Journal of Memory and Language 87 (2016) 84–104

Contents lists available at ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

Learning structure-dependent agreement in a hierarchical artificial grammar

Julie Franck *, Irene Rotondi, Ulrich H. Frauenfelder

Laboratory of Psycholinguistics, University of Geneva, Geneva, Switzerland

ARTICLE INFO

Article history:
Received 16 December 2014
revision received 5 November 2015

Keywords:
Artificial grammar
Structure-dependency
Agreement
Hierarchical structure
Phrase structure
Cue

ABSTRACT

We present a novel way to implement hierarchical structure and test its learnability in an artificial language involving structure-dependent, long-distance agreement relations. In Experiment 1, the grammar was exclusively cued by phonological and prosodic markers similar to those found in natural languages. Experiment 2 contained additional semantic cues in the form of a reference world. At the group level, successful generalization of the phrase structure rules to new words was found in both experiments. Analyses of individual profiles show that a subset of participants also generalized their knowledge to novel phrase structure rules, instantiating a natural extension of the training grammar, based on recursion of coordination. Rule induction improves across-the-board in the presence of semantic cues. It is concluded that adults are able to develop, to some extent, abstract knowledge of hierarchical, structure-dependent representations despite impoverished input data and minimal training.

Introduction

The expressive power of language lies in the organization of words into higher-order phrases organized hierarchically and over which syntactic rules are defined. Hierarchical structure is a defining property of the phrase structure grammars characterizing natural languages (Chomsky, 1965). For example, in the sentence *The daughter of our new neighbors sings in a band*, the verb 'sings' agrees with the head of the subject phrase 'the daughter', and not with the intervening material 'our new neighbors' that is embedded within the subject phrase. One of the major challenges of hierarchical structure for the parser is that it underlies phenomena like agreement, movement and recursion, which have in common the potential to involve long-distance dependencies between syntactically related units, forcing the parser to keep track of the dependents and their dependencies.

The nature of the abilities underlying the learning, representation and processing of hierarchical syntactic relations lies at the core of research on artificial grammar learning (AGL). The use of simplified grammar systems in artificial languages (Reber, 1967) allows manipulating the input participants are exposed to, and therefore identifying the key information necessary for inducing hierarchical structure. This work has addressed questions like whether the ability to learn rule systems based on phrase structure grammar is specific to humans (e.g., Fitch & Hauser, 2004; Gentner, Fenn, Margoliash, & Nusbaum, 2006; Hauser, Chomsky, & Fitch, 2002) and whether, and in which conditions, human adults come to induce hierarchical structure (e.g., Bahlmann, Schubotz, & Friederici, 2008; Corballis, 2007; De Vries, Monaghan, Knecht, & Zwitserlood, 2008; Lai & Poletiek, 2011; Perruchet & Rey, 2005; Poletiek, 2002).

* Corresponding author at: Laboratory of Psycholinguistics, University of Geneva, 40 Bd Pont d'Arve, 1205 Geneva, Switzerland.
E-mail address: julie.franck@unige.ch (J. Franck).

http://dx.doi.org/10.1016/j.jml.2015.11.003

The first section of the Introduction reviews AGL studies that implemented hierarchical structure, focusing on the challenges that these studies have met with respect to the phenomenon targeted, i.e., mirror recursion, and on conditions allowing learning. The second section presents an overview of our work. We designed a novel implementation of hierarchical structure in an AG involving structure-dependent agreement dependencies, which we argue are closer to natural language phenomena than multiple center-embedding. The artificial language created involves the basic ingredients of phrase structure grammars, i.e., constituent structure, syntactic categories, grammatical morphology and long-distance dependencies, implemented by way of phonological and prosodic cues. Experiment 1 explores grammar induction in the absence of semantics, whereas Experiment 2 explores it in the presence of semantic cues in the form of a reference world. After being exposed to the language for 50 min, adult participants were found to generalize the agreement rule to novel words, and a subset of them generalized it to novel structures involving phrase structure rules that were not part of the training grammar. The data suggest that adults show a disposition to represent the grammar of this artificial language in terms of hierarchical phrase structure rather than linear structure, in line with the hypothesis that our system "forces us always to go to the hierarchical abstract rule and always neglect the more elementary linear physical rule" (Chomsky, 1980).

Implementing hierarchical structure in an artificial grammar

Operationalizing hierarchical structure in an artificial grammar requires that some of its formal properties be isolated and mapped onto a perceptual signal. Hierarchical structure underlies a variety of syntactic phenomena like agreement, movement and recursion. These phenomena have in common the potential to have intervening material in the input word string that separates syntactically related units. Whereas a number of studies have explored the possibility of implementing phrase structure grammar in an artificial language (e.g., Langus, Marchetto, Bion, & Nespor, 2012; Moeser & Bregman, 1972; Morgan & Newport, 1981; Mori & Moeser, 1983), some of them incorporating movement (Tettamanti et al., 2002, 2009; Valian & Coulson, 1988), it is only in the last decade that structure-dependent long-distance syntactic dependencies have appeared in AGL research, in the phenomenon of multiple center-embedding. Center-embedding allows an arbitrary number of phrases to be nested within higher order phrases (e.g., [The rat [the cat killed] ate the malt]), and is therefore viewed as exemplifying recursion in natural languages. Two major types of center-embedding grammars have been explored: phrase structure grammars (PSG) and finite state grammars (FSG). The PSG A^nB^n (generated, for example, by the rules $S \rightarrow [ASB]$ and $S \rightarrow 0$) includes strings like AB, A[AB]B and A[A[AB]B]B (e.g., Cho, Szkudlarek, Kukona, & Tabor, 2011; Fitch & Hauser, 2004; Hochmann, Azadpour, & Mehler, 2008; Zimmerer, Cowell, & Varley, 2011, 2014). It involves a type of recursion relying on counting, in which the number of As determines the number of Bs. It is usually contrasted with the corresponding FSG $(AB)^n$ (generated by the rules $S \rightarrow [ABS]$ and $S \rightarrow 0$), which generates structures of the type AB, ABAB or ABABAB. This counting recursion grammar can be fully described by transitional probabilities between a finite set of units. Center-embedding has also been explored in phrase structure grammars implementing mirror recursion ($S \rightarrow [A_iSB_i]$, $S \rightarrow 0$), in which As and Bs are paired within the constituent structure such that A1 is paired with B1, A2 with B2 and A3 with B3 in strings like [A3[A2[A1B1]B2]B3] (e.g., Bahlmann & Friederici, 2006; Bahlmann et al., 2008; Conway, Ellefson, & Christiansen, 2003; De Vries, Petersson, Geukes, Zwitserlood, & Christiansen, 2012; De Vries et al., 2008; Lai & Poletiek, 2011, 2013; Mueller, Bahlmann, & Friederici, 2010; Perruchet & Rey, 2005).

Fitch and Hauser (2004) initiated research with the aim of exploring potential differences between humans and cotton-top tamarins in their ability to learn a PSG as opposed to a FSG. They contrasted sequences generated from the PSG A^nB^n with sequences generated by the FSG $(AB)^n$. When trained on the FSG grammar, both humans and monkeys discriminated PSG strings in the test phase. In contrast, when trained on the PSG grammar, only humans were able to reject ungrammatical FSG strings, suggesting that they induced the PSG grammar from the input. Subsequent studies have questioned the conclusion humans actually did represent the abstract structure of A^n-B^n (e.g., De Vries et al., 2008; Hochmann et al., 2008; Zimmerer et al., 2011, 2014), and Perruchet and Rey (2005) questioned the relevance of the counting recursion A^nB^n grammar as a test case for natural language recursion (see also Corballis, 2007). In the materials used by Fitch & Hauser, pairings between As and Bs are not needed to discriminate between the two types of strings: discrimination could be based on counting or even more rudimentary perceptual processes (like the detection of repetitions or switches between female and male voices). Perruchet and Rey showed that when the materials involved mirror recursion, i.e., genuine center-embedding constraints with systematic pairings between the syllables in the strings, participants failed to successfully represent the dependencies between the syllables (see also Conway et al., 2003). Although some studies have reported successful learning of mirror recursion dependencies (Bahlmann & Friederici, 2006), De Vries et al. (2008, 2012) argue that performance actually can rely on surface distinctions, and that even 2-level center-embedding could not be learned in an AGL setting.

These results seriously question the learnability of center-embedding patterns in artificial grammars. Some studies show that learning may nevertheless take place to some extent under specific conditions. The first condition concerns the learning procedure. Various studies indicate a beneficial effect of 'starting small' (Elman, 1993) or 'staged input', showing that learning is improved when complexity is incrementally added such that participants are first exposed to strings with 0-level of embedding (adjacent dependencies), followed by 1-level and then 2-level embedding (Bahlmann et al., 2008; Conway et al., 2003; Fedor, Varga, & Szathmáry, 2012; Lai & Poletiek, 2011). Furthermore, knowledge of 2-level embedding