Two Types of Hierarchical Linguistic Structure in the Brain

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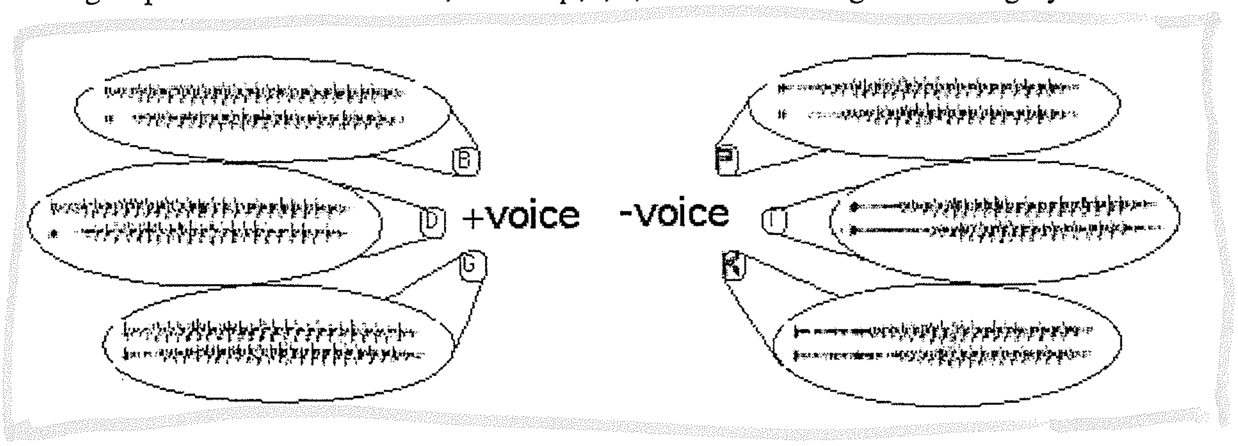
A basic design property of human language is its use of a relatively small number of elements to create substantial expressive power. By combining a small number of categories in many different ways, vast numbers of different expressions can be created. This property is repeated at a number of different levels of language. At the level of phonology, primitive units known as *features* are combined to form phonological categories, and these phonological categories are combined to form morphemes and words. At the level of syntax, words are combined to form sentences. A central part of a speaker's knowledge of his language is knowledge of how to combine elements to form hierarchical linguistic structures, at each of a number of different levels (phonology, morphology, syntax, semantics).

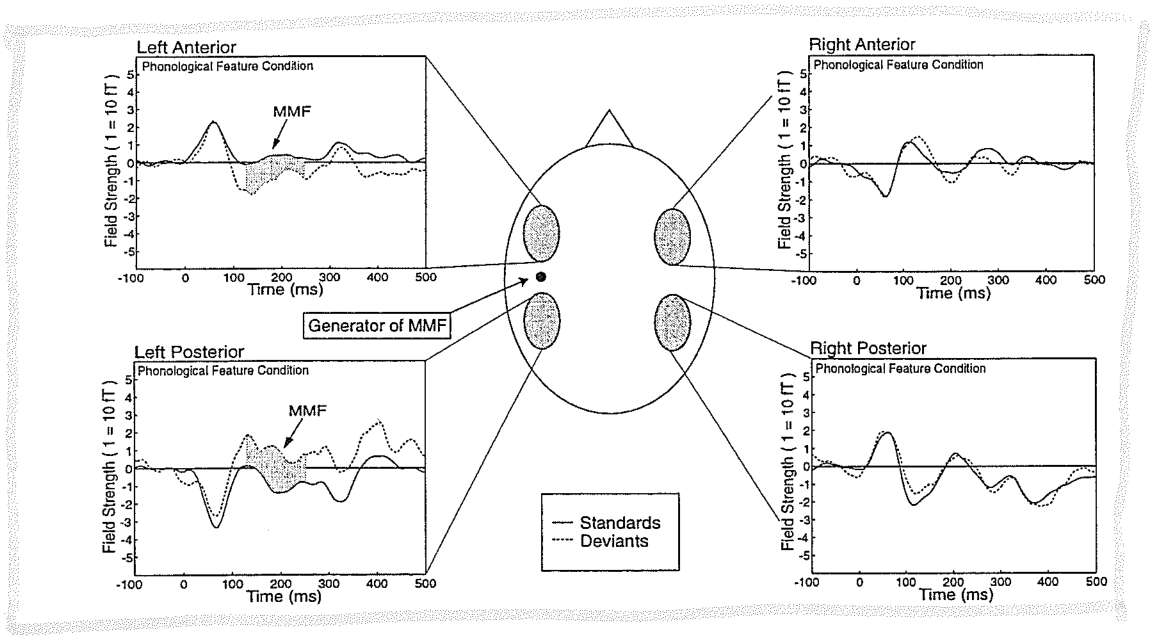
Therefore, in order to understand how the human brain supports language, it is important to understand how the brain supports the grouping of linguistic elements to form larger structures. Our work has investigated this question at both the phonological and syntactic level of language. The objective of this talk will be to show that there are at least two very different notions of hierarchical linguistic structure, each of which place rather different requirements on a brain-level model of language processes. The first type of hierarchical structure is clearly *finite*, and can be stored in long-term memory in the brain. The second type of hierarchical structure is *infinite*, and therefore requires mechanisms which can create novel structured representations over the course of a few hundred milliseconds.

1. Phonological Structures

The categories of phonology involve various types of groupings of sounds. Phonological categories such as /k/, /æ/ and /t/ group together the many different possible pronunciations of each of the categories. In addition, although phonemes are the smallest linguistic units that speakers are usually consciously aware of, a good deal of linguistic evidence indicates that sub-phonemic *features* are the smallest building blocks of language. Sounds which share a feature are thus grouped into natural classes, such as *p*, *t*, *k*, which all belong to the category *voiceless*.



In a series of studies using MEG recordings in an adapted mismatch paradigm, we have investigated the grouping of sounds into phonological categories, and the grouping of phonological categories into feature-based natural classes (Phillips *et al.*, 2000abc). The results of our studies indicate first that discrete phonological category representations are available to human auditory cortex. Second, although representations at the analog, phonetic level may be present in both left and right hemispheres, representations at the discrete, phonological level may be restricted to the left hemisphere.



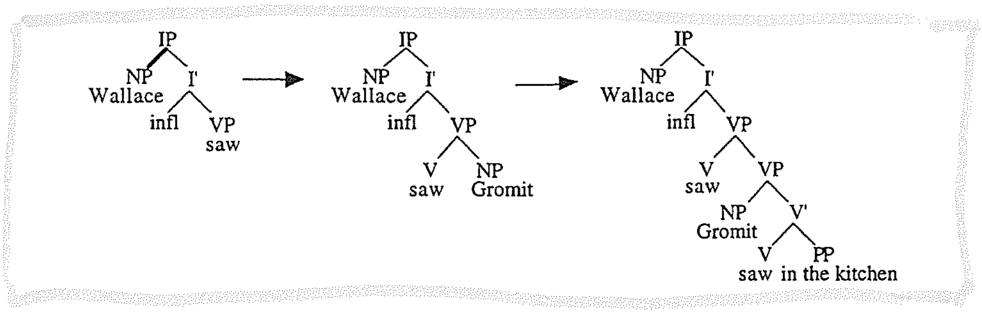
Although our findings suggest a sophisticated role for left hemisphere auditory cortex in phonological processing, this sophistication involves the use of long-term representations of sound groupings. Such long-term groupings of perceptual elements are similar to other relatively well-understood phenomena in neuroscience.

2. Syntactic Structures

Sentence structures pose a problem of a rather different nature. Due to the *iterative* and *recursive* properties of natural language syntax, speakers are able to draw on a finite number of words to create an infinite number of sentences – this is the 'discrete infinity' property of language – and any sentence may be understood within a very brief period of time. Therefore, the brain must provide mechanisms which support representations which are (a) highly structured, and (b) can be created within a few hundred milliseconds. Syntactic structures consist of sets of relations, or 'dependencies', between words and phrases. Therefore, a fundamental task in understanding how the brain supports structural representations is to explain how the brain is able to represent structural dependencies.

Importantly, since sentence structures are too numerous to be stored in long term memory, the brain mechanisms for representing hierarchical sentence structures must be very different from the mechanisms which support hierarchical phonological structures.

In order to bridge the gap between our understanding of sentence structure at the linguistic level and at the brain-level, a number of steps are required. I will briefly review some work by our group with this goal. First, we have begun to develop a dynamic model of human syntactic knowledge, which can be deployed in real-time syntactic processing (Phillips, 1998). Second, fragments of this approach have been implemented in a working computational model (Schneider, 1999). Third, we have run a number of experimental tests of the model, using reading-time paradigms (e.g. Phillips & Wong, 2000; Schneider & Phillips, 2000). Finally, we have begun to explore the representation of sentence structures using ERP brain recordings.



As a first step towards understanding how the brain supports sentence structure representations, we are investigating what are the *limiting factors* which restrict speakers' ability to represent structure. In our studies we are building upon work by Gibson (1998) and others.

As Gibson and others have shown, the construction of syntactic dependencies places severe burdens on the sentence processor. In particular, the construction of *longer* dependencies places a greater demand on the processor than the construction of shorter dependencies. However, it is less clear whether this reflects limitations on *storage* (i.e. only a small number of incomplete dependencies can be stored simultaneously) or limitations on the *computational* abilities of the sentence processor. I will discuss results from an ERP study which aims to distinguish the role of storage and computation by examining the time course of Gibson's length effect.

We use materials like (1a-d), in which conditions containing *wh*-dependencies (1b,d) are contrasted with control conditions which lack a *wh*-dependency (1a,c). Also, shorter *wh*-dependencies (1b) are contrasted with longer *wh*-dependencies (1d). Subjects read 160 examples of these sentences, interspersed with 320 filler sentences, in an RSVP paradigm, while high-density EEG recordings were made.

1. a. The patients thought that the nurse knew that the suspicious visitor had stolen the drugs from the storeroom.
   b. The patients thought that the nurse knew which drugs the suspicious visitor had stolen from the storeroom.
   c. The nurse knew that the patients thought that the suspicious visitor had stolen the charts drugs from the storeroom.
   d. The nurse knew which drugs the patients thought that the suspicious visitor had stolen from the storeroom.

If storage is the limiting factor in representing sentence structure, we expect to observe an effect of dependency length *before* the completion of the *wh*-dependency in (1b,d). On the other hand, if computation is the limiting factor, we expect to observe an effect of dependency length at the point where the *wh*-dependency is completed (i.e. at the embedded verb in 1b,d).

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