



Brief article

Centre-embedded structures are a by-product of associative learning and working memory constraints: Evidence from baboons (*Papio Papio*)

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ABSTRACT

Influential theories have claimed that the ability for recursion forms the computational core of human language faculty distinguishing our communication system from that of other animals (Hauser, Chomsky, & Fitch, 2002). In the present study, we consider an alternative view on recursion by studying the contribution of associative and working memory processes. After an intensive paired-associate training with visual shapes, we observed that baboons spontaneously ordered their responses in keeping with a recursive, centre-embedded structure. This result suggests that the human ability for recursion might partly if not entirely originate from fundamental processing constraints already present in non-human primates and that the critical distinction between animal communication and human language should more likely be found in working memory capacities than in an ability to produce recursive structures *per se*.

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1. Introduction

A critical characteristic of human languages is recursion (Chomsky, 1957). Recursion is defined as a computational device that calls itself (Christiansen & Chater, 1999; Corballis, 2007), allowing the generation of an infinite range of linguistic structures from a finite set of elements. Recursion is notably demonstrated by the production of centre-embedded (CE) linguistic sentences. Suppose two sentences, a_1b_1 and a_2b_2 , each composed of two ordered elements (a and b representing the first and second element, respectively). The resulting sentence $a_1a_2b_2b_1$ has a CE structure because a_2b_2 is hierarchically embedded within a_1b_1 . An example of such embedding in English is “The antelope [a_1] the lion [a_2] ate [b_2] ran like a snail [b_1]”.

Recent hypotheses make the central claim that the ability to process CE structures is a critical cognitive feature

distinguishing human from nonhuman cognition (Hauser, Chomsky, & Fitch, 2002). Supporting this claim, Tamarins failed in processing CE auditory sequences, while humans succeeded in the same conditions (Fitch & Hauser, 2004). To date, the European starling is the only nonhuman species that was found to recognize acoustic patterns defined by a CE grammar (Gentner, Fenn, Margoliash, & Nusbaum, 2006) but conclusions of this study have been extensively debated (Corballis, 2007; De Vries, Monaghan, Knecht, & Zwitterlood, 2008; van Heijningen, de Visser, Zuidema, & ten Cate, 2009). It has indeed been proposed that starlings may discriminate sequences of $aabb$ from sequences of $abab$ by using simple counting or subitizing strategies but not by processing the specific ordered structure of embedded sentences, which allows us to distinguish a sequence like $a_1a_2b_2b_1$ from $a_2a_1b_2b_1$ or $a_1a_2b_1b_2$ (see also, Perruchet & Rey, 2005). Transposed to natural language, taking order information into account leads us to detect a semantic problem in “The lion [a_2] the antelope [a_1] ate [b_2] ran like a snail [b_1]”.

Corballis (2007) suggested that an alternative way to test the ability of nonhuman species to process CE sequences

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would be first, to train them associating pairs of arbitrary elements (i.e., learning a_1 – b_1 and a_2 – b_2 associations) and then, to observe if they could still process these pairs when other pairs are nested within them (i.e., $a_1a_2b_2b_1$, p. 702). Recently, Lai and Poletiek (2011) have even shown with humans that a critical condition for learning CE structures is precisely to start with a sufficient exposure to zero-level-of-embedding before any exposure to CE structures. The present study is a follow up of these two recent propositions.

Using a newly developed operant conditioning device (Fagot & Bonté, 2010), baboons were first trained to learn six different pairs of visual shapes (noted a_1b_1 , a_2b_2 , ..., a_6b_6) presented on a touch screen. For each pair (e.g., a_1b_1), one shape was arbitrarily defined as the first element of the pair (e.g., a_1), and the other as the second element (e.g., b_1). Training consisted of five phases during which baboons learned in various conditions to sequentially touch the first, and then the second element of each pair, while ignoring visual distractors. After this intensive paired-associate training, the ability of baboons to process a pair (e.g., a_2b_2) nested within another pair (e.g., a_1b_1) was evaluated with two different testing procedures.

2. Method

2.1. Participants

Five male and six female guinea baboons (*Papio papio*, age range 2–12 years) from the CNRS primate facility in Rousset (France) participated in this experiment.

2.2. Material

They were tested with learning devices equipped with a touch screen and a food dispenser. The main innovation of the test equipments is that the baboons participated at will, as they had a 24-h access to the computers from the outdoor enclosure, where they live in a social group (see Fagot & Bonté, 2010, for a detailed description of the testing apparatus). Twelve shapes (e.g., Δ , Φ , ϑ , Γ , Σ , Ω , $*$, \ominus , ζ , $\&$, λ) were used to create six arbitrary pairs of stimuli, hereafter noted a_1b_1 , a_2b_2 , ..., a_6b_6 . A different set of 10 neutral shapes served as visual distractors (Υ , \downarrow , ∇ , \times , \square , \blacksquare , \blacktriangleright , \blacktriangleleft , ∇ , ∇ , ∇).

2.3. Procedure

The first part of the experiment was composed of five training sessions during which baboons had to learn ordered associations between six pairs of arbitrary visual shapes. During Training 1, a first pair (e.g., a_1b_1) appeared concurrently on the computer screen at different random locations and, to be rewarded, the baboons had to sequentially touch the stimuli in a pre-specified order (e.g., $a_1 \Rightarrow b_1$). Item selection in an incorrect order triggered a time-out (TO) of 3 s indicated by a green screen. Trials were presented in 100-trial blocks, with inter-trial-interval of 3 s. The six pairs were learned sequentially and baboons had to reach for each pair a criterion of 80% of correct responses on three successive blocks to proceed to the next pair. After the sixth pair had been successfully learned,

mixed blocks containing all the pairs in a random order were presented until the 80% criterion was reached. Training 2 replicated the same procedure as Training 1, but 1–5 occurrences of a fixed distractor (i.e., Υ) were added to each display to increase the task demand. Touching the distractor triggered the 3-s TO. Training 3 also used 1–5 identical distractors, but they were now randomly selected prior to each trial from the set of 10 neutral shapes. In Training 4, the distractor was the second element of another pair (e.g., b_2 if the target pair was a_1b_1). Reward was delivered only when the target stimuli were touched in the pre-specified order (i.e., $a_1 \Rightarrow b_1$). Touching the distractor (i.e., b_2) triggered TO. During Training 5, the first element of a trained pair (e.g., a_1) and one of the 10 neutral distractors were both presented in a first display. The baboon was expected to touch the first element (a_1). Once done, the second element of the target pair (b_1), together with the second element of another trained pair (e.g., b_2), were displayed. Reward was delivered only if b_1 was selected in this second display.

The second part of the experiment was composed of two testing sessions during which the ability of baboons to process nested pairs was evaluated. Tests 1–2 started with the same events. The first element of a pair (e.g., a_1) was presented with a first visual distractor. Baboons had to touch a_1 and to avoid the distractor. After selecting a_1 , the first element of another pair (e.g., a_2) and a second distractor were displayed. Again, they had to select a_2 and to avoid the distractor. The third resulting screen was different for Tests 1 and 2. For Test 1, b_1 , b_2 , and a third visual distractor were displayed while for Test 2, b_1 , b_2 , and b_3 were presented on the screen. To be rewarded in Test 1, baboons had to touch both b_1 and b_2 with no constraint on order and to avoid the distractor. To be rewarded in Test 2, they had to touch two of the three displayed shapes with no constraint on order. Tests 1–2 consisted in 240 trials per baboon with a random selection of the stimulus pairs on each trial. Note that the production of CE structures was never strengthened, neither during training nor during testing.

3. Results

As shown in Appendix, the baboons received an average of 53,349 training trials (SD = 12,175 trials) prior to testing. This over-training guaranteed a perfect acquisition and stabilization of the learned associations, which was critical for the processing of CE structures according to Lai and Poletiek (2011).

After this intensive paired-associate training, the ability of baboons to process nested pairs was tested with two different procedures, in which they were requested to combine the elements of two trained pairs in a 4-item sequence. As there was no constraint on order, their responses during the test reflected the sequence structure they preferred. In Test 1, baboons spontaneously produced more CE structures (i.e., $a_1a_2b_2b_1$; $M_{CE} = 153.3$, SD = 6.7) than non-embedded (NE) structures (i.e., $a_1a_2b_1b_2$; $M_{NE} = 84$, SD = 7; see Fig. 1A). That bias was present in all baboons (see individual performances in Appendix), and was significant for the group, $t(10) = 17.2$, $p < .001$, Cohen's $d = 5.19$.

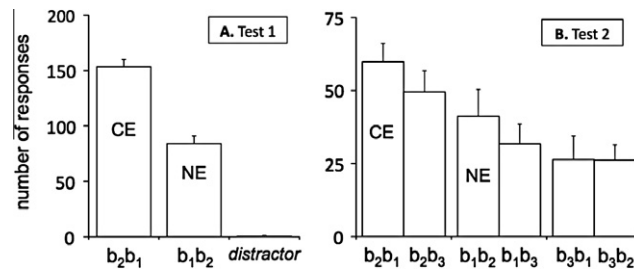


Fig. 1. Panel A: number of CE (e.g., b_2b_1) and NE (e.g., b_1b_2) responses in Test 1. Panel B: number of responses for the six possible response patterns in Test 2 (b_2b_1 = CE; b_2b_3 ; b_1b_2 = NE; b_1b_3 ; b_3b_1 ; b_3b_2). CE = Centre-embedded and NE = non-embedded. Error bars correspond to standard deviations.

In Test 2, baboons continued to significantly produce more CE structures ($M_{CE} = 59.8$, $SD = 6.3$) than NE structures ($M_{NE} = 41.2$, $SD = 9.2$; see Fig. 1B). As in Test 1, that trend was present in all baboons and at the group level (although with a lower magnitude), $t(10) = 5.35$, $p < .001$, Cohen's $d = 1.6$. There was also a significant effect on the first selected item, b_2 being more selected ($M = 109.4$, $SD = 8.9$) than b_1 ($M = 72.9$, $SD = 12.8$), which was more selected than b_3 ($M = 53$, $SD = 11$), $F(2, 20) = 50.1$, $p < .001$. Finally, the difference between b_2b_1 ($M = 59.8$, $SD = 6.3$) and b_2b_3 ($M = 49.5$, $SD = 7.3$) was also significant, $t(10) = 3.3$, $p < .01$, Cohen's $d = 1$, indicating that after selecting b_2 , baboons did not produce the next response at random but had a preference for b_1 (i.e., the last element of the CE structure) over b_3 .

4. Discussion

Contrary to the commonly accepted claim that recursion is human specific (Fitch & Hauser, 2004; Hauser et al., 2002), we found that at least one nonhuman species spontaneously had a preference for producing responses consistent with a CE structure, without such a structure being specifically reinforced. In Test 1, they selected first b_2 over b_1 . However, after selecting b_2 , because they add no other choice than b_1 (or the visual distractor), one may argue that they produced a default response (i.e., b_1 , given that they learned to avoid the distractor items). This objection is ruled out in Test 2, where the second element of a third possible pair (i.e., b_3) was added to the final display. In this case, baboons again significantly produced more b_2 responses as a first choice. When exposed to the remaining items (i.e., b_1 and b_3), they significantly preferred the response associated with the first displayed element of a pair (i.e., a_1), therefore producing a CE sequence (i.e., $a_1a_2b_2b_1$).

Consistent with recent studies on humans (Lai & Poletiak, 2011), baboons displayed a preference for CE structures after an intensive paired-associate training during which they were initially exposed to zero-level-of-embeddings (i.e., simple a_i-b_i associations). However, the resulting preference for CE structures can be simply interpreted as a by-product of elementary associative mechanisms and working memory processes. Indeed, CE structures such as $a_1a_2b_2b_1$ can be described as two intermingled associations, a_1b_1 and a_2b_2 . In a CE structure, the association a_1b_1 is temporarily segmented after the production of its first element (a_1), with its second element (b_1) being maintained in working memory and produced later, after the association

a_2b_2 has been processed. In that context, the preference for producing CE structures requires (1) the capacity to form associations between pairs of elements (e.g., a_1b_1 or a_2b_2) and (2) the ability to segment these associations and maintain in working memory the first element of a pair (a_1) in order to produce later its second associated element (b_1). The present results indicate that these two requirements are satisfied in baboons and are sufficient for producing CE structures having one-level-of-embedding.

One limitation of the present study is related to the number of embeddings that have been tested. A stronger demonstration would certainly require testing baboons on two or more embeddings. However, one may argue that increasing the levels-of-embeddings could be too demanding for baboons. Several studies on sentence comprehension have indeed reported a strong decrease in human comprehension performances associated with an increase of level-of-embeddings (Bach, Brown, & Marslen-Wilson, 1986; Blaubergs & Braine, 1974; King & Just, 1991). Three embeddings are indeed “extremely difficult to understand” for humans (Christiansen & Chater, 1999) and “close to impossible when n is as high as four” (Corballis, 2007). Although the present results indicate that baboons are not qualitatively limited in producing CE structures, their performance could be limited quantitatively to the processing of one or two embeddings.

Previous research on sentence comprehension in humans is also consistent with the idea that working memory capacities play a critical role in processing CE sentences (e.g., King & Just, 1991). Similarly, Elman (1991) has shown that a simple connectionist network can account for the processing of CE sentences indicating that recursive patterns can be generated by simple associative mechanisms and do not necessarily require a sophisticated rule-based computational device. Christiansen and Chater (2001) have also demonstrated that such a network can reproduce the decrease in human comprehension performances as a function of the increase in levels-of-embeddings.

Another limitation of the present study resides in the absence of any semantic relation between the embedded associations. Indeed, in natural languages, an embedded sentence is usually related to an element of the outer sentence. For example, in the sentence “The antelope the lion ate ran like a snail”, “the lion ate” qualifies “the antelope”, giving an integrated meaning to the whole sentence. One may note that this issue has not yet been taken into account in previous studies on recursion. This is likely because Chomsky (1957) focused its attention on the generative

power of recursion, suggesting that an infinite number of sentences can theoretically be embedded within a given sentence, little consideration being devoted to the adding value provided by the semantic link between these sentences. Although not tested here, including a semantic relation between paired-associates should, in principle, facilitate recursive processing and working memory retention by providing a semantic cue to retrieve the second element of a pair.

Overall, these results are consistent with the idea that CE structures produced by humans could have their origins in associative and working memory processes already present in animals. Indeed, our findings do not imply that baboons possess the innate computational device that has been postulated for humans (i.e., the faculty of language in the narrow sense proposed by Hauser et al. (2002)). They rather suggest that the production of CE structures in baboons and humans could be the by-product of associative mechanisms and working memory constraints.

Although this explanation does not yet account for the richness of human language, it suggests that one of its presumably distinctive features (i.e., recursion) could in fact originate in elementary cognitive processes allowing the segmentation and the maintenance in working memory

of time. This rehearsing ability is likely to be a fundamental cognitive tool for the production of recursive structures, although this might not be a sufficient condition for recursion (see Everett, 2005; Everett, 2008, for a discussion about the universality of recursion in human languages). Future studies could gauge this alternative claim by testing the ability of nonhuman primates to learn minimal forms of phonological recoding and by evaluating its potentially strong impact on animal working memory capacities.

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Appendix A

Number of trials required by each baboon to complete each training session; number of centre-embedded (CE) and non-embedded (NE) spontaneous responses obtained during Tests 1 and 2, and number of alternative responses produced in Test 2 (i.e., b_1b_3 , b_2b_3 , b_3b_1 , b_3b_2). SD = standard deviation.

| Participant | Training sessions | | | | | Test 1 | | Test 2 | | | | | |
|-------------|-------------------|------|------|--------|--------|-------------|-------------|-------------|----------|-------------|----------|----------|----------|
| | 1 | 2 | 3 | 4 | 5 | CE b_2b_1 | NE b_1b_2 | CE b_2b_1 | b_2b_3 | NE b_1b_2 | b_1b_3 | b_3b_1 | b_3b_2 |
| 1 | 14,674 | 8002 | 3903 | 19,603 | 7838 | 149 | 89 | 55 | 52 | 42 | 32 | 25 | 32 |
| 2 | 9400 | 6301 | 4500 | 17,301 | 14,584 | 143 | 96 | 57 | 42 | 52 | 31 | 19 | 24 |
| 3 | 19,825 | 5900 | 6096 | 15,901 | 17,210 | 156 | 83 | 57 | 50 | 29 | 27 | 30 | 47 |
| 4 | 16,700 | 9799 | 5501 | 22,098 | 23,076 | 148 | 85 | 71 | 51 | 34 | 31 | 26 | 19 |
| 5 | 10,300 | 5400 | 7574 | 11,306 | 10,396 | 164 | 76 | 53 | 50 | 49 | 28 | 32 | 20 |
| 6 | 8400 | 4998 | 4502 | 5301 | 8964 | 151 | 89 | 60 | 36 | 56 | 42 | 22 | 22 |
| 7 | 18,600 | 3600 | 8802 | 16,705 | 14,066 | 152 | 81 | 71 | 53 | 40 | 22 | 22 | 21 |
| 8 | 7299 | 5702 | 4221 | 15,902 | 11,483 | 162 | 78 | 54 | 64 | 36 | 24 | 32 | 30 |
| 9 | 5600 | 5002 | 4500 | 12,701 | 15,570 | 148 | 90 | 56 | 55 | 27 | 39 | 33 | 28 |
| 10 | 14,000 | 5800 | 4500 | 15,402 | 16,218 | 152 | 85 | 60 | 47 | 43 | 31 | 28 | 26 |
| 11 | 12,100 | 6598 | 6701 | 18,201 | 12,216 | 161 | 72 | 64 | 45 | 45 | 42 | 19 | 21 |
| Mean | 12,445 | 6100 | 5527 | 15,493 | 13,784 | 153 | 84 | 60 | 49.5 | 41 | 31.7 | 26.2 | 26.4 |
| SD | 4707 | 1644 | 1587 | 4496 | 4310 | 6.7 | 7.0 | 6.3 | 7.3 | 9.2 | 6.8 | 5.2 | 8.1 |

of previously associated elements. Following that explanation, the limited ability for recursion in animals should more likely be found in working memory limitations than in an inability to produce recursive structures *per se*.

A critical feature of human working memory is the development of phonological recoding processes that provide a crucial evolutionary advantage for maintaining information in working memory and for computing long-distance dependencies. The richness of phonological recoding processes could be a key factor for producing complex forms of recursive, language-like patterns. Contrary to visual information, a phonological code can be maintained in working memory by entering in the so-called “phonological loop”, allowing any information to be rehearsed for longer periods

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