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What artificial grammar learning reveals about the neurobiology of syntax

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ABSTRACT

In this paper we examine the neurobiological correlates of syntax, the processing of structured sequences, by comparing FMRI results on artificial and natural language syntax. We discuss these and similar findings in the context of formal language and computability theory. We used a simple right-linear unification grammar in an implicit artificial grammar learning paradigm in 32 healthy Dutch university students (natural language FMRI data were already acquired for these participants). We predicted that artificial syntax processing would engage the left inferior frontal region (BA 44/45) and that this activation would overlap with syntax-related variability observed in the natural language experiment. The main findings of this study show that the left inferior frontal region centered on BA 44/45 is active during artificial syntax processing of well-formed (grammatical) sequence independent of local subsequence familiarity. The same region is engaged to a greater extent when a syntactic violation is present and structural unification becomes difficult or impossible. The effects related to artificial syntax in the left inferior frontal region (BA 44/45) were essentially identical when we masked these with activity related to natural syntax in the same subjects. Finally, the medial temporal lobe was deactivated during this operation, consistent with the view that implicit processing does not rely on declarative memory mechanisms that engage the medial temporal lobe. In the context of recent FMRI findings, we raise the question whether Broca's region (or subregions) is specifically related to syntactic movement operations or the processing of hierarchically nested non-adjacent dependencies in the discussion section. We conclude that this is not the case. Instead, we argue that the left inferior frontal region is a generic on-line sequence processor that unifies information from various sources in an incremental and recursive manner, independent of whether there are any processing requirements related to syntactic movement or hierarchically nested structures. In addition, we argue that the Chomsky hierarchy is not directly relevant for neurobiological systems.

1. Introduction

The human capacity for language and communication is subserved by a network of brain regions that collectively instantiate the semantic, syntactic, phonological and pragmatic operations necessary for adequate language comprehension and production. A growing number of studies on the neural architecture of language, using electromagnetic (EEG/MEG) and hemodynamic methods (PET/FMRI), have added to, and also changed previous views on the brain's infrastructure for language. Before elaborating on some current issues related to the neurobiology of syntax, here is what we believe to be the major conclusions from the overall body of literature on the neurobiology of language:

(i) The language network is more extended than the classical language regions (Broca's and Wernicke's areas). It includes, next to Broca's region, adjacent cortex in the left inferior and middle frontal region, as well as substantial parts of superior and middle temporal cortex, inferior parietal cortex, and parts of the basal ganglia. In addition, homotopic regions in the right hemisphere are more often than not engaged in language processing (Hagoort, 2009).
(ii) The division of labor between Broca's region (frontal cortex) and Wernicke's region (temporal cortex) is not language production vs. language comprehension. The neocortex centered on the left inferior frontal region is involved in, at least, syntactic and semantic unification (on-line combinatorial operations during comprehension). Wernicke's region is involved in language production, at least at the level of word-form encoding (Indefrey & Levelt, 2004).

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(iii) None of the language-relevant regions and none of the language-relevant neurophysiological effects are language-specific. All language-relevant ERP effects (e.g., N400, P600, (E)LAN) seem to be triggered by other than language input as well (e.g., music, pictures, gestures).
(iv) For language, as for most other cognitive functions, the function-to-structure mapping as one-area-one-function is almost certainly incorrect. More likely, any cortical region is a node that participates in the function of more than one functional network. Conceivably, top-down connections from supramodal regions could differentially recruit such a cortical node in the service of one network or another (Mesulam, 1990, 1998).

In normal language processing, semantics, phonology and syntax operate in close spatial and temporal contiguity in the human brain. Therefore the artificial grammar learning (AGL) paradigm has been used to create a relatively uncontaminated window onto the neurobiology of syntax (Gómez & Gerken, 2000; Petersson, Forkstam, & Ingvar, 2004; Reber, 1967). In addition, AGL has been used in cross-species comparisons in an attempt to establish the uniquely human component of language (Fitch & Hauser, 2004; Gentner, Fenn, Margoliash, & Nusbaum, 2006; Hauser, Chomsky, & Fitch, 2002; O'Donnell, Hauser, & Fitch, 2005; Saffran et al., 2008). Here, we will present data from an FMRI experiment that speaks to the neurobiology of syntax. In addition, we will discuss some of the theoretical issues resulting from the fact that, from a brain perspective, reference to and application of the Chomsky hierarchy is not directly relevant – a point that can be made on linguistic grounds as well (Pullum & Scholz, 2009, 2010).

The implicit AGL paradigm allows a systematic investigation of aspects of structural (i.e., syntactic) acquisition from grammatical examples alone, without providing explicit feedback, teaching instruction, or engaging the subjects in explicit problem solving based on instruction. These acquisition conditions resemble, in certain important respects, those found in natural-language development. Generally, AGL consists of acquisition and test phases. In the acquisition phase, participants are exposed to an acquisition sample generated from a formal grammar. In the standard version, subjects are informed after acquisition that the sequences were generated according to a complex set of rules, and are asked to classify novel sequences as grammatical or not, based on their immediate intuitive impression (i.e., guessing based on "gut feeling"). A robust finding in this type of paradigm is that after several days of implicit acquisition subjects perform well above chance; they do so on regular (e.g., Folia et al., 2008; Forkstam, Elwér, Ingvar, & Petersson, 2008; Petersson et al., 2004; Stadler & Frensch, 1998) as well as non-regular grammars (Poletiek, 2002; Uddén et al., 2009), generating context-free and context-sensitive non-adjacent dependencies (Uddén, Ingvar, Hagoort, & Petersson, submitted for publication; Uddén et al., 2009). In passing, we note that a qualitative match between the performance of simple recurrent networks and human comprehension of nested (context-free) and crossed (context-sensitive) dependencies has been reported (Christiansen & Chater, 1999; Christiansen & MacDonald, 2009). Because (in a technical sense), noisy or discrete simple recurrent networks are finite-state architectures (Casey, 1996; Maass, Joshi, & Sontag, 2007; Maass & Orponen, 1998; Maass & Sontag, 1999; see also, Petersson, 2005b; Petersson, Grenholm, & Forkstam, 2005), these results suggest that actual language processing uses no more on-line memory resources than can be provided by a finite-state architecture. These simulations, of course, only illustrate that recurrent networks can handle (bounded) non-regular processing at some level of proficiency. However, a correlation between the processing of long-distance-dependencies in natural language and statistical learning of non-adjacent dependencies was recently reported, suggesting a link between natural-language processing and implicit sequence learning. The latter performance was adequately modeled by a simple recurrent network in a visuomotor sequence learning task (Misyak, Christiansen, & Tomblin, 2009, 2010).

The recursion-only hypothesis concerning the faculty of language (Hauser et al., 2002), and subsequent discussion (e.g., Chomsky, Fitch, & Hauser, 2005; Jackendoff & Pinker, 2005; Pinker & Jackendoff, 2005), has inspired research on the neurobiology of syntax to be phrased in terms of recursion and the Chomsky hierarchy. More specifically, the recursion-only hypothesis suggests that some aspects of the language faculty are shared with non-human animals, whereas other aspects are specific to the human language faculty and the quest for "core syntax" in behavioral and functional neuroimaging studies of natural and artificial syntax has sometimes centered on the theoretical construct of the Chomsky hierarchy (Fig. 1).

In particular the syntactic feature of center- or nested embedding has been the focus of recent research (Bahlmann, Schubotz, & Friederici, 2008; Fitch & Hauser, 2004; Friederici, Bahlmann, Heim, Schubotz, & Anwander, 2006; Makuuchi, Bahlmann, Anwander, & Friederici, 2009). In the linguistic and psycholinguistic literature, the Chomsky hierarchy is most often formulated in terms of formal grammars. However, from a neurobiological point of view it is more natural to formulate the Chomsky hierarchy in terms of (equivalent) computational mechanisms (cf. e.g., Cutland, 1980; Davis, Sigal, & Weyuker, 1994; Hopcroft, Motwani, & Ullman, 2000; Savage, 1998; Soare, 1996), since the objective in neurobiology is to identify the neurobiological mechanisms underlying syntax. From the point of view of computability theory, the Chomsky hierarchy is in essence a memory hierarchy, which specifies the necessary (minimal) memory resources required for a given level of computational expressivity. However, it is *not* a complexity hierarchy for the mechanism(s) involved in various computational architectures, which are all equivalent to finite-state architectures (Minsky, 1967; Soare, 1996; Turing, 1936a, 1936b; Wells, 2005). We will return to the significance of this fact in the discussion section.

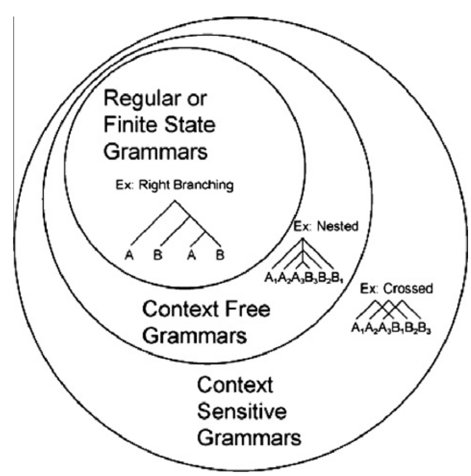

Fig. 1. The Chomsky hierachy. Informally, regular (finite-state) or right-linear phrase-structure grammars are built from a collection of production rules of the form $S \rightarrow abS$ and $S \rightarrow ab$ (where lower case indicates terminal symbols and S a non-terminal sentence or start symbol). It is the inclusion of the start symbol on the right hand side of the first regular rule ($S \rightarrow abS$) that makes this grammar recursive (Soare, 1996). The non-regular context-free case allows the right hand side to involve terminal symbols around the sentence symbol additional as in $S \rightarrow aSb$ and $S \rightarrow ab$. In the non-regular context-sensitive case, the left hand side has a "context" as exemplified in $a_1a^nSb_1b^n \rightarrow a_1a^na_{n+2}Sb_1b^nb_{n+2}$ (cf., Davis et al., 1994).