases. In this network, there would be an initial slot for a quantifier, followed by a determiner or possessive, then a series of adjectives, and finally the noun. The compilation of smaller patterns into larger patterns of this type can proceduralize and facilitate both listening and production.

Incremental processing and storage

Dependency grammars such as the GRASP model can be grounded neurologically on IFG pattern detectors of the type outlined here. However, by themselves, dependency relations are not enough to achieve parsing or generation of longer strings of words. Some additional recursive control mechanism is needed to allow for the embedding of the results of one sequence processor in another. Here, one can imagine two neurologically-grounded approaches. One approach would emphasize composition of X-bar structure and trees directly within IFG. However, neurological evidence for such embedded groupings of sequence processors is currently absent. Instead, current evidence suggests that areas outside of IFG are involved in the construction of larger conceptual trees from the sequential fragments detected by IFG. In accounts such as MacWhinney (1987b) or Gibson (1998), smooth processing relies on the incremental construction of interpretable units. Consider a sentence, such as *my coat has a missing button*. As soon as the sequence *my coat* is detected, the predicate is linked to its argument and the whole is then treated as a single cluster in the mental model being constructed. Mental model construction proceeds in accord with the principle of starting points introduced by MacWhinney (1977) and supported in detail by Gernsbacher (1990). The starting point of *my coat* then becomes the perspective from which the rest of the sentence is interpreted. At this point, resonant activation involves items in posterior lexical space, continued processing in IFG, and resultant model elements in dorsal processing. Next, the sequential processor takes this whole active assembly as input to the verb-based frame for *have*. This predicate has argument slots for both a possessor perspective and an object possessed. Even before the second slot is filled, incremental processing activates a mental model expectation for

a thing possessed. Then the phrase a missing button is processed by the two relevant sequence processors and the result then fills the second slot of the verb *has*, thereby completing the mental model of a coat that has a missing button. Of course, the model itself may generate additional associated ideas. Perhaps the button is removed in some overt way; perhaps it is seen on the floor; or perhaps there is a focus on the thread left on the coat after the button has fallen off.

The filling of argument slots in feature-based patterns is driven by a series of cues that have been studied in detail in the context of the Competition Model of MacWhinney (1987a, 1987b) with additional illustrations in McDonald, Pearlmutter, & Seidenberg (MacDonald, Pearlmutter, & Seidenberg, 1994), and O'Grady (2005). The model specifies a series of steps for the ways in which incremental processing triggers competition between constructions:

1. Sounds are processed as they are heard in speech.
2. Competition during sound processing controls activation of a current word.
3. Each new word activates its own item-based patterns along with related feature-based patterns (see below).
4. Item-based patterns then initiate tightly specified searches for slot fillers.
5. Slots may be filled either by single words or by whole phrases. In the latter case, the attachment is made to the head of the phrase.
6. To fill a slot, a word or phrase must receive support from cues for word order, prosody, affixes, or lexical class.
7. If several words compete for a slot, the one with the most cue support wins.

Most work on the Competition Model has focused on comprehension, which is easier to control experimentally. However, the model applies equally well as an account for sentence production. The details of the operation of this parser are controlled by the competitions between specific lexical items and the cues that support alternative assignments. Consider the case of prepositional phrase attachment. Prepositions such as *on* take two arguments; the endohead is the object of the preposition, the exohead is the head of the prepositional phrase (i.e. the word or phrase to which the prepositional phrase attaches). Consider the sentence *the man positioned the coat on the rack*. Here, the endohead of *on* is *rack* and its exohead could be either *positioned* or *the coat*. These two alternative attachment sites for the prepositional phrase are in competition with each other. For detailed examples of the step-by-step

operations of this type of processor consult MacWhinney (1987a), MacDonald, Seidenberg, & Perlmutter (1994), or O'Grady (2005).

In this model, syntax involves nothing more than the repetitive clustering of the results of basic linear detectors. Of course, not all sentences are as simple as the one chosen to illustrate the basic process. Often uninterpreted arguments will build up on sentence memory waiting for merger with their predicates. MacWhinney & Pléh (1988) suggested that the capacity of memory for uninterpreted phrases was no greater than three and Gibson (2001) and others argue for a similar limit. But all analysts agree that there must be a mechanism for storing at least two or maybe three such uninterpreted items during processing. Because of its role in the phonological loop and other memory processes, there is reason to believe that dorsolateral prefrontal cortex (DLPFC) provides the necessary store for not-yet-merged items. This frontal mechanism then provides an additional engine for the maintenance and diversification of linguistic complexity.

But can a mechanism like this really control complex syntax? Don't we need the full power of transformational grammar, or at least context-sensitive phrase structure grammars? What about empty categories, traces, indices, interfaces, and so on? Addressing questions like this is difficult, since there are often many additional suppositions. However, it is important to explain how a linear mechanism of this type can indeed compute complex structures. First, because the slots of feature-based patterns refer to whole classes of items, the power of this machine is beyond that of finite-state processors that operate only on terminal symbols. As Hausser (1992) has shown, finite state grammars that operate on category symbols are formally equivalent to phrase-structure grammars.

Second, the results of individual linear patterns can be combined or clustered through attachment in mental model space. As a result of this, the final model implicitly encodes a full X-bar structure. Third, many of the linguistic phenomena that have been used to motivate complex syntax are actually better represented through memory processes in mental models. Consider the case of the tangled dependencies caused by Dutch serial verbs or the English "respectively" construction. The fact that *John and Bill ordered steak and fish, respectively* can be interpreted best by a mnemonic device that establishes actual spatial positions in mental model space for John and Bill and then engages in the mental action of parceling out steak and fish to these positions in mental model space. This type of mental model processing is basic for anaphoric processing. There is no reason

not to think that it is used to process these constructions too. Of course, the problem here is that, by itself, the syntax would not yield a complete parse tree in such cases. But that is because syntax is not doing this work alone.

A Neural Basis for Mental Models

Recent work in neuroscience has benefitted from four fundamental insights, each relating to the construction of mental models. First, in the 1980s, we learned that the visual system separates processing into an image-oriented ventral stream and an action-oriented dorsal stream.² Second, we have learned from imaging work through the last decade that the brain relies on a perception-action cycle to interpret incoming messages. This cycle involves the generation of mental representations for objects in terms of the ways in which we typically act upon them. Much of this cycle is grounded on interactions that include the action-oriented processing of the dorsal stream. Third, we have learned that the brain provides specific mechanisms for mapping the body images of others onto ours. One consequence of this ability is the fact that certain “mirror neurons” controlling actions, facial gestures, and postures can fire equally strongly when the actor is the self or the other. As we are now learning, these mirror systems are just one of the various components of a general system for social cognition, that also involve temporal facial processing and amygdala and striatal areas for empathy and projection. Fourth, we have learned that the basal ganglia and hippocampus play a central role in the consolidation of memories, often driven by rewards and error minimization.

Piecing together these results, and following the lead of Tucker et al (this volume), we can see that one of the additional consequences of the dorsal-ventral dichotomy is a shift of discrete processing of

² Following the lead of Givon (1995), Hurford (2002) relates the separation of processing into the dorsal and ventral streams to the predicate-argument distinction in language. However, as Bickerton (2002) notes in his commentary to the Hurford’s article, this analysis fails in two important regards. First, predicates and arguments are not “raw sensory feeds” but rather complex lexical items that can themselves involve embedded predications, as we noted earlier in our discussion of words like “promise” or “grandfather”. Second Hurford’s model fails to provide a method by which the brain can integrate predicates and arguments. The mechanism proposed in the current paper is not linked in any clear way to the dorsal-ventral contrast, depending instead on interactions across IFG, distributed lexical processing, and frontal mechanisms for mental model construction.

individual elements to the ventral stream and a shift of global model construction to the dorsal stream, with particular additional regulatory control from frontal areas. In recent papers, I have suggested that this frontal-dorsal system provides the neurological basis for a system that constructs dynamic mental models from linguistic input. At the core of this system is the notion of the self as actor. During sentence interpretation, this fictive self is then projected onto the role of sentence subject, and the self reenacts the image underlying the sentence. Because narrative and dialog often involve rapid shifts between agents, this system has to be able to use linguistic devices to control perspective shifting. As a result of this core dynamics, we can refer to this system as the Perspective Shift System.

This system constitutes the highest level of support for linguistic complexity. Without the mental model construction supported by this system, complex syntax would be useless. This is because the fundamental purpose of virtually all the devices of complex syntax is the marking of perspective shift. This analysis applies across all the major grammatical constructions, including passivization, relativization, clefting, pronominalization, dislocation, existentials, shift reference, split ergativity, serialization, complementation, conjunction, ellipsis, adverbialization, long-distance anaphora, reflexivization, PP-attachment, and participial ambiguity. Each of these structures allows the speaker to combine, maintain, and shift perspectives in communicatively important ways. And these devices allow the listener to trace these movements of the speaker's attention across all of these shifts.

Building Mental Models

The conventional view of mental model construction focuses on the linking of predicates into a coherent propositional graph (Budiu & Anderson, 2004; Kintsch, 1998). This activity is much like the process of clause-combining that we learn in writing class. You can combine "the dog chased the bird" and "the bird flew away" to form "the dog chased the bird that flew away." All that one needs here is a grammatical device that serves to mark the fact that *the bird* plays a role in both clauses. The processing of the grammatical relations within clauses relies on the positional patterns in IFG which then activate role slots in mental model construction. The relativizer is recognized by the lexicon and triggers a the perspective shift in mental model construction. In this case, the shift moves smoothly from *bird* as the object of *chased* to *bird* as the subject of *flew away*. However, if the sentence is "the dog chased the bird that the girl loved" then the

perspective shift is far more difficult, since a brand new perspective is introduced and the perspectives of both *the dog* and *the bird* must be dropped. These shifts of perspective are triggered either by syntactic patterns or by lexical devices. In each case, the child must learn how to operate on signals from the lexicon or IFG to control the correct shifting in frontal cortex. As the developmental literature amply demonstrates, the learning of this control takes many years (Franks & Connell, 1996). Later in this paper, we will explore some of these processes in further detail, since this is one of the primary loci of the consolidation of linguistic complexity.

Perspective and Gesture

The frontal-dorsal system for perspective shifting is not a recent evolutionary adaptation. Chimpanzees (Tomasello, Call, & Gluckman, 1997), dogs, and other mammals make extensive use of symbolic behaviors in social contexts. However, lacking a lexicon and positional patterns, other animals cannot organize these behaviors into recursive structures³ However, Donald (1991) and others have argued that the production of symbolic communication can rely on gestural and vocal devices that may well have been readily accessible to *homo erectus*. Because gestures can be formed in ways that map iconically to their referents, it is relatively easy to build up communal recognition of a gestural system. As Tucker et al. (this volume) argue, such a system would rely primarily on gestures and affordances specific to the action-oriented processes in the dorsal stream. It appears that learners of contemporary sign languages are able to use posterior lexical areas to structure a lexicon of signs, just as they use IFG in the left hemisphere to control the ordering of signs. It is possible that protosign could also have relied on these same neuronal structures for lexical organization. However, looking back two million years, it is likely that the depth of support for lexical storage and positional patterning of gesture was still very incomplete. As a result, it is likely that protosign was incompletely lexical and heavily reliant on dorsal processes for direct perspective taking and shifting.

Although sign may not have triggered full linguistic structure, it provided a fertile social bed that supported the development of further articulatory, lexical, and sequence systems. As Darwin (1872) notes,

³ Gentner, Fenn, Margolish, & Nusbaum (2006) claim that starlings demonstrate recursive processing for strings such as AAABBB. However, Corballis (2007) points out that these strings can be detected through a subitization-based counting mechanism that has been demonstrated for birds.

vocal and gestural communication coexisted as parallel streams from the beginning of human evolution. Gesture and prosody were able to keep humans engaged in protoconversations, during which the further elaboration of vocal patterns could refine and complement communication in the gestural-prosodic mode. Of course, humans are not the only primates that engage in conversation. However, as argued in MacWhinney (2005b), the shift in *homo habilis* to a full upright posture led to two important consequences. One was the freeing of the hands for additional conversational interaction and the other was the encouragement of full face-to-face interactions linked to full display of the hands and torso. This increasing support for gestural communication brought along with it a supportive social context for the further development of accompanying vocalizations. However, both of these modalities continue to provide important input to conversation in modern humans. Thus, we can best view the transition from a primarily gestural communication to a primarily vocal communication system as gradual, but unbroken, process (MacWhinney, 2005b) with no sudden break based on the sudden introduction of an ability to process recursion.

Digression: Accounting for Critical Periods

The vision of language processing elaborated here has interesting implications for our understanding of age-related processes in second language acquisition and bilingualism. Much current work in these fields has been shaped by the Critical Period Hypothesis (CPH), as proposed by Lenneberg (1967). According to Lenneberg, fundamental hormonal changes at puberty lead to a consolidation of brain lateralization and a loss of neuronal plasticity. Before this critical period, children can easily learn a second language to native-like proficiency. After this critical period, languages can no longer be learned in a natural way. There are now many hundreds of articles and scores of books discussing the pros and cons of this hypothesis. Although few researchers continue to accept the hypothesis as originally formulated, there is still widespread awareness of the fact that it becomes increasingly difficult to acquire a nativelike account in a second language after perhaps ages 6 or 7 (Flege, Yeni-Komshian, & Liu, 1999). Moreover, there is evidence that some forms of syntactic processing are difficult to restructure in second language learning during adulthood.

One way of understanding these age-related patterns focuses on the ways in which neuronal maps become “entrenched” over time. For example, in Figure 4 above, it was more and more difficult in the later

epochs of learning in DevLex to produce major changes in the shape of the lexical map. Emergentist accounts of age of learning effects for L2 learning (Hernandez, Li, & MacWhinney, 2005; MacWhinney, in press) have relied on this notion of entrenchment as a simple replacement for the notion of a hormone-based critical period. However, the analysis presented here suggests that the picture is not that simple. Studies of neuronal regeneration have shown that, in fact, there is a great deal of regeneration and local rewiring in cortical areas throughout adulthood. Thus, the entrenchment we are hypothesizing for L1 cannot be due simply to the loss of local plasticity. Instead, I believe we need to look at the ways in which local areas connect to distal processing areas through axonal projections. In fact, all six of the modules we have examined are connected in this way to other areas. The problem the brain faces in learning a second language is not to reorganizing local connections, but to figure out how to restructure these inter-module connections.

Consider the case of connections between output phonology and the lexicon. Here, the lexicon must maintain somatotopic connections to areas in IFG and motor cortex that control specific phonemic or syllabic gestures. These units are organized topologically during the first two years of life so that input and output phonology are properly coupled to the contrasts of the target language. When the second language learner comes to learn a new word in L2, this new word must be connected initially to L1 output gestures. For example, when producing the Spanish word "taco" and English speaker will map the initial stop onto the aspirated /t/ of English, thereby producing a form with a decidedly foreign accent. It may well be impossible to establish new axonal connections to support this new L2 articulatory gesture. Instead, it is likely that secondary modifications are produced in IFG and motor cortex that systematically modify the English /t/ by reducing its aspiration when the area receives modulation from subcortical structures consistent with the use of Spanish. This new version of /t/ will slowly develop a status as a competitor to English /t/ in the same general region of motor cortex. Over time, the final branches of the axonal projections from the lexicon will tend to innervate this new area so that the connection between new Spanish words and Spanish output phonology will be smoother. However, this reorganization is fundamentally more difficult than that involved in restructuring forms within a local module.

These difficulties apply equally to both output phonology and positional patterns, since in both cases, there must be fine-tuning at a distance across long axonal projections. They also apply to input phonology, although in that case top-down lexical processes may tend

to mask problems with reshaping the effects of a foreign accent in auditory processing.

But, if this is true for these three modules, then why do we not see similar limitations in the learning of new L2 lexical items? This is because this learning is “parasitic” on L1 lexical forms in a way that makes the semantic range of the new words accurate enough to pass as correct. For example, the semantic range of Spanish *mesa* is close enough to that of English *table* to make them essentially equivalent for the beginning learner. A similar analysis is true for the L2 perspective shifting system and the learning of L2 methods for relying on short term storage.

Engines of Complexity

We have now finished our survey of an account of neurolinguistic processing grounded on self-organizing feature maps, sequence processing mechanisms, limbic consolidation, and topological preservation of feature map resonance across six linguistic modules. The core mechanisms of neural connectivity and firing are fundamental to all animals from molluscs to mammals. Mechanisms for sequence detection and control can also be found in both invertebrates such as insects and vertebrates such as amphibians. Systems of topographic organization can be found even in animals with no cortex. Systems controlling memory consolidation and value-based projection are found in bees. What is new in the engines supporting language are not the pieces, but the ways in which the pieces are being combined. Let us review these innovative configurations in the context of the six modules supporting language processing:

1. Input phonology. This system is available to all mammals. However, it is tuned during development to produce a sharpening of contrasts found in the target language (Kuhl, 1991; Werker, 1995) and central to the lexicon and the morphosyntax. This system works to reduce an enormous perceptual complexity into a much smaller set of meaningful contrasts.
2. Output phonology. Once linked to input phonology, this system takes control of a complex production mechanism to align with the greatly reduced contrast space of input phonology. Thus, like input phonology, this is a system that reduces complexity to simpler contrasts.
3. Lexicon. This system relies on hierarchically linked self-organizing feature maps to link distributed conceptual structures to phonological forms.

4. Lexical Analysis. This system works to analyze input forms into predicate-argument structures. The predicates in these structures are then linked to item-based patterns in IFG and morphophonological patterns associated with affixes in the lexicon.
5. Syntax. This system extracts patterns in lexical sequencing. Beginning with simple word pairs, generalization moves through item-based patterns, feature-based patterns, and global patterns. These sequence detectors maintain tight links both to the lexicon and to mental model construction. These patterns can also be compiled into longer chains to improve fluency.
6. Discourse. The linking of syntactic patterns into mental models relies on initial storage in a frontal STM buffer. Once an item can be linked into a growing mental model, it can be released from short-term storage. The growing mental model is interpreted in terms of an ego-based system of perspective shifting.

We can now ask how these engines support linguistic complexity. One answer that has been offered by Hauser, Chomsky, & Fitch (2002) as well as Bickerton (this volume) is that linguistic complexity arises from the Merge operation of minimalist syntax. Certainly, the Merge operation is a crucial step in the construction of complex syntax. However, it is important to avoid oversimplification of this issue. In neuronal terms, the Merge operation can be decomposed into several component processes.

1. In sentence production, lexical items must be activated before they can fill slots in positional patterns.
2. In models of sentence production such as those proposed by Garrett and Levelt, the activation of words occurs in parallel or even after the activation of a syntactic frame. In any case, it is likely that relations in mental model space prime IFG positional patterns, preparing them to accept candidate lexical forms. This priming must be viewed as a separate process.
3. The filling of slots is governed by a process of competition. Merger cannot occur until this competition is resolved.
4. There must also be lateral connections between alternative, competing positional patterns. In particular, larger, more specific patterns formed from the composition of shorter patterns must inhibit the corresponding shorter patterns.
5. Merger produces sentence fragments that must be stored in a short-term memory buffer to permit X-bar cluster formation. This storage is not itself a part of merger and without it, merger would only succeed in processing the simplest sentences.

6. Finally, the merger that occurs on the syntactic level is not itself enough to control either recognition or production. Merger must be connected to mental model processing. By itself, a merger system would have no adaptive utility and no evolutionary advantage.

These six processes must work together to produce recursion. Without the complete set of all six, along with further support from the lexicon and social support, the full construction of grammatical complexity would not be possible.

Mimetic Processes

Our discussion so far has confined itself to the neural engines of linguistic complexity. However, without social input, these engines would produce nothing more than fuzzy and incoherent inner speech. Through the process of language learning, this neuronal substrate is molded and shaped into complex patterns that reflect those inherent in the input. Human language has the shape it does, because it must be learnable by children (Christiansen & Chater, 2008). Moreover, this learnability has been maintained now in a consistent fashion for perhaps two million years, as humans moved from one step of protogesture and protolanguage to the next, always relying on the fact that what they were producing was in good alignment with things that the next generation could learn. The close relation between the mother and the infant certainly plays a central role in this process, as mothers move their children into a linguistically profitable “zone of proximal development” through processes of imitation, recasting, scaffolding, and vocal play.

Once a child becomes an adult, the linguistic power derived from initial learning can now be turned back upon language itself. Adults can create new words, collocations, expressions, prosodies, gestures, constructions, poems, jargon, and grammatical devices. If they build these new creations upon devices that can be easily learned by others and which express interesting social goals, then these devices will spread across the language community through processes of mimetic drift, eventually producing language change. When we then come to look at the results of these processes, we can then return to our original analysis and ask how the underlying neuronal mechanisms we have surveyed functioned to incorporate this mimetic changes into the stable core of the language of the community.

Applications of the Model

With this linkage between the brain and social processes in mind, we are now ready to consider the genesis of specific forms of linguistic complexity. Let us consider these four processes: nominalization, colexicalization, compilation, and construction formation.

(to be written -- I expect about five pages here -- sorry for the delay)

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