★ EDITORIAL ★

Biolinguistic Perspectives on Recursion: Introduction to the Special Issue

Uli Sauerland & Andreas Trotzke

1.   Introduction

Recursion is a central issue of the biolinguistic investigation of language. This special issue brings together seven new contributions on recursion from several different perspectives: theoretical syntax, neurolinguistics, language acquisition, genetics, and psycholinguistics. In this introduction, we first briefly characterize the background on recursion that the contributions share and that led to this special issue of *Biolinguistics*. Secondly, we situate the advances of the individual contributions in this issue against the background of studies on recursion.

The notion of recursion has played a significant role in the development of the field of linguistics and specifically of the generative approach. The concern that lead to recursion is very old: Descartes (2003 [1637]: 38) hypothesized that the crucial difference between man and animal manifests itself most clearly in the fact that an animal "never […] arranges its speech in various ways […] in order to reply appropriately to everything that may be said in its presence, as even the lowest type of man can do". In a similar vein, and two centuries later, Wilhelm von Humboldt (1999 [1836]: 91) pointed out the human capacity to "make infinite employment of finite means" in language. Recursive rules provide one solution to the problem of accounting for an infinite number of possible sentences by means of a finite memory space. However, Descartes and Humboldt didn't yet talk about recursion specifically, and infinity could be produced by means other than recursion. In the 1950s, Noam Chomsky developed formal language theory as a mathematically precise model of language and, using it, specified a precise role of recursion within formal models of language. In fact, recursion in one specific way proved to be essential to set apart the phrase structure models of language Chomsky proposed from the behaviorist models of language prevalent

at the time. Chomsky, however, didn't use the term *recursion* for this notion, but defined the notion of *self-embedding* as follows:

(1)   A language L is *self-embedding* (s.e.) if it contains an A
        such that for some ϕ, ψ $(\phi \neq I \neq \psi)$, $A \Rightarrow \phi A \psi$.   (Chomsky 1959: 148)

The definition characterizes as self-embedding any language that contains a string A and allows the derivation from A of a string that properly contains A, that is, A is preceded and followed by two non-trivial strings. Over two papers, (Chomsky 1956, 1959) showed that the concept of self-embedding precisely sets apart context-free grammars from less complex models of grammar (specifically, finite state Markov process based models): All and only the languages produced by a context-free grammar that are self-embedding cannot be given an analysis using the less complex models.

    Chomsky (1957) furthermore showed that English is self-embedding. In a nutshell, this demonstration consists of the observation that patterns such as (2) exist in English (slightly modified from Chomsky 1957: 22) and clearly satisfy the definition of self-embedding in (1).

(2)   a. $S \Rightarrow$ If S, then it's true.
        b. $S \Rightarrow$ Either S or not.

Finite state Markov chain models of language cannot capture the long-distance dependencies between *if* and *then* and *either* and *or*. Therefore, Chomsky established that behaviorist accounts of language were insufficient, whereas the phrase structure grammars Chomsky introduced could be sufficient. In this way, recursion was crucial for the development of phrase structure based approaches to language. However, subsequently recursion was not a major topic: Once phrase structures were established, recursion became part of the background. Chomsky and many other linguists proceeded to develop concrete phrase structure based grammars for specific languages.

    Almost ten years ago, recursion became an active topic of research again due to work of Marc Hauser, Noam Chomsky, and Tecumseh Fitch. In an influential paper, Hauser *et al.* (2002) formulate a new hypothesis involving recursion. For this purpose, they differentiate between the broad and the narrow sense of faculty of language, drawing on the basic biolinguistic distinction between human traits that can be relegated to more general cognitive capacities, which, as Hauser *et al.* claim, are shared with other animals, and traits that are both human- and language-specific. They then hypothesize that only syntactic recursion belongs to the faculty of language in the narrow sense. With syntactic recursion, Hauser *et al.* seem to have in mind a general ability that underlies Chomsky's (1959) notion of self-embedding language in (1): a property of languages that distinguishes between phrase structure grammars and less powerful grammars (cf. Fitch 2010, Tomalin 2011, Luuk & Luuk 2011). Specifically, Hauser *et al.* write that "[n]atural languages go beyond purely local structure by including a capacity for recursive embedding of phrases within phrases" (p. 1577). Recursion is more general than self-embedding, though: The natural numbers, for example, also

rely on recursion, though possibly recursion within a finite-state grammar. Following much of the subsequent psychological literature (e.g. Gentner *et al.* 2006, Friederici *et al.* 2006), we assume that only a grammar that can account for self-embedding languages should be called *recursive*, and will use the term in this restricted sense in the following.

The hypothesis of Hauser *et al.* and their arguments captured the imagination of many researchers from different disciplines. Even though an enormous amount of progress has been made, many of the debates Hauser *et al.* triggered are still not resolved. This special issue takes up three major concerns that have developed since 2002. The first concern is how to test for recursion in experimental psychology: Since we cannot test humans on infinite sets of sentences and furthermore self-embedding in the sense of (1) is difficult for humans to process, how can recursion best be tested for? The second major concern is the role of recursion in linguistic theory: Is recursion an integral part of any syntactic structure building or is recursion better viewed as something on top of more basic structure building? Finally, the third major concern this issue addresses is the relation of recursion to the genetic and neural basis of language. Can recursion be separated from other parts of language in the genetic and neural domain?

2.   Testing Recursion in Experimental Psychology

Testing recursion in experimental psychology crucially rests on the Artificial Grammar Learning (AGL) paradigm, which goes back to Reber (1967) and enables psychologists to isolate fundamental mechanisms involved in natural language syntax in sophisticated test designs. The first AGL study interpreted to be relevant for understanding syntactic recursion at the behavioral level was carried out by Fitch & Hauser (2004). They focused on the comparison between a self-embedding language and one that isn't. The two types of structures can be illustrated with the two English sentences in (3) and (4):

(3)   [*The man*]$_A$ [*the dog*]$_A$ [*bit*]$_B$ [*comes*]$_B$.

(4)   [*The man*]$_A$ [*comes*]$_B$; [*the dog*]$_A$ [*bit the man*]$_B$.

As already mentioned, a finite-state grammar cannot account for center-embedded languages. Fitch & Hauser created stimuli that correspond to the artificial grammar A^nB^n, generating structures like (3) with n=2, and $(AB)^n$, yielding for n=2 structures like (4). The actual stimuli were not created using English words, however, but classes of syllables. With these stimuli, Fitch & Hauser compared the parsing abilities of cotton-top tamarins (*Saguinus oedipus*) and humans regarding both grammar types. The result of their study was "that tamarins suffer from a specific and fundamental computational limitation on their ability to spontaneously recognize or remember hierarchically organized acoustic structures" (p. 380). That is, while tamarins were able to process structures generated by the $(AB)^n$ grammar, they were not capable of mastering structures according to the A^nB^n formula. Accordingly, this experimental study supports the hypothesis that "the acquisition of hierarchical processing ability

may have represented a critical juncture in the evolution of the human language faculty" (p. 380) and thus may be of direct relevance to the hypothesis suggested by Hauser *et al.* (2002).

However, a finite set of experimental materials such as that of Fitch & Hauser couldn't in principle exclude all alternative explanations other than a recursive phrase structure grammar of the performance of the human subjects. For the materials of Fitch & Hauser, specifically, humans may have relied on counting rather than grammar building when processing the A^nB^n sequences or on additional cues specific to their stimuli. Research since has explored different experimental methods and formal grammars to more precisely pin down specific human abilities. One focus has been the fact that natural human language requires the ability to process sequences in which a consistent coupling of AB-pairs is involved (cf. Perruchet & Rey 2005, de Vries *et al.* 2008). To visualize, the more exact representation of our sentence (3), according to this objection, must be (5), where the pairing of particular As an Bs is marked by numbers:

(5)   [*The man*]$_{A1}$ [*the dog*]$_{A2}$ [*bit*]$_{B2}$ [*comes*]$_{B1}$.

The results for formal grammars eliciting such structures have been mixed. Given several methodological issues, it is now a central concern in this field of inquiry "that the relation between artificial language studies and natural language must be clarified" (Hauser *et al.* 2007: 127). As a consequence, experimental methods and insights have become more differentiated. Two contributions in this issue, one by de Vries et al. and one by Poletiek, advance this agenda.

Meinou de Vries, Morten H. Christiansen, and Karl Magnus Petersson argue that research focusing only on nested dependencies like (3) cannot provide us with a complete picture of where the boundaries of human language processsing lie. They show that crossed dependencies, another type of non-adjacent dependencies, are easier to learn than nested dependencies, if the number of dependencies exceeds two. In light of this finding, they argue that the different complexity levels formulated in the Chomsky hierarchy (cf. Chomsky 1956) and used by studies such as Fitch & Hauser (2004) and Gentner *et al.* (2006) are less relevant. Instead, they propose a new complexity hierarchy, which is based on the assumption that syntactic complexity is determined by (i) the number of dependencies that need to be resolved and (ii) the specific ordering of these dependencies.

Fenna Poletiek argues that the so-called 'staged input effect' is relevant for learning an artificial grammar with center-embedded structures. Referring to studies that have shown that artificial grammars with center-embedded structures are difficult to learn by induction, Poletiek claims that participants do better if the input used to train human subjects is presented in an incremental organization, starting with the least complex and ending with the most complex exemplars. Crucially, this staged input effect is argued to be helpful for hierarchical structures only and shows no effect for learning a finite state grammar. Like de Vries *et al.*, Poletiek advances the perspective that competence models for language complexity like the Chomsky hierarchy should care about performance factors such as learnability.

3. Locating Recursion in Linguistic Theory

Syntactic theories describe generalizations at various levels of the typology of phrases. At the least specific level of the phrasal typology, any word or phrase belongs to the same type. All that can be said for this type of phrase is that two phrases can form a complex syntactic constituent, as is captured by the operation *Merge* in minimalist syntax. Many syntactic generalizations, however, make reference to a more articulated typology of phrases. For example, a generalization across several languages is that single words (heads) are distinguished from complete phrases for word order phenomena: Languages can therefore be described as either head-initial (e.g. English) or head-final (e.g. Japanese). This supports a typology of phrases that distinguishes between heads (single words) and maximal projections (complete phrases). A second distinction between types of phrases is important within minimalist syntax: the distinction between phases and non-phases. Phases are special phrases that are distinct from other phrases by their intonational and semantic properties.

The debate over the appropriate typology of phrases does not directly relate to the formal notion of self-embedding as characterized in (1), since the formal notion applies to languages — not to concrete grammars. However, there exists also a natural notion of recursion that applies to specific structures in a phrase structure based syntax: A structure is recursive if there is a phrase of type X that contains as a proper part another phrase of type X. Recursion of a concrete phrase structure grammar is evidently a different notion from self-embedding as defined in (1). The link between the notions is the following: If a language is self-embedding, any phrase structure grammar must be such that some strings are analyzed as having a recursive structure. But, importantly, the notion of self-embedding never predicts which specific strings must receive a recursive analysis, nor is any language that can be analyzed with phrase-structure grammar that allows some recursive structures necessarily self-embedding in the formal sense.

The notion of recursive structure is nevertheless an important one, especially since for natural language other sources of evidence (for example, intonational and semantic evidence) are available to determine the phrase structure of a specific sentence. Which structures are recursive, however, is closely tied the typology of phrases. As already mentioned, current minimalist syntax assumes an abstract operation *Merge* as the only phrase structure rule. *Merge* always structures exactly two items into one phrase. Therefore, any sentence consisting of three or more words must involve a recursive operation of phrase structure building on this view, as Nevins *et al.* (2009) point out. But if the typology of phrases assumed is richer, a smaller set of structures are analyzed as recursive. For example, the traditional phrase structure rules S ⇒ NP V and NP ⇒ D N allow the analysis of the sequence D N V without recursion. Moreover, some scholars committed to more 'strong' derivational approaches like phase theory or other models implying multiple points of Spell-Out have recently argued that the narrow structure-building operations of grammar are not recursive at all and that recursion might better be described as an interface phenomenon (cf. Arsenijević & Hinzen 2010, Surányi 2010).

Jan-Wouter Zwart assumes a minimalist background and claims that syntactic recursion should not be defined in terms of embedding, but in terms of derivation layering. Comparing iterative and recursive procedures to build phrase structures, he argues that one cannot decide that a language is recursive by simply looking at its structures. Instead, one has to investigate the structure building procedure itself. After showing that embedding structures can also be generated without recursion, Zwart defines recursion in language as the interaction between derivation layers. He then applies these concepts to the analysis of the Amazonian language Pirahã. Everett (2005) claims that Pirahã does not exhibit recursion which has led to intense discussion on the relevance of this finding with respect to the status of recursion as a linguistic universal. According to Zwart's approach, both complex subjects and structured lexical items imply recursion. Zwart then demonstrates, using uncontested data, that both complex subjects and structured lexical items are attested in Pirahã, and thus, he argues that the grammar of Pirahã allows for recursive structures.

Tom Roeper starts with the assumption that if variation is attested regarding what particular forms of recursion natural languages allow, then an acquisition challenge exists. In the light of acquisition evidence from adjectives, possessives, verbal compounds, and sentence complements, he outlines an acquisition path for specific forms of recursion. In particular, he distinguishes three mechanisms to build recursive structures: direct recursion, indirect recursion, and Generalized Transformations (GTs), as realized in an adaptation of Tree Adjoining Grammar. Since children first analyze adjacent identical structures as direct recursion with a conjunctive reading, Roeper argues that direct recursion is the acquisition default and can thus be viewed as the first stage in the acquisition of recursive structures. Assuming that children must 'experience' specific forms of recursion in order to allow them in their language, he goes on to discuss several evidences that may help account for the path of how to acquire the more complex forms of both indirect recursion and recursion in the form of GTs.

4.   Localizing Recursion in Cognitive Neuroscience and Genetics

The testing of human and non-human subjects regarding their capacities to process artificial language grammars inspired neuropsychological studies that ask to what extent the core computational faculty of processing hierarchical embedded structure can be segregated from other brain functions. Let us briefly look at this field of research.

Friederici *et al.* (2006) build on the findings of Fitch & Hauser (2004) and hence assume that humans differ from non-human primates in their capacity to master sequences that are generated by the A^nB^n grammar. In their study, they ask, broadly speaking, whether the differences of processing the two grammars used by Fitch & Hauser are reflected in the human brain. To explore this question, they test human subjects by visually presenting sequences of consonant-vowel syllables that were modeled to represent the different grammar types. After having used these stimuli and after having applied several sophisticated testing procedures, they indeed conclude that there are differences

in processing in the brain. In particular, Friederici *et al.* report that processing of local transitions within a finite-state grammar is subserved by the left frontal operculum, whereas a specific section of Broca's area holds responsible for the computation of hierarchical dependencies involved in syntactic recursion within a phrase structure grammar. However, like in experimental psychology, the testing methods have been refined in subsequent studies, which is the starting point for three contributions in the present volume.

Angela D. Friederici, Jörg Bahlmann, Roland Friedrich, and Michiru Makuuchi report such refinements by reviewing recent neuroimaging experiments that evaluate the neural basis of processing embedded structures, which, as they argue, allows for conclusions regarding the localization of processing recursion in the brain. Based on numerous studies, they conclude that a special region of Broca's area, left Brodmann area 44, is the neural correlate of computing linguistic recursion. They segregated this correlate from activation of Broca's area due to working memory, from activation due to the processing of visual-event sequences, and from areas involved in processing hierarchically structured mathematical formulae. Friederici *et al.*'s cross-study review thus suggests two different computational systems in the lateral prefrontal cortex dealing with hierarchical structures, one which is domain-general and is active when processing complex hierarchies in non-language domains, and one which is domain-specific and deals with recursive language or language-like hierarchies.

Vasiliki Folia, Christian Forkstam, Martin Ingvar, Peter Hagoort, and Karl Magnus Petersson compare the brain networks engaged in processing grammaticality judgments and in processing preference judgments in an artificial grammar learning experiment. Their results show that preference and grammaticality classification engage virtually identical brain regions. That is, the subjects also engage brain regions central to natural syntax processing when they are not explicitly instructed or receive any information concerning the existence of a grammatical rule system that underlies the presented stimuli. In addition, Folia *et al.* present some initial efforts to understand the genetic basis of the capacity for artificial syntax acquisition by exploring the potential role of the CNT-NAP2 gene, which is controlled by the FOXP2 transcription factor and whose expression is enriched in frontal brain regions in humans.

Eleonora Russo and Alessandro Treves ask what evolutionary changes have occurred in the human neocortex that allow for the crucial feature of recursion in human language. After having reviewed salient features of cortical organization, they discuss recent work that shows that the human cortex has more neurons (in absolute number) than any other mammal, or, more specifically, that the number of spines present on the dendrites of pyramidal cells are significantly higher in the human cortex than in any other species. They then argue that these quantitative differences can produce qualitative changes in the functionality of a neural network. Discussing the phenomenon of latching dynamics, that is, the 'hopping' of the network from one attractor state to another, they refer to their previous analyses of this phenomenon and sketch the boundary between finite and infinite latching. In particular, they claim that a network latches indefinitely when the memory load is above a certain critical value. By assuming that latching is a property that emerges when crossing

certain threshold, they suggest the evolutionary scenario that recursion in human language has evolved due to a slowly evolving quantitative increase in the connectivity of the cortex that has suddenly crossed a critical threshold. Accordingly, syntactic recursion may have emerged in a manner entirely unrelated to the appearance of a novel piece in the neural circuitry, that is, without altering the intrinsic make-up of the network.

In addition to the seven research papers, a book review by **David J. Lobina** is included in this volume. Lobina reviews the recently published volume *Recursion and Human Language,* edited by Harry van der Hulst. We feel the review should be read in addition to the editorial to elaborate further the background for the research presented in this volume.

References

Arsenijević, Boban & Wolfram Hinzen. 2010. Recursion as a human universal and as a primitive. *Biolinguistics* 4, 165–173.

Chomsky, Noam. 1956. Three models for the description of language. *IRE Transactions of Information Theory IT-2* 3, 113–124.

Chomsky, Noam. 1957. *Syntactic Structures.* The Hague: Mouton.

Chomsky, Noam. 1959. On certain formal properties of grammars. *Information and Control* 2, 137–167.

Descartes, Réne. 2003 [1637]. Discourse on method. In Elizabeth S. Haldane & George R. Thomson (trans.), *Discourse on Method and Meditations*, 1–52. Mineola, NY: Dover.

de Vries, Meinou H., Padraic Monaghan, Stefan Knecht & Pienie Zwitserlood. 2008. Syntactic structure and artificial grammar learning: The learnability of embedded hierarchical structures. *Cognition* 107, 763–774.

Everett, Daniel L. 2005. Cultural constraints on grammar and cognition in Pirahã: Another look at the design features of human language. *Current Anthropology* 46, 621–634.

Fitch, W. Tecumseh. 2010. Three meanings of 'recursion': Key distinctions for biolinguistics. In Richard K. Larson, Viviane Déprez & Hiroko Yamakido (eds.), *The Evolution of Human Language: Biolinguistic Perspectives*, 73–90. Cambridge: Cambridge University Press.

Fitch, W. Tecumseh & Marc D. Hauser. 2004. Computational constraints on syntactic processing in a nonhuman primate. *Science* 303, 377–380.

Friederici, Angela D., Jörg Bahlmann, Stefan Heim, Ricarda I. Schubotz & Alfred Anwander. 2006. The brain differentiates human and non-human grammars: Functional localization and structural connectivity. *Proceedings of the National Academy of Sciences of the United States of America* 103, 2458–2463.

Gentner, Timothy Q., Kimberly M. Fenn, Daniel Margoliash & Howard C. Nusbaum. 2006. Recursive syntactic pattern learning by songbirds. *Nature* 440, 1204–1207.

Hauser, Marc D., Noam Chomsky & W. Tecumseh Fitch. 2002. The faculty of language: What is it, who has it, and how did it evolve? *Science* 298, 1569–

> 1579.

Hauser, Marc D., David Barner & Tim O'Donnell. 2007. Evolutionary linguistics: A new look at an old landscape. *Language Learning & Development* 3, 101–132.

von Humboldt, Wilhelm. 1836/1999. The diversity of human language-structure and its influence on the mental development of mankind. In Peter Heath (trans.), *Wilhelm von Humboldt: On Language*, 1–287. Cambridge: Cambridge University Press.

Luuk, Erkki & Hendrik Luuk. 2011. The redundancy of recursion and infinity for natural language. *Cognitive Processing* 12, 1–11.

Nevins, Andrew, David Pesetsky & Cilene Rodrigues. 2009. Pirahã exceptionality: A reassessment. *Language* 85, 355–404.

Perruchet, Pierre & Arnaud Rey. 2005. Does the mastery of center-embedded linguistic structures distinguish humans from nonhuman primates? *Psychonomic Bulletin & Review* 12, 307–313.

Reber, Arthur S. 1967. Implicit learning of artificial grammars. *Journal of Verbal Learning & Verbal Behavior* 6, 855–863.

Surányi, Balázs. 2010. Toward a strongly derivational syntax. In Michael T. Putnam (ed.), *Exploring Crash-Proof Grammars*, 167–212. Amsterdam: John Benjamins.

Tomalin, Marcus. 2011. Syntactic structures and recursive devices: A legacy of imprecision. *Journal of Logic, Language and Information*, doi:10.1007/s10849-011-9141-1.

Uli Sauerland
Zentrum für Allgemeine Sprachwissenschaft (ZAS)

Schützenstraße 18
10117 Berlin
Germany
uli@alum.mit.edu

Andreas Trotzke
Universität Konstanz
Fachbereich Sprachwissenschaft
Universitätsstraße 10
78457 Konstanz
Germany
andreas.trotzke@uni-konstanz.de