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Non-adjacent Dependencies Processing
in Human and Non-human Primates

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Abstract

1 Human and non-human primates share the ability to extract adjacent dependencies
2 and, under certain conditions, non-adjacent dependencies (i.e., predictive relationships
3 between elements that are separated by one or several intervening elements in a sequence). In
4 this study, we explore the online extraction dynamics of non-adjacent dependencies in
5 humans and baboons using a serial reaction time task. Participants had to produce three-target
6 sequences containing deterministic relationships between the first and last target locations. In
7 Experiment 1, participants from the two species could extract these non-adjacent
8 dependencies, but humans required less exposure than baboons. In Experiment 2, the data
9 show for the first time in a non-human primate species the successful generalization of
10 sequential non-adjacent dependencies over novel intervening items. These findings provide
11 new evidence to further constrain current theories about the nature and the evolutionary
12 origins of the learning mechanisms allowing the extraction of non-adjacent dependencies.

Keywords: language evolution, statistical learning, sequence learning, long-distance
dependencies, animal cognition

13

14 Statistical learning can be defined as the implicit learning of regularities embedded in
15 the environment, which has been proposed to play an important role in language acquisition
16 (for a review, see Romberg & Saffran, 2010) and many other aspects of cognition (e.g., in
17 visual perception, Fiser & Aslin, 2001). Several experimental paradigms have been used to
18 study these fundamental learning mechanisms such as the Artificial Grammar Learning
19 paradigm (AGL, Reber, 1967), the Artificial Language Learning paradigm (ALL, Saffran et
20 al., 1996) or the Serial Response Time paradigm (SRT, Nissen & Bullemer, 1987). In these
21 experiments, participants are typically exposed to sequences of nonsense stimuli (e.g.,
22 syllables, tones or visual shapes) that are organized with a specific grammar. Learning of the
23 predictive relationships embedded in the input can then be assessed by presenting novel
24 sequences that are either consistent or inconsistent with this grammar.

25 Comparative human/non-human studies can inform us about the nature and dynamic
26 of these learning mechanisms, and their occurrence during the evolution, by distinguishing
27 domain-general and evolutionary old processes from those that might have appeared more
28 recently in the human lineage. Comparative experiments have demonstrated so far that
29 animals, like humans, are highly proficient in learning predictive relationships between
30 *adjacent* elements (i.e., elements that are presented one after the other in a sequence, without
31 any delay or element in between; see for a review: Cate & Okanoya, 2012; Conway &
32 Christiansen, 2001; Wilson, Marslen-Wilson, & Petkov, 2017). This ability has been reported
33 in several primates (tamarins: Hauser, Newport, & Aslin, 2001; macaques: Wilson et al.,
34 2013; Wilson, Smith, & Petkov, 2015; and baboons: Minier, Fagot, & Rey, 2016), and non-
35 primate species (pigeons: Froehlich, Herbranson, Loper, Wood, & Shimp, 2004; rats: Toro &

36 Trobalón, 2005; and songbirds: Takahasi, Yamada, & Okanoya, 2010). Along with
37 neuroimaging data (e.g., Wilson, Kikuchi, et al., 2015), these behavioral data have led to the
38 hypothesis that the extraction of adjacent dependencies relies on evolutionarily conserved
39 mechanisms (Friederici, 2004; Wilson et al., 2017).

40 In contrast, the evolutionary origins of the capacity to extract non-adjacent
41 dependencies (i.e., predictive relationships between elements that are separated by one or
42 several intervening elements in a sequence, hereafter “NADs”) remain a matter of debate. A
43 standard example of NADs in English is the relationship between auxiliaries and inflectional
44 morphemes that are separated in the speech stream by the verbal root (e.g., *is reading*).
45 Crucially, extracting and recognizing these dependencies requires generalization over a
46 variable verb. Studies conducted in humans indicate that NADs extraction is more challenging
47 for humans than the extraction of regularities between adjacent elements (Cleeremans &
48 McClelland, 1991; Gebhart, Newport, & Aslin, 2009; Newport & Aslin, 2004; Pacton,
49 Sobaco, & Perruchet, 2015; Perruchet & Rey, 2005; Wilson, Smith, et al., 2015). This
50 capacity develops later in human infancy (Gómez & Maye, 2005) than the sensitivity to
51 adjacent dependencies (Saffran, Aslin, & Newport, 1996; but see Marchetto & Bonatti, 2013,
52 for different findings). Moreover, the extraction of NADs looks especially challenging in
53 human adults outside some specific facilitative contexts. For instance, it is facilitated when
54 the non-adjacent elements have a high degree of perceptual (e.g., phonological) similarity
55 (Creel, Newport, & Aslin, 2004; Gebhart et al., 2009; Onnis, Monaghan, Richmond, &
56 Chater, 2005), when the intervening elements are highly variable (Gómez, 2002; Onnis,
57 Monaghan, Christiansen, & Chater, 2005), or when the non-adjacent elements are located at

58 the edge of the sequences (Peña, Bonatti, Nespó, & Mehler, 2002). Studies also revealed
59 similar performances and constraints on NADs learning in experiments using linguistic and
60 nonlinguistic stimuli, such as tones (Creel et al., 2004; Endress, 2010; Gebhart et al., 2009), or
61 actions (Endress & Wood, 2011), suggesting that the learning mechanisms involved in this
62 ability are not language-specific. Several experiments aimed to test whether animals can also
63 extract NADs. Wilson et al. (2015) exposed human participants and macaques to a complex
64 grammar involving multiple adjacent and non-adjacent dependencies. All participants from
65 both species detected violations of the adjacent dependencies. By contrast, half of the tested
66 humans, and none of the monkeys were sensitive to the NADs. The authors concluded that
67 when multiple regularities are present, monkeys rely preferentially on local ones, whereas
68 humans exhibit more flexibility. Human learners can encounter some difficulties with the
69 learning of several regularities simultaneously (e.g., Kovács & Mehler, 2009), but Wilson et
70 al. (2015) suggests that this might be even more difficult for non-human learners. Animals'
71 focus on various local cues rather than on NADs has also been reported when multiple
72 embedded NADs must be processed, as in the so-called center-embedded grammars (e.g.,
73 Heijningen, Visser, Zuidema, & Cate, 2009). However, these results may point to a limitation
74 in the monkeys' ability to track several NADs simultaneously, rather than an inability to
75 extract NADs *per se*.

76 Complementary information on animals' ability to learn NADs has been obtained
77 from experiments using simpler grammars of the form $AX^{(n)}B$. In these grammars, A and B
78 are two paired elements, with a non-adjacent transitional probability of 1, and $X^{(n)}$ is one or
79 several (n) variable intervening elements. Two main types of NAD have been investigated

80 thus far using these grammars: dependencies between elements that are perceptually more
81 similar compared to the interspersed element(s) (i.e., that belong to the same perceptual
82 category, hereafter “feature-based NAD”), and learning of NADs without such perceptual
83 cues (often called “arbitrary associations”).

84 Successful learning of feature-based NADs has been recently reported in two primate
85 species, with visual (Sonnweber, Ravignani, & Fitch, 2015) and auditory stimuli (Ravignani,
86 Sonnweber, Stobbe, & Fitch, 2013). Successful generalization across isomorphic visual and
87 auditory sequences was also demonstrated recently (Ravignani & Sonnweber, 2017). In
88 addition, positive results were obtained in rats, with NADs between elements that were
89 phonologically similar (i.e., vowels vs. consonants, and *vice-versa*; de la Mora & Toro, 2013),
90 whereas previous experiments conducted on NADs extraction in this species led to negative
91 results in the absence of phonological similarity (Toro & Trobalón, 2005). Perceptual
92 similarity therefore appears to facilitate the extraction of NADs in some non-human animal
93 species, as it does in humans (e.g., Onnis et al., 2005). These findings support the hypothesis
94 that NADs extraction is sustained by a general-purpose learning mechanism, interacting with
95 general perceptual constraints (i.e., extra-linguistic, such as Gestalt principle of similarity,
96 Creel et al., 2004), both being shared by phylogenetically distant species (Newport & Aslin,
97 2004; see however de la Mora & Toro, 2013, and Toro, Nespors, Mehler, & Bonatti, 2008, for
98 a discussion of potential human-specific constraints on speech processing).

99 Evidence for successful NADs learning in the absence of such perceptual cues can also
100 be found in non-human animals. To date, three distinct experiments were conducted on that
101 topic. Newport, Hauser, Spaepen, and Aslin (2004) assessed the ability of tamarins (*Saguinus*

102 *oedipus*) to extract dependencies between non-adjacent syllables in a speech stream, using a
103 familiarization procedure. Six 3-syllable nonsense words of the form AXB (three
104 instantiations of A-B pairs and one of two X syllables inserted in the middle) were presented
105 in a continuous stream during several minutes via a loudspeaker. After this familiarization
106 phase, the tamarins' reactions to words (e.g., A₁XB₁) *versus* part-words (B₁A₂X) were tested.
107 Tamarins exhibited a higher rate of orientation responses towards the speaker after a part-
108 word than after a word, suggesting that they learned the NADs. The authors concluded that
109 the tamarins accurately segmented this continuous stream into triplets of syllables based on
110 these NADs. However, one limitation of this study is that the tamarins' ability to generalize
111 these dependencies over novel intervening X syllables was not tested. Therefore, this
112 experiment leaves unexplored the question of how the NADs were processed and stored in
113 their memory. Indeed, they could have extracted the three A-B non-adjacent relationships, or
114 instead memorized the six AXB "words" as wholes. The same limitation also applies to Milne
115 et al. (2016) who used a passive listening method in rhesus macaques (*Macaca mulatta*) and
116 the recording of event-related potentials. Despite the results suggesting the learning of NADs,
117 this study failed to provide generalization tests to confirm that the learned NADs could be
118 maintained over novel intervening events.

119 To our knowledge, Sonnweber et al. (2015) is the only study proposing this kind of
120 test in a non-human species. These data were obtained in one subgroup of chimpanzees (*Pan*
121 *troglydytes*) referred to as the "arbitrary associative dependencies" group. These chimpanzees
122 were presented on each trial with two "strings" of visual shapes depicted concurrently on a
123 screen in a two-alternative forced choice task. The task required to choose the strings of the

124 form AX^nB (with five instantiations of A-B pairs and 60 instantiations of X items, with $n = 1$
125 or 2) over XX^nX strings. What the participants precisely learned was evaluated by a series of
126 tests proposed after the training phase. The two main generalization tests (Test 2: extension of
127 the number of X elements, and Test 3: introduction of novel X shapes) were successfully
128 completed by one participant over the three tested chimpanzees. However, the fact that the
129 items were presented concurrently rather than sequentially raises potential issues. The
130 processing of associations between spatially distant elements, especially at rather small
131 distance (up to 12 cm from each other during training, with a maximum of 30 cm in Test 2,
132 according to the reported pixel measures), can arguably rely on strategies different from those
133 available for the extraction of sequential NADs. For instance, once the chimpanzees have
134 learned that only the left- and right-most shapes of each string matter in this task, they can
135 make quick eye-movements from one to the other and process them as if they were adjacent,
136 despite the spatial distance. Extraction and recognition of sequential NADs, in contrast, may
137 require to hold an element in working memory and relate it to another element occurring later
138 in the sequence (Wilson et al., 2017). Therefore, Sonnweber et al. (2015) offers promising
139 findings about non-human primates' ability to generalize NADs, but these researches would
140 need to be extended to the case of sequential NADs. Another limitation of the comparative
141 literature is that it contains no comparative data on the temporal dynamics of NADs learning
142 in human and non-human animal species. Earlier, we reported that baboons and humans
143 learned adjacent dependencies at the same speed (Minier et al., 2016; Rey, Minier, Malassis,
144 Bogaerts, & Fagot, submitted). A remaining issue is whether this is also true for NADs.

145 The aim of the present study was twofold in this context. It was firstly to provide
146 human and baboon comparative data on the fine-grained dynamics of NADs extraction. It was
147 secondly to test whether baboons can generalize sequential NADs over novel intervening
148 elements. In Experiment 1, baboons and humans performed a serial response time task (SRT,
149 Nissen & Bullemer, 1987), requiring to follow a stimulus appearing sequentially at different
150 locations on a touchscreen. In a subset of the presented sequences, the first target location
151 predicted the last target location, while the second target location varied. Response times
152 provided an online behavioral metric of NADs learning. In Experiment 2, generalization of
153 the NADs over novel intervening locations was tested. During this test, novel consistent
154 sequences were contrasted with novel sequences violating the dependencies. This violation
155 method was inspired from Gómez (2002). Only baboons took part in this second part of the
156 study, as generalization has already been demonstrated in humans (Endress & Bonatti, 2007;
157 Frost & Monaghan, 2016; Marchetto & Bonatti, 2015).

158

159

Experiment 1

160 Method

161

Baboons

162

Participants and apparatus

163

Participants are 16 Guinea baboons (*Papio papio*, 11 females, age range 4-21 years)

164

from the CNRS primate facility (Rousset-sur-Arc, France). They live within a larger group of

165

26 individuals, within a 700 m² outdoor enclosure and had a permanent access to ten

166

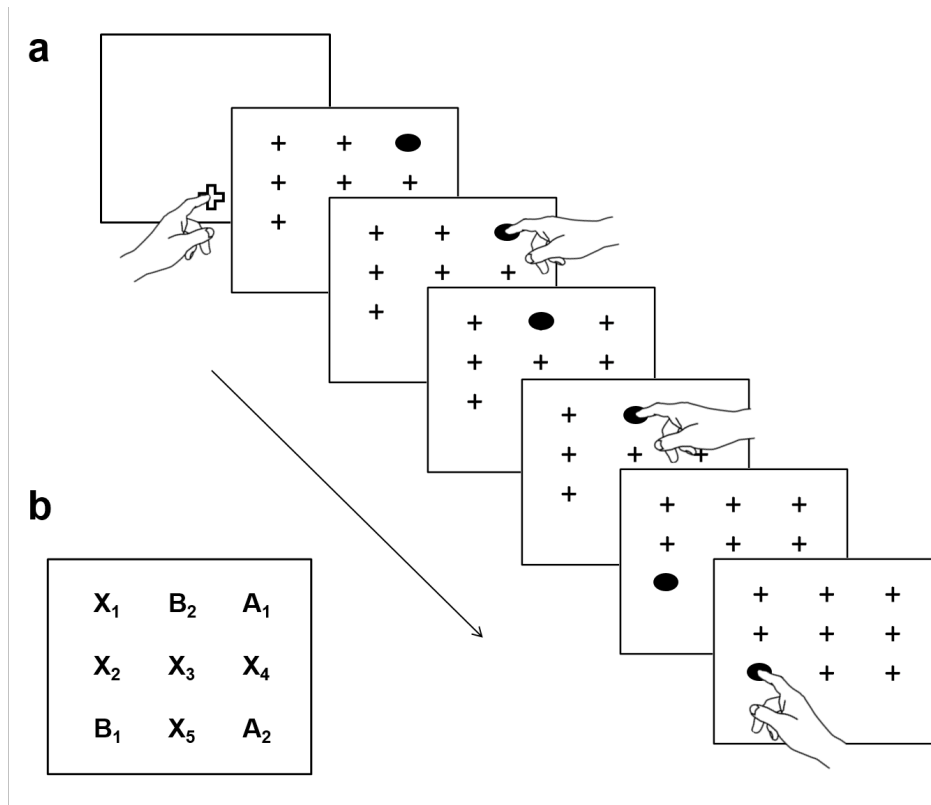
Automated Learning Devices for Monkeys (ALDM, for a detailed description, see Fagot &

167 Bonté, 2010; Fagot & Paleressompouille, 2009) equipped with a 19-inch touch screen and a
168 food dispenser. The main feature of ALDM equipment is that a radio frequency identification
169 reader (RFID) identifies each baboon via a microchip implanted in each arm. The baboons
170 can therefore participate to the research at will, without being captured, as the test programs
171 recognize them automatically. All baboons had previously participated to numerous
172 computerized experiments using the ALDM test systems, including experiments on sequence
173 processing (Minier et al., 2016), but they have never been exposed to tasks requiring the
174 learning of NADs. The experiment was controlled by the EPrime software (Version 2.0,
175 Psychology Software Tools, Pittsburgh).

176 *Procedure*

177 Participants had to perform a serial response time (SRT) task which required following
178 and touching a dot moving in a pre-defined order on a touch screen. Each trial began by the
179 display of a fixation cross (120x120 pixels) presented at the bottom of the screen (see Fig.
180 1a). Touching this stimulus triggered the display of a matrix of 9 locations (3x3) which
181 contained 8 white crosses (60x60 pixels each) and a red circle target (80x80 pixels).
182 Participants had to touch the target. The target then disappeared and moved to the next
183 location on the screen. There was no delay between the offset of the target and its next
184 display. A trial consisted in a sequence of three targets. An accurate completion of the 3-target
185 sequence delivered grains of dry wheat inside the ALDM test unit. An incorrect response (i.e.,
186 selection of an incorrect location) stopped the trial and triggered a 5-sec timeout without food
187 reward. Trials in which the participants failed to select a stimulus within 5-sec after the
188 target's appearance were aborted and presented again in the next trial. The time elapsed
189 between the appearance of the target (i.e., the red circle) and the baboon's touch on this target

190 was recorded as the response time. Response times were recorded for each response in the 3-
 191 target sequence.



192

193 **Figure 1:** (a) General procedure of the serial response time task in Experiment 1. After
 194 touching the fixation cross, participants had to touch the red circle target that appeared
 195 successively at three different locations. (b) Locations on the touchscreen. Letters are given
 196 for illustrative purposes but were not displayed.

197

198 Two types of 3-target sequences were presented. In the first type (“NAD” condition),
 199 the first location of the target systematically predicted its last location, leading to a non-
 200 adjacent Transitional Probability (TP) of 1. Two pairs of A-B locations were used (A₁-B₁ and
 201 A₂-B₂), and a variable X location was inserted between A and B locations. The sequences
 202 were therefore of the form A₁XB₁ and A₂XB₂. The full set of 9 possible locations consisted in
 203 4 locations for A₁, B₁, A₂ and B₂, and 5 locations for X elements (i.e., X₁, X₂, X₃, X₄, X₅; see

204 Fig. 1b). These locations were chosen pseudo-randomly among the nine possible spatial
205 locations of the matrix, with the sole constraint that neither A_1 and B_1 , nor A_2 and B_2 , could
206 be located next to each other. As the five X locations were presented at equal frequencies, the
207 second location was uninformative about the third target location. The TP between the first
208 and the second target locations was equal to 0.2, and the TP between the second and the third
209 was equal to 0.5. A total of ten (two A-B pairs * five X locations) NAD sequences were used
210 (see Table 1).

211 The second type of sequences had an XXB_1 and XXB_2 structure. These sequences
212 were used in the control condition. To equate for the number of sequences per condition, 10
213 control sequences were constructed, as illustrated in Table 1. TPs between the first and third
214 locations, as well as between the second and third locations, were equal to 0.5 in these
215 sequences. It was therefore impossible to use adjacent or non-adjacent dependencies to predict
216 the third target location. NAD and control sequences were presented at equal frequencies
217 across the experiment. This equates motor practice in the two conditions. Experiment 1
218 involved a total of twenty 100-trial blocks. Each block contained five randomly intermixed
219 presentations of the 10 NAD and 10 control sequences described above. All baboons were
220 presented with the same sequences. Custom-written Python code (www.python.org) was used
221 to generate the sequences.

222

223

Table 1 The 20 sequences presented in Experiment 1.

NAD	Control
A ₁ X ₁ B ₁	X ₃ X ₁ B ₁
A ₁ X ₂ B ₁	X ₅ X ₂ B ₁
A ₁ X ₃ B ₁	X ₂ X ₃ B ₁
A ₁ X ₄ B ₁	X ₁ X ₄ B ₁
A ₁ X ₅ B ₁	X ₄ X ₅ B ₁
A ₂ X ₁ B ₂	X ₃ X ₁ B ₂
A ₂ X ₂ B ₂	X ₅ X ₂ B ₂
A ₂ X ₃ B ₂	X ₂ X ₃ B ₂
A ₂ X ₄ B ₂	X ₁ X ₄ B ₂
A ₂ X ₅ B ₂	X ₄ X ₅ B ₂

224

225 ***Training***

226 The baboons were familiar with the general principle of the task at the beginning of
 227 the experiment, as they previously performed a SRT task involving 9-target sequences
 228 (Minier et al., 2016). Before the experimental phase described above, the baboons received an
 229 initial training phase of twenty 100-trial blocks in which the first, second and third target
 230 locations were selected randomly in the matrix. These random sequences were constructed
 231 with the constraint to systematically avoid the repetition of any given target location within
 232 the 3-target sequence. The aim of the training phase was twofold: (1) to familiarize the
 233 baboons with the 3-target sequences (instead of 9 as in Minier et al., 2016), and (2) to limit
 234 any long-term effect of the regularities previously learned.

235 *Data analyses*

236 Our set of statistical analyses compared response times on the third target (RTs) in the
237 NAD and control conditions. Remember that the NAD and control sequences were presented
238 at equal frequencies across the experiment. This procedure allowed us distinguishing response
239 time accelerations due to a practice effect, as participants performed the control and NAD
240 sequences an equal number of times, and those attributable to the learning of the predictive
241 relationships present in the NAD sequences. Importantly, the final transitions between the
242 second and the third target locations were the same across conditions (i.e., X₁₋₅-B₁ and X₁₋₅-
243 B₂). Motor constraints were therefore controlled for that last transition. Shorter RTs in the
244 NAD compared to the control condition would therefore indicate successful learning of the
245 NADs.

246 For statistical analyses, the data of the exposure phase were grouped in five blocks of
247 400 trials. For each participant, mean response times on the third target (RTs) was computed
248 for each condition and block. These data were then analyzed using repeated-measures
249 ANOVA involving the Condition (NAD and Control) and Block (1-5) as within-participant
250 factors. Post-hoc comparisons were performed using Tukey Honestly tests ($p < .05$)

251 On average, the sixteen baboons required five days of testing (range 3-7 days) to
252 complete the experiment. Incorrect trials were removed from the data set (1.6%), as were
253 removed all the trials with response times greater than two standard deviations from the mean
254 (5.0% of the remaining trials, computed for each participant and each block).

255

256 **Humans**257 *Participants and apparatus*

258 Ten human participants participated in this experiment (five females, age range 19-
259 24). All participants were students of Aix-Marseille University and were paid for their
260 participation. All participants were right-handed, had normal or corrected-to-normal vision,
261 and were naïve as to the goal of the study. Participants performed the task while sited in front
262 of a 19-inch touch screen. The experiment lasted approximately three hours per participant,
263 and was divided in two sessions. Testing sessions were separated by two days at most.

264 *Procedure and data analyses*

265 The task and stimuli were similar in their general principles for humans and for
266 baboons, with only slight differences between species. First, the number of blocks was
267 reduced by half in humans ($n = 10$), in comparison to baboons ($n = 20$). This reduction was
268 motivated by the long duration of the experiment (i.e., three hours with the current design).
269 Second, humans did not receive a food reward at the end of each correct trial, contrary to
270 baboons. The duration of the time-out and inter-trial interval were otherwise similar in the two
271 species. Third, humans were instructed at the beginning of the experiment to follow the red
272 target as quickly and accurately as possible. They were also told that a green screen meant
273 that they did not correctly touch the target. Participants were interviewed at the end of the
274 experiment to assess their declarative knowledge of the regularities embedded in the
275 sequences. They were asked: “Did you notice any regularity, or rule, in some of the
276 sequences?”.

277 Regarding the training phase, human participants were first trained on the SRT task
278 using the same procedure as for baboons, but their number of training trials was reduced to

279 ten 100-trial blocks. Statistical analyses were the same as for baboons, except that blocks of
280 the exposure phase were grouped in five blocks of 200 trials (instead of 400).

281 Incorrect trials were removed from the data set (7.3%), as well as trials with response
282 times greater than two standard deviations from the mean (3.3% of the remaining trials,
283 computed for each participant and each block).

284

285 **Results**

286 **Baboons**

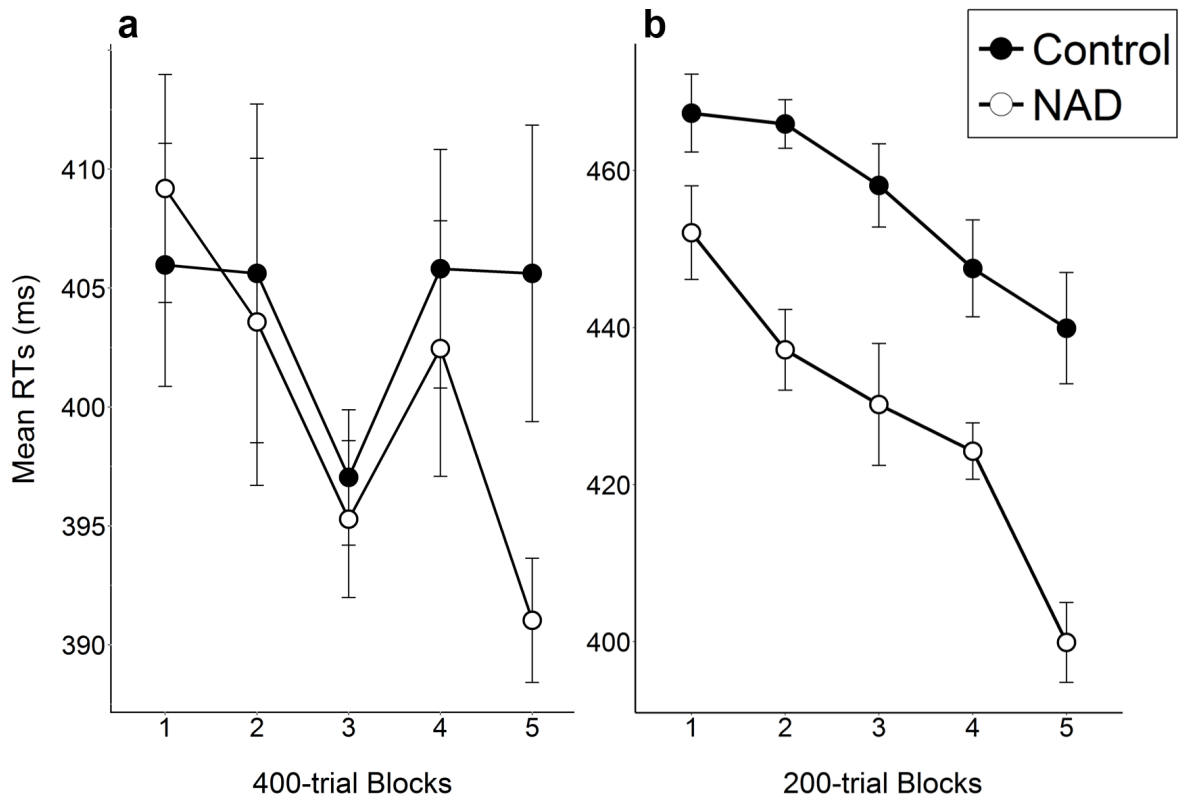
287 Mean RTs obtained in baboons are reported for each condition and block in Fig. 2a.

288 The repeated measures ANOVA revealed that the effect of Condition did not reach the
289 standard significance level (i.e., .05), $F(1, 15) = 4.21, p = .06, \eta_p^2 = .22$. No main effect of
290 Block was found¹, $F(1, 15) = 1.21, p = .29$, but there was a significant interaction between
291 these two factors, $F(1, 15) = 13.73, p < .01, \eta_p^2 = .48$. Post-hoc analyses revealed that RTs
292 were significantly shorter in NAD compared to the control trials for the last block (Block 5,
293 Cohen's $d = .29$), but not for the previous blocks (1-4). Altogether, the findings suggest that
294 baboons successfully learned the NADs in our task, but that this learning took a substantial
295 number of trials.

296

¹ As noted by some reviewers, an increase in RTs for both conditions is observed between Blocks 3 and 4 (see Fig. 2a). We have no definitive explanation to this increase, which can be explained by a series of factors not directly related to the task, such as an interfering social event in the group of baboons, or a change in weather conditions.

297



298

299 Figure 2. Response times for the third target (RTs) depending on the block, for the control and
 300 the non-adjacent dependencies (NAD) conditions in Experiment 1, for baboons (a) and for
 301 humans (b). The bars represent standard errors from normalized data.

302

303

304

Humans

305

Mean RTs are reported for each condition and block in Fig. 2b. Repeated measure

306

ANOVAs revealed a main effect of Condition, $F(1, 9) = 38.60, p < .001, \eta_p^2 = .81$, indicating

307

faster responses in the NAD (429 ± 65 ms) compared to the control condition (456 ± 58). A

308

reliable main effect of Block was found as well, $F(1, 9) = 30.99, p < .001, \eta_p^2 = .77$, as was

309

found a significant Block*Condition interaction, $F(1, 9) = 11.87, p < .01, \eta_p^2 = .57$. Post hoc

310 analyses on this interaction indicated a RTs advantage in the NAD condition compared to the
311 control condition that was significant from the first block (d_s = Block 1: .25, Block 2: .42,
312 Block 3: .39, Block 4: .39, Block 5: .70). These results suggest that humans began to learn the
313 NADs earlier than baboons, during the first block, and that this learning was amplified
314 throughout the course of the experiment.

315 Post-experiment interviews revealed that none of the participants reported the
316 existence of a predictive relationship between the first and the last locations (i.e., neither A₁-
317 B₁ nor A₂-B₂ relationships were reported). However, 4 out of 10 participants correctly
318 reported that two locations only were used at the last step of the sequence. In addition, four
319 participants could explicitly verbalize some of the triplets (from one to four triplets,
320 depending on the participant). Six of these triplets of locations were NAD sequences, and four
321 were control sequences. To assess whether the results we obtained were triggered by the
322 participants' declarative knowledge of this subset of sequences, we replicated the analysis
323 described above after removing from the dataset the corresponding trials, and these exclusions
324 did not change the pattern of statistical results. Overall, these data suggest that human
325 participants could extract the NADs. They further suggest that while human participants
326 exhibited learning of the regularities, as inferred from their response times, this learning was
327 implicit.

328

329 **Discussion**

330 In Experiment 1, baboons and humans could extract the NADs, as both species
331 responded faster to the third target when its location was predicted by the first target location

332 (NAD condition) than when it was not (control condition). Fig. 1 suggests that this difference
333 progressively increased in both species, with substantial differences between them. A
334 significant difference in RTs between the two conditions was found from the first block of
335 exposure in humans. This effect only emerged after five blocks in baboons, revealing a
336 substantial difference in the amount of exposure necessary for each species to exhibit
337 successful learning of the NADs. Considering that each of the two NADs was presented 100
338 times within a 400-trial block, we estimate that baboons demonstrated learning after 400 (100
339 * 4 blocks) presentations of each NAD. In contrast, this advantage in response times reached
340 significance since the first 200-trial block in humans, meaning that learning took place within
341 the first 50 presentations of these NADs. Moreover, effect size of the difference between the
342 two conditions on the last block was small to medium in baboons ($d = .29$), while it was
343 medium to large in humans ($d = .70$).

344 However, a discrepancy in task practice between the two species might partly explain
345 these differences between humans and baboons. Indeed, all our baboons had already
346 participated to a study involving a SRT task (Minier et al., 2016), and performed 20 blocks of
347 random sequences before completing the current experiment. In contrast, human participants
348 only performed 10 random blocks and never had been trained to the SRT task before. This
349 discrepancy in task practice between the two species might explain why humans' response
350 times decreased progressively throughout the experiment in both the control and the NAD
351 conditions, whereas baboons only showed this acceleration in the NAD condition.
352 Importantly, the baboons responded faster on average than humans on the first block (Mean \pm
353 SD = 406 \pm 43 and 460 \pm 62 ms, respectively, $t(24) = 2.58$, $p = .02$, $d = .99$), probably as a
354 consequence of their extensive practice with the task, while the two species show comparable

355 RTs on the last block (400 ± 54 and 420 ± 56 ms, respectively, $t(24) = 0.89$, $p = .38$). These
356 data suggest that a ceiling effect might have limited baboon's acceleration in the NAD
357 condition.

358 One limitation of this first experiment is that it does not rule out the possibility that the
359 participants progressively learned the NAD sequences by rote, or a subset of them, and
360 responded faster at the third location because of this rote learning, but without extracting the
361 NADs embedded in these sequences. Experiment 2 addresses this hypothesis in baboons by
362 testing their ability to generalize the NADs over novel intervening locations.

363

364

Experiment 2

365 Experiment 2 tested whether baboons merely learned the ten A_1XB_1 and A_2XB_2
366 sequences as wholes, or extracted instead the $A_1_B_1$ and $A_2_B_2$ non-adjacent relationships.
367 Baboons were exposed successively to two different "languages"² in a within-participant
368 design, and two experimental phases were proposed for each language. The first phase
369 corresponded to the exposure phase of Experiment 1, except that the set of possible locations
370 was increased from 9 to 16 locations. Six of these locations remained unused during that
371 phase. During the second phase, which is referred to as the test phase, the baboons were
372 presented with two types of novel sequences. In half of these sequences, the NADs learnt
373 during the exposure phase were presented over the six locations not used during the exposure

² We borrow here the term "language" to the literature on artificial language learning, the set of sequences being considered here as a set of "words".

374 phase. The dependencies were inconsistent in the remaining half of the sequences (i.e., A_1
375 was presented with B_2 and A_2 with B_1). Importantly, the consistent sequences in Language 1
376 were the inconsistent sequences in Language 2, and *vice-versa*. This two-language design
377 therefore guaranties that any difference in response times between the conditions will reflect
378 the learning and generalization of the NADs, rather than idiosyncratic sequence features
379 related to differences in motor constraints.

380

381 **Methods**

382 *Participants and apparatus*

383 Experiment 2 involved 14 (10 females, age range 4-21 years) out of 16 baboons of
384 Experiment 1, because we were unable to test two of the previous participants for reasons
385 unrelated to our research. The apparatus was the same as in the previous experiment. The
386 general testing procedure was also the same as in Experiment 1, except that the display
387 contained 16 (4x4) possible locations rather than only 9 (3x3).

388 *Procedure*

389 Table 2 provides the full lists of sequences used in Languages 1 and 2. The first
390 exposure phase was identical to Experiment 1 in both languages. In Language 1, sequences
391 took the form A_1XB_1 and A_2XB_2 for the NAD trials (50% of the trials), and XXB_1 and XXB_2
392 for the control trials (50% of the trials; see Table 2), with six different instantiations of the X
393 locations. In Language 2, the sequences took the form A_1XB_2 and A_2XB_1 for the NAD trials,
394 and control sequences were the same as in Language 1. The remaining six locations (noted
395 Y_{1-6}) were never used during the exposure phase. Locations have been chosen pseudo-

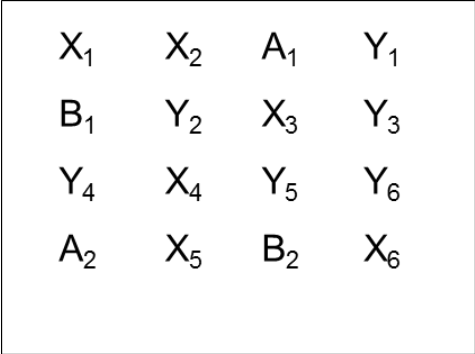
396 randomly, with the sole constraint that A_1 and B_1 , as well as A_2 and B_2 , could not be located
397 next to each other in the matrix. Fig. 3 shows the sixteen locations on the touchscreen that
398 were used in Experiment 2. Note that the locations were the same in both languages, and that
399 only the NADs differed between them.

400 Baboons then received three types of sequences during the test phase. The first type
401 (50% of the trials) corresponded to the NAD sequences of the exposure phase. For the two
402 other types of trials, sequences were either consistent with the NADs of the exposure phase
403 (“Consistent” condition, 25% of the test trials), or inconsistent with those dependencies
404 (“Inconsistent” condition, 25%). In these two latter conditions, the second location of the
405 sequence was drawn from the set of Y locations never used during the exposure phase.
406 Therefore, sequences were novel in these two conditions. In Language 1, consistent sequences
407 took the form A_1YB_1 and A_2YB_2 , while inconsistent sequences took the form A_1YB_2 and
408 A_2YB_1 . In Language 2, the consistent sequences were the inconsistent sequences of Language
409 1 (i.e., A_1YB_2 and A_2YB_1), while the inconsistent sequences were the consistent ones of
410 Language 1 (i.e., A_1YB_1 and A_2YB_2). Twelve sequences were constructed for each condition.
411 NAD, consistent and inconsistent trials were randomly intermixed within each block of the
412 test phase.

413 Each baboon participated successively to the two language sessions. For each
414 language, the baboons received 40 blocks of 96 trials during the exposure phase, and 20
415 blocks of 96 trials in the test phase. Note that the amount of exposure changed from 20 blocks
416 in Experiment 1 to 40 in Experiment 2, for both languages, because we hypothesized that
417 learning was still in progress during the last blocks of Experiment 1. To limit potential

418 influences of Language 1 acquisition on the learning of Language 2, six months elapsed
419 between the two language sessions, during which the baboons were exposed to different
420 unrelated tasks. Furthermore, a random phase consisting of 35 blocks of 96 trial blocks was
421 given to the baboons at the beginning of the Language 2 session.

422



423

424 Figure 3. Locations on the touchscreen in Experiment 2. Letters are given for illustrative
425 purposes but were not displayed. Note that the locations were the same for Languages 1 and
426 2.

427

428

429

Table 2. The 48 sequences presented during Experiment 2, for Language 1 (L1) and Language 2 (L2).

NAD (L1)	NAD (L2)	Control (L1 & L2)	Consistent (L1) / Inconsistent (L2)	Inconsistent (L1) / Consistent (L2)
A ₁ X ₁ B ₁	A ₂ X ₁ B ₁	X ₂ X ₁ B ₁	A ₁ Y ₁ B ₁	A ₂ Y ₁ B ₁
A ₁ X ₂ B ₁	A ₂ X ₂ B ₁	X ₃ X ₂ B ₁	A ₁ Y ₂ B ₁	A ₂ Y ₂ B ₁
A ₁ X ₃ B ₁	A ₂ X ₃ B ₁	X ₆ X ₃ B ₁	A ₁ Y ₃ B ₁	A ₂ Y ₃ B ₁
A ₁ X ₄ B ₁	A ₂ X ₄ B ₁	X ₁ X ₄ B ₁	A ₁ Y ₄ B ₁	A ₂ Y ₄ B ₁
A ₁ X ₅ B ₁	A ₂ X ₅ B ₁	X ₄ X ₅ B ₁	A ₁ Y ₅ B ₁	A ₂ Y ₅ B ₁
A ₁ X ₆ B ₁	A ₂ X ₆ B ₁	X ₅ X ₆ B ₁	A ₁ Y ₆ B ₁	A ₂ Y ₆ B ₁
A ₂ X ₁ B ₂	A ₁ X ₁ B ₂	X ₂ X ₁ B ₂	A ₂ Y ₁ B ₂	A ₁ Y ₁ B ₂
A ₂ X ₂ B ₂	A ₁ X ₂ B ₂	X ₃ X ₂ B ₂	A ₂ Y ₂ B ₂	A ₁ Y ₂ B ₂
A ₂ X ₃ B ₂	A ₁ X ₃ B ₂	X ₆ X ₃ B ₂	A ₂ Y ₃ B ₂	A ₁ Y ₃ B ₂
A ₂ X ₄ B ₂	A ₁ X ₄ B ₂	X ₁ X ₄ B ₂	A ₂ Y ₄ B ₂	A ₁ Y ₄ B ₂
A ₂ X ₅ B ₂	A ₁ X ₅ B ₂	X ₄ X ₅ B ₂	A ₂ Y ₅ B ₂	A ₁ Y ₅ B ₂
A ₂ X ₆ B ₂	A ₁ X ₆ B ₂	X ₅ X ₆ B ₂	A ₂ Y ₆ B ₂	A ₁ Y ₆ B ₂

430 *Data analyses*

431 Two separated sets of analyses were conducted on the exposure and test phases.
 432 Blocks were grouped for these analyses in 10 (Exposure) and 5 (Test) blocks of 384 trials
 433 each. Learning of NADs during the exposure phase was evaluated with repeated-measures
 434 ANOVA performed on RTs and involving the Condition (NAD, Control), Language (1, 2)
 435 and Block (1-10) as within-participant factors. Post-hoc comparisons were performed using
 436 Tukey Honestly tests ($p < .05$).

437 Generalization was evaluated in the test phase with repeated-measures ANOVA on
 438 RTs involving the Condition (NAD, Consistent, Inconsistent), Language (1, 2) and Block (1-

439 5) as within-participant factors. RTs in the consistent and inconsistent conditions were further
440 compared for the first test block using repeated-measures ANOVA involving the Condition
441 (Consistent, Inconsistent) and Language (1, 2) as within-participant factors. RTs in the
442 consistent and inconsistent conditions were further compared for the first test block using a
443 repeated-measures ANOVA involving the Condition (Consistent, Inconsistent) and Language
444 (Language 1, Language 2).

445 We also investigated potential effects of spatial factors on the generalization of NADs.
446 This analysis was conducted with an ANOVA using the Condition (Consistent, Inconsistent)
447 and Pair (A_1-B_1 , A_2-B_2 , A_1-B_2 , A_2-B_1) as within-participant factors, and the RTs obtained in
448 the first test block as dependent variable. An additional set of analyses tested whether
449 generalization occurred for every novel Y location. One-tailed paired t-tests ($p < .05$) were
450 used to assess if RTs were reliably longer in the inconsistent compared to the consistent
451 condition for each Y location.

452 To complete Language 1 session, the fourteen baboons required 8 days (range 5-12)
453 on average. The same baboons required on average 10 days (range 5-17) of testing to
454 complete Language 2 session. Incorrect trials were removed from the data set (Language 1:
455 1.7%, Language 2: 2.1%), as well as trials with RTs greater than two standard deviations from
456 the mean (4.9 % and 5.1%, respectively, computed for each participant and each block).

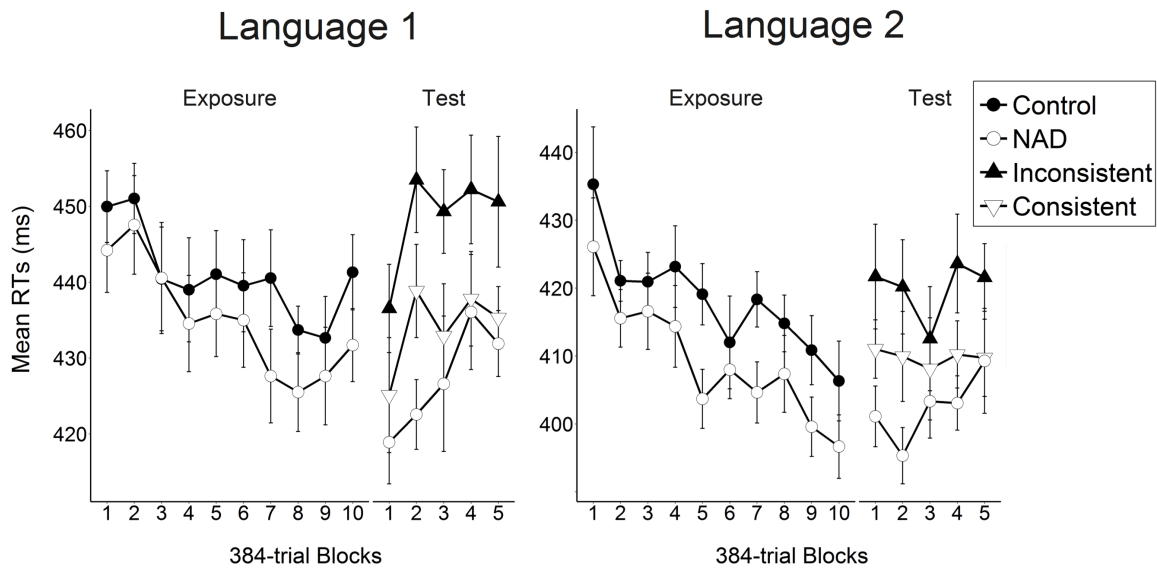
457

458 **Main Results**

459 Mean RTs are reported in Fig. 4 for each language, phase and condition. For the
460 exposure phase, the main effect of Condition was significant, $F(1, 13) = 16.28$, $p = .001$, $\eta_p^2 =$

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461 .56, corresponding to faster response times in the NAD (Mean \pm SD = 422 \pm 44 ms) than in
462 the control condition (430 \pm 43 ms). Also significant was the main effect of Block, $F(1, 13) =$
463 16.88, $p = .001$, $\eta_p^2 = .56$, showing that RTs decreased with practice. Finally, the main effect
464 of Language was also significant, $F(1, 13) = 6.60$, $p < .01$, $\eta_p^2 = .34$, indicating faster
465 response times on average for the second (414 \pm 32 ms) compared to the first language (438 \pm
466 50 ms). The Condition*Block interaction was close to significance level, $F(1, 13) = 3.21$, $p =$
467 .10, $\eta_p^2 = .20$. There were no other interactions (all $ps > .42$). The main effect of condition,
468 along with the absence of Condition*Language interaction, indicate that the baboons were
469 able to learn the NADs in both languages.
470



471

472 **Figure 4.** Mean response times (RTs) on the third target obtained in each condition of the
 473 exposure and test phases of Experiment 2 and for each language. Bars represent standard
 474 errors from normalized data.

475

476 Analyses conducted on the test phase revealed a significant effect of Condition, $F(2,$

477 $26) = 13.39, p < .001, \eta_p^2 = .51$. Post hoc analyses revealed that the three conditions differed

478 significantly on average from each other. Baboons were faster to respond to the third target in

479 the NAD condition (415 ± 46 ms) than in the two other conditions (Inconsistent condition:

480 434 ± 47 ms, $d = .41$; Consistent condition: 441 ± 46 ms, $d = .15$). Critically, they were also

481 significantly slower in the inconsistent compared to the consistent condition ($d = .26$). A main

482 effect of Language was found, $F(1, 13) = 8.75, p = .011, \eta_p^2 = .40$, RTs being faster in the

483 second compared to the first language session. No reliable effect of Block was found, $F(1,$

484 $13) = 1.52, p = .24$, but the Block*Condition interaction was significant, $F(2, 26) = 3.82, p <$

485 $.05, \eta_p^2 = .23$, RTs in the NAD condition only progressively increasing throughout the test

486 phase. No other reliable interactions among these factors were found (all $ps > .54$). An

487 ANOVA conducted on the first test block confirmed that a significant difference between the

488 consistent and inconsistent conditions was already present at the onset of that phase, as
489 revealed by a main effect of Condition, $F(1, 13) = 9.53, p < .01, \eta_p^2 = .42$. No other main
490 effect or interaction were found ($ps > .12$).

491

492 **Spatial factors**

493 An ANOVA revealed a significant interaction between Condition and Pair, $F(3, 39) =$
494 $4.56, p < .01, \eta_p^2 = .26$. Post-hoc tests revealed significantly longer RTs in the inconsistent
495 compared to the consistent condition for two pairs: A₂-B₂ (416 ± 68 and 389 ± 44 ms,
496 respectively, $d = .44$) and A₂-B₁ (467 ± 61 and 438 ± 53 ms, $d = .50$), but not for the A₁-B₁
497 (458 ± 38 and 463 ± 58 ms) and A₁-B₂ (379 ± 45 and 384 ± 43 ms) pairs. These results
498 suggest that baboons have been able to generalize two out of the four NADs.

499 Table 3 reports the results of the one-tailed paired t-tests evaluating whether the
500 generalization obtained with the two NADs mentioned above occurred on every novel Y
501 location. RTs were longer in the inconsistent compared to the consistent condition for all Y
502 locations, and this difference was significant for four out of the six Y locations (i.e., Y₂, Y₃,
503 Y₄, Y₆), and approached significance for a fifth one (i.e., Y₅). Therefore, these results suggest
504 that the baboons generalized the NADs over several novel Y locations, with only one
505 exception for Y₁.

506

507

Table 3 Response times (Mean \pm SD, ms) and results of the one-tailed paired t-tests assessing generalization over each novel Y locations, for the A₂-B₁ and A₂-B₂ NADs during the first test block. *dfs* were all equal to 13.

	Y ₁	Y ₂	Y ₃	Y ₄	Y ₅	Y ₆
Inconsistent	426 \pm 33	445 \pm 69	434 \pm 37	472 \pm 76	435 \pm 54	436 \pm 49
Consistent	419 \pm 39	391 \pm 40	413 \pm 35	423 \pm 49	419 \pm 65	415 \pm 38
t	0.91	3.51	3.36	2.72	1.32	1.80
Cohen's <i>d</i>	.15	.96	.60	.77	.27	.48
<i>p</i>	.19	< .01	< .01	< .01	.10	< .05

508

509 Discussion

510 Two results were obtained in Experiment 2. First, baboons successfully learned the
 511 NADs during the exposure phase, replicating the findings already obtained in Experiment 1.
 512 Second, for two NADs response times were slower for inconsistent than for consistent test
 513 trials. This finding suggests generalization of these NADs over the novel intervening
 514 locations. Importantly, these results suggesting generalization cannot be accounted for by
 515 learning of the consistent sequences, since each beginning of a sequence (i.e., A₁-Y₁₋₆ and A₂-
 516 Y₁₋₆) was followed by a B₁ or B₂ location at equal frequency within each language session.
 517 Analyses moreover confirmed that the speed advantage for consistent sequences was already
 518 present at the onset of the test phase.

519 Interestingly, reliable generalization was only observed for the two NADs beginning
 520 by A₂ which was located in the lower-left corner of the matrix (see Fig. 3). By contrast, the
 521 baboons failed to properly generalize the two NADs beginning at the A₁ location, which was
 522 not located in a corner. This result suggests that the saliency of the predictive target had an
 523 impact on baboons' ability to generalize NADs in this task. We also note that generalization

524 of the above two NADs was not observed for the only Y element located in a corner of the
525 matrix (Y_1), possibly because of its greater saliency, or eccentricity in the matrix, compared to
526 the other Y locations which were more central. Taken together, these findings suggest that the
527 baboons can generalize NADs over novel locations, but that this ability may be hindered by
528 spatial factors.

529

530

General discussion

531 In Experiment 1, humans and baboons responded faster to the last target in the NAD
532 compared to the control sequences. Importantly, participants did not merely learn that the
533 sequences always finished by one of two locations (with a probability of .5 for each), but
534 processed the conditional probabilities of the third location, given the first location. This
535 result was replicated in baboons in Experiment 2. These data overall provide evidence of
536 baboons' ability to learn NADs. However, while humans presented a significant difference in
537 response times between the two conditions within the first exposure block, this difference
538 appeared after approximately 400 presentations of each NAD in baboons. This difference in
539 learning speed differs from what has been found for adjacent dependencies (Minier et al.,
540 2016; Rey et al., in press). In these earlier studies, baboons and humans learned at similar
541 speed (in less than 200 trials) the predictive relationships between two locations presented at
542 the end of three different triplets. This suggests that learning of NADs is more difficult for
543 baboons than humans, while these two species seem equally fast for learning adjacent
544 dependencies. Importantly, the amount of exposure required by the baboons to extract NADs
545 in the current experiment is in the same range as previously found with habituation-

546 dishabituation paradigms in other primate species (e.g., 672 presentations in Newport et al.,
547 2004). This amount may serve as a reference for designing future experiments investigating
548 related topics.

549 For two NADs we found that when presented with novel intervening locations the
550 baboons were slower to respond when the sequences were inconsistent with the learned NADs
551 than when the dependencies were preserved. To our knowledge, this result is the first
552 demonstration in a non-human species of a successful generalization of sequentially non-
553 adjacent dependencies over novel intervening elements. The current results therefore extend
554 to the case of sequential NADs Sonnweber et al.'s findings (2015), in which generalization of
555 NADs was tested between visual shapes presented concurrently. Along with previous findings
556 in humans (e.g., Frost & Monaghan, 2016), our study indicates that this ability is shared
557 across different primate species. However, successful generalization of the NADs in the
558 current SRT study appeared to be modulated by spatial features of the stimuli. Indeed, the
559 baboons only generalized the two NADs whose predictive target was located in a corner of
560 the matrix and generalization was not observed for one of the novel intervening location
561 which was also located in a corner. These data present some similarities with previous
562 findings in the auditory domain. For instance, Endress, Scholl, and Mehler (2005, see also
563 Peña et al., 2002) reported that human participants could properly extract some specific
564 regularities from auditory sequences only when the relevant stimuli were presented at an edge
565 of the sequences. Moreover, several studies manipulating the phonological parameters of the
566 stimuli suggested that the relative saliency of the non-adjacent and intervening elements
567 impacts the extraction of NADs (Creel et al., 2004; Onnis et al., 2005; Toro & Trobalón,
568 2005). Taken together, these findings suggest (1) that perceptual factors constrain the

569 extraction of NADs, and (2) that this effect occurs in both the auditory and visuo-spatial
570 domains.

571 The exact nature of the processes involved in NADs extraction and recognition is still
572 debated in the literature, and at least three theories are proposed. According to a first theory,
573 the mechanisms that support NADs extraction are the same associative mechanisms as those
574 allowing the learning of adjacent dependencies (Perruchet, Tyler, Galland, & Peereman,
575 2004). This single-process account proposes that the joint attentional processing of two
576 elements is a necessary and sufficient condition to associate them, even when these are distant
577 in space or time (Pacton & Perruchet, 2008). A second and complementary theory proposes
578 that the extraction of adjacent and non-adjacent dependencies involves similar statistical
579 learning mechanisms, but emphasize the role played by working memory for NADs
580 extraction (Conway, Deocampo and Smith, 2016; Wilson et al., 2017). According to this dual-
581 system theory, the detection of adjacent relationships would be sustained by modality-specific
582 processes involving perceptual-motor neural networks (Conway et al., 2016), or ventral
583 regions of the frontal cortex (Wilson, Kikuchi, et al., 2015), while the extraction of non-
584 adjacent relationships would additionally recruit more dorsal areas (Wilson et al., 2017).
585 According to a last hypothesis (Endress & Bonatti, 2007; Endress, Nespors, & Mehler, 2009;
586 Peña et al., 2002), humans and possibly other animals (Endress, Carden, Versace, & Hauser,
587 2010) may be endowed with some rule-based mechanisms dedicated to fast learning of
588 “classes” of elements occurring at the edges of sequences (e.g., here, learning that A₁ and A₂
589 always occur in the first position), as well as statistical learning mechanisms for the
590 computation of transitional probabilities (e.g. A₁_B₁). The current experiment did not aim at

591 assessing the edge-based positional learning hypothesis but examined the extraction time
592 course of those transitional probabilities.

593 In humans, learning occurred early in the experiment, and was strengthened
594 throughout the entire exposure phase. In baboons, learning of the NADs occurred later in the
595 experiment, but a similar progressive emergence was observed. In previous SRT experiments,
596 we found that the learning of adjacent dependencies in triplets (Minier et al., 2016), or pairs of
597 shapes (Fagot, Malassis, & Medam, 2017) gave rise to similar progressive (albeit earlier)
598 decrease in response times throughout the exposure to these regularities. These data, along
599 with previous findings (Frost & Monaghan, 2016; Romberg & Saffran, 2013; Vuong et al.,
600 2016), suggest that adjacent and non-adjacent dependencies might be extracted by similar
601 statistical learning mechanisms. However, they do not allow disentangling between the single-
602 process and the dual-system proposals described above. Indeed, the difference in speed
603 learning that is observed between baboons and humans might reflect an involvement of
604 working memory in NADs extraction, as working memory capacity differ between these
605 species (e.g., Fagot & De Lillo, 2011). However, addressing this question would require
606 additional behavioral and brain imaging studies. Regarding behavioral studies, correlational
607 designs in humans and non-human primates would allow examining individual differences in
608 statistical learning ability across different types of dependencies (i.e., adjacent and non-
609 adjacent, Siegelman, Bogaerts, Christiansen, & Frost, 2017; Siegelman & Frost, 2015), as
610 well as exploring the relationships between working memory capacity and NADs extraction.
611 Comparative neuroimaging studies have already suggested that adjacent dependencies are
612 processed by evolutionary conserved brain structures, including the frontal operculum and
613 anterior insula (Wilson, Kikuchi, et al., 2015). However, further researches are also needed in

614 this domain to discover whether NADs processing is sustained by similar or different neural
615 substrates in human and non-human primates (Milne et al., 2016; Wilson et al., 2017).

616 Another important question is the domain generality of the mechanisms involved
617 during the learning of NADs. For instance, are the extraction of NADs in the current SRT task
618 and the extraction of NADs in natural languages (such as in *is reading*) supported by the same
619 learning mechanisms? Evidences accumulated so far reveal a contrasted pattern (Frost,
620 Armstrong, Siegelman, & Christiansen, 2015). On the one hand, individuals with specific
621 language impairment have been found to exhibit poor performance in auditory statistical
622 learning tasks (e.g., Evans, Saffran, & Robe-Torres, 2009) as well as in SRT tasks (Lum,
623 Conti-Ramsden, Morgan, & Ullman, 2014), compared with typically-developing individuals.
624 They also express greater difficulties in processing NADs in an AGL-SRT task (Hsu,
625 Tomblin, & Christiansen, 2014). In another study, Misyak, Christiansen, and Tomblin (2010)
626 found a positive correlation between typically-developing individuals' ability to process long-
627 distance dependencies from a natural language and NADs in an AGL-SRT task. On the other
628 hand, statistical learning appears to be subject to modality and stimulus specificity (e.g.,
629 Conway & Christiansen, 2005, 2006). Siegelman and Frost (2015) reported for instance that
630 the performance of their participants did not correlate between any of four statistical learning
631 tasks they have used (auditory-verbal, auditory-nonverbal, visual, and SRT tasks). These
632 results suggest the existence of modality and stimulus specific constraints on statistical
633 learning mechanisms, which prevent drawing strong conclusions regarding the similarity
634 between NADs extraction in natural languages and in our visuo-spatial task.

635 From an evolutionary standpoint, the ability to keep track of predictive relationships
636 between non-adjacent events might present various functional advantages, for instance for

637 planning complex behavioral or motor sequences, or for monitoring social interactions and
638 their outcomes (Sonnweber et al., 2015). In baboons, this process may allow for instance to
639 detect that a threat behavior from an individual A is followed by a scream from an individual
640 B, even if other individuals emit unrelated vocalizations in between. One general advantage of
641 the learning of NADs might also be a reduction in memory demands. For instance in song
642 birds, admitting an optional or variable song element between two others (thereby being non-
643 adjacent) could limit the number of pairwise transitions needed to be memorized (Petkov &
644 Wilson, 2012). In our experiments, the extraction of two NADs may be cognitively less
645 demanding than the learning and storage of ten sequences.

646

647

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648

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References

659

660 Cate, C. ten, & Okanoya, K. (2012). Revisiting the syntactic abilities of non-human animals:
661 natural vocalizations and artificial grammar learning. *Philosophical Transactions of the Royal*
662 *Society of London B: Biological Sciences*, 367(1598), 1984–1994.
663 <https://doi.org/10.1098/rstb.2012.0055>

664 Cleeremans, A., & McClelland, J. L. (1991). Learning the structure of event sequences.
665 *Journal of Experimental Psychology. General*, 120(3), 235–253.

666 Conway, C. M., & Christiansen, M. H. (2001). Sequential learning in non-human primates.
667 *Trends in Cognitive Sciences*, 5(12), 539–546. [https://doi.org/10.1016/S1364-6613\(00\)01800-](https://doi.org/10.1016/S1364-6613(00)01800-3)
668 3

669 Conway, C. M., & Christiansen, M. H. (2005). Modality-constrained statistical learning of
670 tactile, visual, and auditory sequences. *Journal of Experimental Psychology. Learning,*
671 *Memory, and Cognition*, 31(1), 24–39. <https://doi.org/10.1037/0278-7393.31.1.24>

672 Conway, C. M., & Christiansen, M. H. (2006). Statistical learning within and between
673 modalities: pitting abstract against stimulus-specific representations. *Psychological Science*,
674 17(10), 905–912. <https://doi.org/10.1111/j.1467-9280.2006.01801.x>

675 Conway, C. M., Deocampo, J., A., & Smith, G..N.L. (2016). Multiple Routes to Implicit
676 Statistical Learning? A Dual-System Perspective. Abstracts of the Psychonomic Society, 57th
677 annual meeting, Boston.

- 678 Creel, S. C., Newport, E. L., & Aslin, R. N. (2004). Distant melodies: statistical learning of
679 nonadjacent dependencies in tone sequences. *Journal of Experimental Psychology. Learning,*
680 *Memory, and Cognition, 30*(5), 1119–1130. <https://doi.org/10.1037/0278-7393.30.5.1119>
- 681 de la Mora, D. M., & Toro, J. M. (2013). Rule learning over consonants and vowels in a non-
682 human animal. *Cognition, 126*(2), 307–312. <https://doi.org/10.1016/j.cognition.2012.09.015>
- 683 Endress, A. D. (2010). Learning melodies from non-adjacent tones. *Acta Psychologica,*
684 *135*(2), 182–190. <https://doi.org/10.1016/j.actpsy.2010.06.005>
- 685 Endress, A. D., & Bonatti, L. L. (2007). Rapid learning of syllable classes from a perceptually
686 continuous speech stream. *Cognition, 105*(2), 247–299.
687 <https://doi.org/10.1016/j.cognition.2006.09.010>
- 688 Endress, A. D., Carden, S., Versace, E., & Hauser, M. D. (2010). The apes' edge: positional
689 learning in chimpanzees and humans. *Animal Cognition, 13*(3), 483–495.
690 <https://doi.org/10.1007/s10071-009-0299-8>
- 691 Endress, A. D., Nespors, M., & Mehler, J. (2009). Perceptual and memory constraints on
692 language acquisition. *Trends in Cognitive Sciences, 13*(8), 348–353.
693 <https://doi.org/10.1016/j.tics.2009.05.005>
- 694 Endress, A. D., Scholl, B. J., & Mehler, J. (2005). The role of salience in the extraction of
695 algebraic rules. *Journal of Experimental Psychology. General, 134*(3), 406–419.
696 <https://doi.org/10.1037/0096-3445.134.3.406>

- 697 Endress, A. D., & Wood, J. N. (2011). From movements to actions: two mechanisms for
698 learning action sequences. *Cognitive Psychology*, *63*(3), 141–171.
699 <https://doi.org/10.1016/j.cogpsych.2011.07.001>
- 700 Evans, J. L., Saffran, J. R., & Robe-Torres, K. (2009). Statistical Learning in Children With
701 Specific Language Impairment. *Journal of Speech, Language, and Hearing Research*, *52*(2),
702 321–335. [https://doi.org/10.1044/1092-4388\(2009/07-0189\)](https://doi.org/10.1044/1092-4388(2009/07-0189))
- 703 Fagot, J., & Bonté, E. (2010). Automated testing of cognitive performance in monkeys: use of
704 a battery of computerized test systems by a troop of semi-free-ranging baboons (*Papio papio*).
705 *Behavior Research Methods*, *42*(2), 507–516. <https://doi.org/10.3758/BRM.42.2.507>
- 706 Fagot, J., & De Lillo, C. (2011). A comparative study of working memory: Immediate serial
707 spatial recall in baboons (*Papio papio*) and humans. *Neuropsychologia*, *49*(14), 3870–3880.
708 <https://doi.org/10.1016/j.neuropsychologia.2011.10.003>
- 709 Fagot, J., Malassis, R., & Medam, T. (2017). The processing of positional information in a
710 two-item sequence limits the emergence of symmetry in baboons (*Papio papio*), but not in
711 humans (*Homo sapiens*). *Learning & Behavior*. <https://doi.org/10.3758/s13420-017-0290-1>
- 712 Fagot, J., & Paleressompouille, D. (2009). Automatic testing of cognitive performance in
713 baboons maintained in social groups. *Behavior Research Methods*, *41*(2), 396–404.
714 <https://doi.org/10.3758/BRM.41.2.396>
- 715 Fiser, J., & Aslin, R. N. (2001). Unsupervised statistical learning of higher-order spatial
716 structures from visual scenes. *Psychological Science*, *12*(6), 499–504.

- 717 Friederici, A. D. (2004). Processing local transitions versus long-distance syntactic
718 hierarchies. *Trends in Cognitive Sciences*, 8(6), 245–247.
719 <https://doi.org/10.1016/j.tics.2004.04.013>
- 720 Froehlich, A. L., Herbranson, W. T., Loper, J. D., Wood, D. M., & Shimp, C. P. (2004).
721 Anticipating by Pigeons Depends on Local Statistical Information in a Serial Response Time
722 Task. *Journal of Experimental Psychology: General*, 133(1), 31–45.
723 <https://doi.org/10.1037/0096-3445.133.1.31>
- 724 Frost, R., Armstrong, B. C., Siegelman, N., & Christiansen, M. H. (2015). Domain generality
725 versus modality specificity: the paradox of statistical learning. *Trends in Cognitive Sciences*,
726 19(3), 117–125. <https://doi.org/10.1016/j.tics.2014.12.010>
- 727 Frost, R. L. A., & Monaghan, P. (2016). Simultaneous segmentation and generalisation of
728 non-adjacent dependencies from continuous speech. *Cognition*, 147, 70–74.
729 <https://doi.org/10.1016/j.cognition.2015.11.010>
- 730 Gebhart, A. L., Newport, E. L., & Aslin, R. N. (2009). Statistical learning of adjacent and
731 nonadjacent dependencies among nonlinguistic sounds. *Psychonomic Bulletin & Review*,
732 16(3), 486–490. <https://doi.org/10.3758/PBR.16.3.486>
- 733 Gómez, R. L. (2002). Variability and detection of invariant structure. *Psychological Science*,
734 13(5), 431–436.
- 735 Gómez, R., & Maye, J. (2005). The Developmental Trajectory of Nonadjacent Dependency
736 Learning. *Infancy*, 7(2), 183–206. https://doi.org/10.1207/s15327078in0702_4

- 737 Hauser, M. D., Newport, E. L., & Aslin, R. N. (2001). Segmentation of the speech stream in a
738 non-human primate: statistical learning in cotton-top tamarins. *Cognition*, 78(3), B53–B64.
739 [https://doi.org/10.1016/S0010-0277\(00\)00132-3](https://doi.org/10.1016/S0010-0277(00)00132-3)
- 740 Heijningen, C. A. A. van, Visser, J. de, Zuidema, W., & Cate, C. ten. (2009). Simple rules can
741 explain discrimination of putative recursive syntactic structures by a songbird species.
742 *Proceedings of the National Academy of Sciences*. <https://doi.org/10.1073/pnas.0908113106>
- 743 Hsu, H. J., Tomblin, J. B., & Christiansen, M. H. (2014). Impaired statistical learning of non-
744 adjacent dependencies in adolescents with specific language impairment. *Frontiers in*
745 *Psychology*, 5, 175. <https://doi.org/10.3389/fpsyg.2014.00175>
- 746 Kovács, Á. M., & Mehler, J. (2009). Flexible Learning of Multiple Speech Structures in
747 Bilingual Infants. *Science*, 325(5940), 611–612. <https://doi.org/10.1126/science.1173947>
- 748 Lum, J. A. G., Conti-Ramsden, G., Morgan, A. T., & Ullman, M. T. (2014). Procedural
749 learning deficits in specific language impairment (SLI): A meta-analysis of serial reaction
750 time task performance. *Cortex; a Journal Devoted to the Study of the Nervous System and*
751 *Behavior*, 51(100), 1–10. <https://doi.org/10.1016/j.cortex.2013.10.011>
- 752 Marchetto, E., & Bonatti, L. L. (2013). Words and possible words in early language
753 acquisition. *Cognitive Psychology*, 67(3), 130–150.
754 <https://doi.org/10.1016/j.cogpsych.2013.08.001>
- 755 Marchetto, E., & Bonatti, L. L. (2015). Finding words and word structure in artificial speech:
756 the development of infants' sensitivity to morphosyntactic regularities. *Journal of Child*
757 *Language*, 42(4), 873–902. <https://doi.org/10.1017/S0305000914000452>

- 758 Milne, A. E., Mueller, J. L., Männel, C., Attaheri, A., Friederici, A. D., & Petkov, C. I.
759 (2016). Evolutionary origins of non-adjacent sequence processing in primate brain potentials.
760 *Scientific Reports*, 6, 36259. <https://doi.org/10.1038/srep36259>
- 761 Minier, L., Fagot, J., & Rey, A. (2016). The Temporal Dynamics of Regularity Extraction in
762 Non-Human Primates. *Cognitive Science*, 40(4), 1019–1030.
763 <https://doi.org/10.1111/cogs.12279>
- 764 Misyak, J. B., Christiansen, M. H., & Bruce Tomblin, J. (2010). Sequential Expectations: The
765 Role of Prediction-Based Learning in Language. *Topics in Cognitive Science*, 2(1), 138–153.
766 <https://doi.org/10.1111/j.1756-8765.2009.01072.x>
- 767 Newport, E. L., & Aslin, R. N. (2004). Learning at a distance I. Statistical learning of non-
768 adjacent dependencies. *Cognitive Psychology*, 48(2), 127–162.
- 769 Newport, E. L., Hauser, M. D., Spaepen, G., & Aslin, R. N. (2004). Learning at a distance II.
770 Statistical learning of non-adjacent dependencies in a non-human primate. *Cognitive*
771 *Psychology*, 49(2), 85–117. <https://doi.org/10.1016/j.cogpsych.2003.12.002>
- 772 Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from
773 performance measures. *Cognitive Psychology*, 19(1), 1–32. [https://doi.org/10.1016/0010-](https://doi.org/10.1016/0010-0285(87)90002-8)
774 [0285\(87\)90002-8](https://doi.org/10.1016/0010-0285(87)90002-8)
- 775 Onnis, L., Monaghan, P., Christiansen, M. H., & Chater, N. (2005). Variability is the spice of
776 learning, and a crucial ingredient for detecting and generalizing in nonadjacent dependencies
777 [Proceedings paper].

- 778 Onnis, Luca, Monaghan, P., Richmond, K., & Chater, N. (2005). Phonology impacts
779 segmentation in online speech processing. *Journal of Memory and Language*, 53(2), 225–237.
780 <https://doi.org/10.1016/j.jml.2005.02.011>
- 781 Pacton, S., & Perruchet, P. (2008). An attention-based associative account of adjacent and
782 nonadjacent dependency learning. *Journal of Experimental Psychology. Learning, Memory,*
783 *and Cognition*, 34(1), 80–96. <https://doi.org/10.1037/0278-7393.34.1.80>
- 784 Pacton, S., Sobaco, A., & Perruchet, P. (2015). Is an attention-based associative account of
785 adjacent and nonadjacent dependency learning valid? *Acta Psychologica*, 157, 195–199.
786 <https://doi.org/10.1016/j.actpsy.2015.03.002>
- 787 Peña, M., Bonatti, L. L., Nespors, M., & Mehler, J. (2002). Signal-driven computations in
788 speech processing. *Science (New York, N.Y.)*, 298(5593), 604–607.
789 <https://doi.org/10.1126/science.1072901>
- 790 Perruchet, P., Tyler, M. D., Galland, N., & Peereman, R. (2004). Learning nonadjacent
791 dependencies: no need for algebraic-like computations. *Journal of Experimental Psychology.*
792 *General*, 133(4), 573–583. <https://doi.org/10.1037/0096-3445.133.4.573>
- 793 Petkov, C. I., & Wilson, B. (2012). On the pursuit of the brain network for proto-syntactic
794 learning in non-human primates: conceptual issues and neurobiological hypotheses.
795 *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367(1598), 2077–
796 2088. <https://doi.org/10.1098/rstb.2012.0073>
- 797 Ravignani, A., & Sonnweber, R. (2017). Chimpanzees process structural isomorphisms across
798 sensory modalities. *Cognition*, 161, 74–79. <https://doi.org/10.1016/j.cognition.2017.01.005>

- 799 Ravignani, A., Sonnweber, R.-S., Stobbe, N., & Fitch, W. T. (2013). Action at a distance:
800 dependency sensitivity in a New World primate. *Biology Letters*, *9*(6), 20130852.
801 <https://doi.org/10.1098/rsbl.2013.0852>
- 802 Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and*
803 *Verbal Behavior*, *6*(6), 855–863. [https://doi.org/10.1016/S0022-5371\(67\)80149-X](https://doi.org/10.1016/S0022-5371(67)80149-X)
- 804 Rey, A., Minier, L., Malassis, R., Bogaerts, L., & Fagot, J. (in press). Regularity extraction
805 across species: associative learning mechanisms shared by human and non-human primates.
806 *Topics in Cognitive Science*.
- 807 Romberg, A. R., & Saffran, J. R. (2010). Statistical learning and language acquisition. *Wiley*
808 *Interdisciplinary Reviews. Cognitive Science*, *1*(6), 906–914. <https://doi.org/10.1002/wcs.78>
- 809 Romberg, A. R., & Saffran, J. R. (2013). All Together Now: Concurrent Learning of Multiple
810 Structures in an Artificial Language. *Cognitive Science*, *37*(7), 1290–1320.
811 <https://doi.org/10.1111/cogs.12050>
- 812 Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old
813 infants. *Science (New York, N.Y.)*, *274*(5294), 1926–1928.
- 814 Siegelman, N., Bogaerts, L., Christiansen, M. H., & Frost, R. (2017). Towards a theory of
815 individual differences in statistical learning. *Philosophical Transactions of the Royal Society*
816 *of London. Series B, Biological Sciences*, *372*(1711). <https://doi.org/10.1098/rstb.2016.0059>
- 817 Siegelman, N., & Frost, R. (2015). Statistical learning as an individual ability: Theoretical
818 perspectives and empirical evidence. *Journal of Memory and Language*, *81*, 105–120.
819 <https://doi.org/10.1016/j.jml.2015.02.001>

- 820 Sonnweber, R., Ravignani, A., & Fitch, W. T. (2015). Non-adjacent visual dependency
821 learning in chimpanzees. *Animal Cognition*, *18*(3), 733–745. [https://doi.org/10.1007/s10071-](https://doi.org/10.1007/s10071-015-0840-x)
822 [015-0840-x](https://doi.org/10.1007/s10071-015-0840-x)
- 823 Takahasi, M., Yamada, H., & Okanoya, K. (2010). Statistical and Prosodic Cues for Song
824 Segmentation Learning by Bengalese Finches (*Lonchura striata* var. *domestica*). *Ethology*,
825 *116*(6), 481–489. <https://doi.org/10.1111/j.1439-0310.2010.01772.x>
- 826 Toro, J. M., Nespors, M., Mehler, J., & Bonatti, L. L. (2008). Finding words and rules in a
827 speech stream: functional differences between vowels and consonants. *Psychological Science*,
828 *19*(2), 137–144. <https://doi.org/10.1111/j.1467-9280.2008.02059.x>
- 829 Toro, J. M., & Trobalón, J. B. (2005). Statistical computations over a speech stream in a
830 rodent. *Perception & Psychophysics*, *67*(5), 867–875. <https://doi.org/10.3758/BF03193539>
- 831 Vuong, L. C., Meyer, A. S., & Christiansen, M. H. (2016). Concurrent Statistical Learning of
832 Adjacent and Nonadjacent Dependencies. *Language Learning*, *66*(1), 8–30.
833 <https://doi.org/10.1111/lang.12137>
- 834 Wilson, B., Kikuchi, Y., Sun, L., Hunter, D., Dick, F., Smith, K., ... Petkov, C. I. (2015).
835 Auditory sequence processing reveals evolutionarily conserved regions of frontal cortex in
836 macaques and humans. *Nature Communications*, *6*, 8901.
837 <https://doi.org/10.1038/ncomms9901>
- 838 Wilson, B., Marslen-Wilson, W. D., & Petkov, C. I. (2017). Conserved Sequence Processing
839 in Primate Frontal Cortex. *Trends in Neurosciences*, *0*(0).
840 <https://doi.org/10.1016/j.tins.2016.11.004>

- 841 Wilson, B., Slater, H., Kikuchi, Y., Milne, A. E., Marslen-Wilson, W. D., Smith, K., &
842 Petkov, C. I. (2013). Auditory Artificial Grammar Learning in Macaque and Marmoset
843 Monkeys. *The Journal of Neuroscience*, 33(48), 18825–18835.
844 <https://doi.org/10.1523/JNEUROSCI.2414-13.2013>
- 845 Wilson, B., Smith, K., & Petkov, C. I. (2015). Mixed-complexity artificial grammar learning
846 in humans and macaque monkeys: evaluating learning strategies. *The European Journal of*
847 *Neuroscience*, 41(5), 568–578. <https://doi.org/10.1111/ejn.12834>
- 848