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Brief article

The impact of adjacent-dependencies and staged-input on the learnability of center-embedded hierarchical structures

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ABSTRACT

A theoretical debate in artificial grammar learning (AGL) regards the learnability of hierarchical structures. Recent studies using an A^nB^n grammar draw conflicting conclusions (Bahlmann & Friederici, 2006; De Vries, Monaghan, Knecht, & Zwitserlood, 2008). We argue that 2 conditions crucially affect learning A^nB^n structures: sufficient exposure to zero-level-of-embedding (0-LoE) exemplars and a staged-input. In 2 AGL experiments, learning was observed only when the training set was staged and contained 0-LoE exemplars. Our results might help understanding how natural complex structures are learned from exemplars.

1. Introduction

Recursion, as in sentences with hierarchically built up center-embeddings, is regarded as a crucial property of human language (Hauser, Chomsky, & Fitch, 2002). However, sentences with several levels of embedding (LoE) are difficult to process, even for native speakers (Bach, Brown, & Marslen-Wilson, 1986; Hudson, 1996; Newmeyer, 1988; Vasishth, 2001). *The rat the cat the dog chased killed ate the malt* (Chomsky & Miller, 1963, pp. 286–287) is a typical center-embedded sentence incorporating two sub-clauses. The dependencies between related constituents become harder to associate as more clauses are inserted, not least since the counterparts get further away from each other.

Recursion refers to structures that are self-referential, and infinitely productive. In center-embedded structures, inserting a grammatical sentence within another generates a new grammatical sentence. This operation can be applied infinitely, generating numerous output sentences. Since Hauser et al. (2002) stressed the crucial importance of recursive rules in natural languages, a renewed interest has risen concerning the learnability of recursion. Most studies use the artificial grammar learning (AGL) paradigm (Corballis, 2007; Gentner, Fenn, Margoliash, & Nusbaum, 2006; Perruchet & Rey, 2005). In particular, Fitch and Hauser (2004) proposed that the ability of mastering hierarchical structures was critical to distinguish human and nonhuman primates. They argued that humans could grasp hierarchical structures generated by an A^nB^n grammar (see Fig. 1), while tamarins were incapable. Moreover, Bahlmann and Friederici (2006) (henceforth B&F) and Bahlmann, Schubotz, and Friederici (2008) carried out an fMRI study to probe into the neural basis of processing long-distance dependencies. Significantly greater blood flow was observed in Broca's area during processing of hierarchical-dependency A^nB^n compared to adjacent-dependency $(AB)^n$.

However, as indicated by Perruchet and Rey (2005), the mapping of A-to-B is the essential characteristic of hierarchical center-embedding recursion. At each LoE, this mapping has to be legal according to the grammar.[1] Therefore, Fitch and Hauser (2004), whose grammar did not specify

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[1] For instance, $A_1A_2A_3B_3B_2B_1$ is grammatical, whereas $A_1A_2A_3B_1B_2B_3$ is not.

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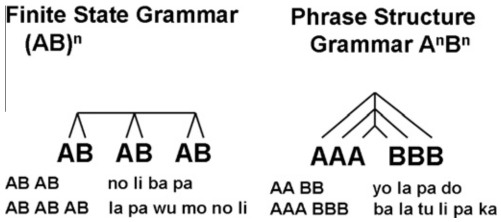

Fig. 1. Structures of finite state grammar $(AB)^n$ and phrase structure grammar A^nB^n used by Fitch and Hauser (2004). Examples of Category A words are: no, ba, la, wu and Category B words are: li, pa, ka, do.

such mapping, could not demonstrate knowledge of center-embeddings in their experiment. The same problem applies for B&F. Though B&F did use a grammar specifying a hierarchical A–B mapping, their test materials were incapable of detecting center-embedded structure learning. When the test materials were controlled, participants failed to learn, as showed by De Vries, Monaghan, Knecht, and Zwitserlood (2008), who argued that performance in B&F is based on superficial heuristics, like counting the A's and B's, or repetition-monitoring, instead of learning the center-embedded principle.[2]

Previous research has mainly focused on the cognitive learnability of center-embedded structures, rather than on features of the environmental input. Here, we propose two crucial but previously poorly attended environmental factors: One is the organization of the input by stages (*starting small*, henceforth SS) and the second is sufficient exposure to the grammar's basic adjacent-dependencies in the earliest stage of learning. The purpose of the present research is to explore the impact of these two closely-related conditions on learning center-embeddings.

Considering natural language learning, child-directed speech globally satisfies these conditions, as it has, in the earliest stage, short linguistic constituents, simple grammatical constructions, and little syntactical variability (Pine, 1994; Tomasello, 2003). As children grow, child-directed speech develops gradually into more mature speech types (Bellinger, 1980; Garnica, 1977). Hence, the input on which the learning process operates, does not come in a random order. Therefore, if we can demonstrate experimentally the facilitation effect of a growing environmental input, and early exposure to zero-level-of-embedding (0-LoE) exemplars, this result might help understanding the role of the environment in complex natural language learning.

The notion of SS was first raised by Elman (1991, 1993). He trained a connectionist network to parse complex structures which contained embedded subordinates. The network succeeded only if provided with a staged-input, but not after exposure to the entire input as a whole. Subsequent studies yielded mixed results, though. Some findings are consistent with Elman's effect (Conway, Ellefson, & Christiansen, 2003; Kersten & Earles, 2001; Krueger & Dayan, 2009; Newport, 1988, 1990; Plunkett & Marchman, 1990). However, other research reported no effect of staged-input (Fletcher, Maybery, & Bennett, 2000; Ludden & Gupta, 2000; Rohde & Plaut, 1999).

In the current study, two AGL experiments were carried out using similar materials as B&F and de Vries et al. (2008). In Experiment 1, we compared learning with a staged-input and a random input. Both learning sets contained 0-LoE exemplars. In Experiment 2, 0-LoE learning items were omitted.

2. Experiment 1

All participants were exposed to the same strings, generated by grammar $\underline{G}$ (Fig. 2). In the SS condition, syllable strings were presented progressively according to their LoE.[3] In the random condition, exactly the same set was presented randomly. We hypothesize that the SS group outperforms the random group.

2.1. Method

2.1.1. Participants

Twenty-eight students (20 female), from Leiden University participated. All were native Dutch speakers.

2.1.2. Materials and design

There were two sets of syllables, categorized by their vowels. Category A contained -e/-i, i.e. {be, bi, de, di, ge, gi}, whereas Category B contained -o/-u, i.e. {po, pu, to, tu, ko, ku} (see Appendix). Each A-syllable was connected with its counterparts in Category B according to another cue: their consonants, i.e. {be/bi-po/pu}, {de/di-to/tu} and {ge/gi-ko/ku}. Strings were constructed with two, four, or six paired-syllables following the A^nB^n rule. Frequencies of syllable occurrence were controlled for.

The experiment consisted of 12 blocks, with a learning phase and a testing phase each. Twelve strings were presented in each learning phase, and 12 novel strings in each testing phase, of which six were grammatical and six ungrammatical. Both groups were presented the same test strings with 0-, 1-, or 2-LoE. Ungrammatical strings were created by mismatching A-syllables with B-syllables. For two-syllable strings, violations appeared necessarily in the second position ($A_1\underline{\mathbf{B_2}}$); for four-syllable strings, in the fourth position ($A_1A_2B_2\underline{\mathbf{B_3}}$); and for six-syllable strings, in the fifth or sixth position ($A_1A_2A_3B_3\underline{\mathbf{B_4}}B_1$, $A_1A_2A_3B_3B_2\underline{\mathbf{B_4}}$). For instance, the violation B_4 in $A_1A_2A_3B_3B_2\underline{\mathbf{B_4}}$ means that the last B mismatches any A in this sequence. In this manner, no adjacent AB violations in the middle of a string could occur, except, necessarily, for two-syllable test strings. Moreover, in contrast to B&F, no repetition of exactly the same syllable appeared in the same sequence, and all test strings had an equal number of A's and B's.

[2] Indeed, in B&F, violations were *replacement violations* (e.g. $A_1A_2A_3B_3A_2B_1$) and *concatenation violations* (e.g.$A_1A_2B_2B_3$). Contrarily, de Vries et al. (2008) tested two other types: *scrambled* (e.g. $A_1A_2A_3B_1B_3B_2$) and *scrambled + repetition* ($A_1A_2A_3B_1B_3B_1$). Their participants could detect the scrambled + repetition violations, but not the scrambled ones.

[3] For the SS group, in the first four blocks, only 0-LoE learning items were presented. The following four blocks displayed 1-LoE items only. In the last four, 2-LoE items were presented. The ordering of strings within one block was counterbalanced over participants.