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The different time course of phonotactic constraint learning in children and adults:

Evidence from speech errors

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### Abstract

Speech errors typically respect the speaker’s implicit knowledge of language-wide phonotactics (e.g., /ŋ/ cannot be a syllable onset in the English language). Previous work demonstrated that adults can learn novel experimentally-induced phonotactic constraints by producing syllable strings in which the allowable position of a phoneme depends on another phoneme within the sequence (e.g., /t/ can only be an onset if the medial vowel is /i/), but not earlier than the second day of training. Thus far, no work has been done with children. In the current 4-day experiment, a group of Dutch-speaking adults and nine-year-old children were asked to rapidly recite sequences of novel word-forms (e.g., *kieng nies siet hiem*) that were consistent with phonotactics of the spoken Dutch language. Within the procedure of the experiment, some consonants (i.e., /t/ and /k/) were restricted to onset or coda position depending on the medial vowel (i.e., /i/ or “ie” versus /ø:/ or “eu”). Speech errors in adults revealed a learning effect for the novel constraints on the second day of learning, consistent with earlier findings. A post-hoc analysis at trial-level showed that learning was statistically reliable after an exposure of 120 sequence-trials (including a consolidation period). Children started learning the constraints already on the first day. More precisely, the effect appeared significantly after an exposure of 24 sequences. These findings indicate that children are rapid implicit learners of novel phonotactics, which bears important implications for theorizing about developmental sensitivities in language learning.

**Key words:** children, implicit learning, phonotactic constraints, speech errors

45           Phonotactics refer to the constraints for allowed sound sequences in a language. For example, an  
46 English speaker easily accepts that “ming” is a possible English word, but that “ngim” is not. This is  
47 because the sound combination /ŋ/ always occurs at a coda position (e.g., as in “king” or “sing”) and  
48 never at onset in English words, although other languages may allow this (e.g., as in the word “nghiệp”,  
49 which is Vietnamese for “industry”). Sensitivity to phonotactic constraints in one’s native language starts  
50 very early in life (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993). Evidence for this also  
51 comes from the statistical-learning literature in which infants not older than 8 months are already able to  
52 track the distributional probabilities of syllables within and across word boundaries (Saffran, Aslin, &  
53 Newport, 1996). The ability to acquire phonotactic patterns in a language, as is demonstrated in artificial  
54 language paradigms, continues in adulthood (e.g., Onishi, Chambers, & Fisher, 2002). This is an  
55 important skill for learning second languages that sometimes contain phonotactics that deviate from the  
56 native language system.

57           A series of experiments provided evidence for adults’ ability to pick up novel phonotactics by  
58 looking at their speech errors (Dell, Reed, Adams, & Meyer, 2000; Warker, 2013; Warker & Dell, 2006,  
59 2015; Warker, Dell, Whalen, & Gereg, 2008). Speech conforms to the phonotactic constraints of a  
60 language and therefore these constraints are rarely violated when speech errors are made (Fromkin, 1971).  
61 For example, it is extremely unlikely that a native English speaker will spontaneously slip the phoneme  
62 combination /ŋ/ to an onset position as in “ngik” when intending to say “king” because an initial /ŋ/  
63 violates English phonotactics (Dell et al., 2000). The sensitivity of slips to the sound distributions in one’s  
64 language changes with experience. In 2000, Dell and colleagues introduced the novel phonotactic  
65 constraint paradigm as an experimental analogue of this phenomenon. They argued that speech errors can  
66 be used as a promising tool to implicitly measure the acquisition of new arbitrary phonotactic constraints  
67 after limited exposure. In this paradigm, English native participants are exposed to written sequences of  
68 consonant-vowel-consonant (CVC) syllables that form novel word-forms (e.g., *hes meg fen keng*), which  
69 they are asked to recite. Some consonants are restricted in the native language and are therefore *language-*

70 *wide* restrictions (e.g., /h/ can only be onset and /ŋ/ can only be coda) while other consonants are  
71 *unrestricted* according to the English language (e.g., /k/, /m/, /n/ and /g/ can appear both as onset and as  
72 coda). Crucially, there are also two consonants that, although they are unrestricted in English, appear  
73 restricted within the setting of the experiment. For example, for some participants, the consonant /f/  
74 always appears as onset in the experiment and the consonant /s/ always appears as a coda, while the  
75 inverse is true for other participants. These are called the *experiment-wide* constraints. Across four days,  
76 participants are asked to repeat each sequence of four CVC word-forms three times at a fast tempo  
77 applied to elicit speech errors. Consonants that erroneously move to another syllable position (i.e., from  
78 onset to coda or from coda to onset) are counted and labeled as “other-position” errors. Consonants that  
79 erroneously move but thereby do not change syllable position (i.e., from onset to another onset or from  
80 coda to another coda) are also counted and labeled as “same-position” (or legal) errors. The erroneous  
81 consonant movements are coded according to the constraint type, i.e., language-wide, experiment-wide or  
82 unrestricted. Errors involving the language-wide consonants should be 100% legal, which means that the  
83 consonants will never slip to the opposite syllable position. This is also better known as the phonotactic  
84 regularity effect (Fromkin, 1971).

85         The key aspect of the paradigm concerns the contrast between errors involving the experiment-  
86 wide constraints and those involving the unrestricted consonants (see, for instance, Dell et al., 2000). For  
87 the unrestricted consonants, the percentage of errors that are “same-position” provides a baseline measure  
88 of the extent to which a participant’s speech errors preserve their syllable position within a trial. This is  
89 also called the syllable-position effect (Dell et al., 2000; Fromkin, 1971; Warker et al., 2008). For  
90 experiment-wide consonants, the key question is whether the percentage of errors that is legal (i.e., same-  
91 position movements) *rises significantly above* this unrestricted baseline rate. This would be evidence that  
92 new phonotactic constraints have been acquired and significantly influence production (errors) in the  
93 longer term. In other words, the difference between experiment-wide and unrestricted same-position  
94 percentages is described as the phonotactic learnings score (with positive values suggesting that

95 phonotactic learning has taken place). It thus reflects implicit learning of the novel experiment-induced  
96 constraint that cannot solely be explained by correctly labeling the syllable positions within the recited  
97 sequence (i.e., the syllable-position effect).

98           Using this paradigm, Dell and colleagues (2000) observed that adult speech errors for the  
99 experiment-wide (restricted) consonants obeyed their position almost 100% of the time, close to what one  
100 observes for errors involving language-wide constraints (that never violate their constrained positions),  
101 while only between 65 to 80% of the errors involving unrestricted consonants were of same-position.  
102 When the position of the consonants did not depend on other phonemes within the syllable sequence (i.e.,  
103 the constraints were simple or of first-order; e.g., */s/ occurs as onset or /s/ occurs as coda*), learning  
104 occurred already from the first day, suggesting that adults learned these simple constraints very quickly  
105 (see also, Goldrick, 2004; Taylor & Houghton, 2005). However, when the novel constraints were more  
106 complex by making the consonant's position dependent on the type of other phonemes within the  
107 sequence (e.g., *the consonant /f/ always appears as an onset if the medial vowel is /a/, but as a coda if the*  
108 *medial vowel is /e/*), learning was slower and less robust than with the first-order constraints. Later, this  
109 finding was replicated in subsequent work by Warker and colleagues (Warker & Dell, 2006; Warker et  
110 al., 2008). These authors demonstrated that adult speakers were in fact able to learn new second-order  
111 constraints, but not until the second day of learning. More precisely, the effect occurred after an exposure  
112 of 144 sequences, and the effect was most substantial after an offline consolidation period involving sleep  
113 (see also, Gaskell et al., 2014; Warker, 2013). The dissociation in time course with first-order constraints  
114 is explained within a self-interfering principle (for computational evidence, Warker & Dell, 2006; Warker  
115 et al., 2008): due to dependence on the characteristics of other phonemes within the sequence, similar  
116 inputs do not always lead to similar outputs. As an example, the consonant /f/ is sometimes associated  
117 with a /f/-onset output and sometimes with a /f/-coda output depending on the medial vowel. This results  
118 in interference that does not occur in first-order constraints (in which /f/ is always associated with a /f/-  
119 onset output or a /f/-coda output). As a result, more exposure, and a consolidation period with sleep is

120 needed to overcome interference and learn the contextual associations between syllable structures and  
121 phoneme position.

122 In some interesting developmental work, Janacsek and colleagues tested nine different age  
123 cohorts from age 4 to age 84 on the ability to implicitly learn sequential regularities (Janacsek, Fiser, &  
124 Nemeth, 2012). She showed superior performance for children that were between seven and twelve years  
125 of age. Phonotactic constraint learning is an important aspect of novel word(-form) learning that relies on  
126 implicit sequential learning abilities (Gupta & Tisdale, 2009; Ullman, 2004). Word-learning is an activity  
127 that does not end and even accelerate at school age (Altman, 1997; Pinker, 1994). In light of the ongoing  
128 debate about age-sensitivities in different aspects of language-learning (Kennedy & Norman, 2005;  
129 Newport, Bavelier, & Neville, 2001; Werker & Hensch, 2015), it is important to investigate children on  
130 the ability to rapidly acquire novel phonotactics.

131 There has been some relevant work within the comprehension domain showing that young infants  
132 are able to learn (and generalize) novel second-order phonotactic constraints quickly after a short auditory  
133 exposure to a small set of input exemplars (e.g., Chambers, Onishi, & Fisher, 2003; Gerken & Knight,  
134 2015). However, experiments testing children's ability to learn novel phonotactics through speech  
135 production are entirely missing. In the current study, we were interested in investigating children's ability  
136 to rapidly pick up novel phonotactic constraints by looking at their speech errors. With this aim, and with  
137 respect to Janacsek's developmental findings on implicit learning skills, we tested a group of nine-year-  
138 old children on Dell's phonotactic constraint paradigm. The main focus of the study concerned the time  
139 course of the phonotactic learning patterns in the speech error data of the children. A group of Dutch-  
140 speaking adults was also tested to see whether the (slowly developing) speech error patterns for second-  
141 order constraints found in previous studies could be replicated in a group of Dutch speaking adults. All  
142 participants returned to the lab on four consecutive days for production of sequences of CVC syllables  
143 that were constrained with language-wide, experiment-wide and unrestricted consonants. Similar to  
144 previous work, half of the participants were informed about the constraints and half were told nothing

145 about the crucial manipulations. This was done to investigate whether phonotactic learning indeed  
146 develops under incidental learning conditions, which would indicate that it is not dependent on explicit  
147 information and therefore on implicit statistical learning (Warker & Dell, 2006).

## 148 **Method**

### 149 **Participants**

150 Twelve young adults between 18 and 25 years old ( $M = 21.42$ ,  $SD = 2.27$ ; 2 males), and twelve 9-  
151 to 10-year-old children ( $M = 9.74$ ,  $SD = .37$ ; 5 males) participated in the study. The children were  
152 recruited from three different schools. Adults were recruited by advertising. Testing took place  
153 individually in a testing room at Ghent University, for the adults, and in a secluded classroom at school  
154 for the children. All participants were native Dutch speakers and none of them suffered from any  
155 developmental or neurological disorder. Half of the participants were assigned to the informed condition  
156 and were briefed about the experiment-wide constraints in the task. The other half of the adults remained  
157 uninformed. Participants in the informed and uninformed groups were matched for (age-adjusted)  
158 percentile scores on the Raven's Progressive Matrices (Raven, Raven, & Court, 2000) and for  
159 performance on the Digit Span subtest of the WISC-III-NL (Kort et al., 2005). Percentile scores on the  
160 Raven's Progressive Matrices were comparable between children and adults. This was done to assure that  
161 the groups were comparable for general cognitive abilities. All adults completed informed consent and  
162 received financial compensation for their time at the end of the experiment. Parental consent was obtained  
163 for the children and they were compensated with sweets. The study was approved by the local Ethics  
164 Committee at Ghent University.

### 165 **Materials**

166 Each participant received a set of 96 sequences on each day. Each sequence contained four novel  
167 word-forms of the structure CVC (e.g., *kieng nies siet hiem*). In total, eight different consonants (i.e., /k/,  
168 /ŋ /, /n/, /f/, /s/, /t/, /h/ and /m/) were used. Each consonant appeared once per sequence. These consonants

169 belonged to three different constraint groups: language-wide (/h/, /ŋ/), experiment-wide (/t/, /k/), and  
 170 unrestricted (/m/, /n/, /f/, /s/). The vowels were either /i/ (as in the English word “deep” or the Dutch word  
 171 “fiets”) or /ø:/ (as in the Dutch word “deur”)<sup>1</sup>, and this alternated between sequence-trials. This means  
 172 that half of the trials contained sequences with solely /i/ vowels and half with solely /ø:/ vowels. All  
 173 sequences were constructed so that in each sequence /h/ was always an onset and /ŋ/ was always a coda in  
 174 accordance to Dutch phonotactics. The consonants in the unrestricted groups appeared both as coda and  
 175 as onset throughout the experiment (also in accordance to Dutch phonotactics). The consonants appeared  
 176 equally often at both positions across the entire experiment. The positions of the consonants in the  
 177 experiment-wide groups are unrestricted in the Dutch language but appeared restricted within the setting  
 178 of the experiment. Half of the participants experienced the experiment-wide constraint */t/ is an onset and*  
 179 */k/ is a coda if the vowel is /i/; /k/ is an onset and /t/ is coda if the vowel is /ø:/*. We call this the “tiek-  
 180 keut” restriction. The other half of the participants experienced the reverse constraint. We call this the  
 181 “kiet-teuk” restriction.

182 Four lists of 96 sequences were randomly generated for each participant by use of a computer  
 183 program. Letter combinations that resulted in existing words were avoided. The sequences were printed in  
 184 80-point bold Courier New and white font on a black background. The sequence appeared in one line and  
 185 remained on the screen until reciting was finished, after which a new sequence line was presented.  
 186 Because the main focus of the study was to test children, the sequences were also presented auditorily in  
 187 support of reading ability. Each CVC syllable (or word-form) was recorded separately by a male voice  
 188 and noise-cancelled. During sequence presentation, the syllables were presented at 60dB using  
 189 headphones (Sennheiser PC 131) at a rate of one syllable per second.

## 190 **Procedure**

191 Half of the participants were first informed about the experiment-wide constraints. This was done  
 192 step-by step using a Powerpoint presentation. Each experiment-wide constraint was accompanied by two  
 193 examples, one that followed and one that violated the constraint. The children and adults in the



194 uninformed condition were not informed about the constraints. After task instructions, all participants  
195 were presented with four practice sequences to familiarize themselves with the task. Participants first  
196 heard the sequence once (together with the visual presentation on the screen), and were then asked to  
197 recite the sequences in time with a metronome. They first recited the sequence slowly at a rate of one  
198 syllable per second (in time with the metronome) and subsequently repeated this sequence three times  
199 without pause at a faster rate of 2.53 syllables per second (in time with the metronome). The sequence  
200 remained on the screen until reciting was finished. In total, one set of 96 sequences was completed per  
201 day. Each session was digitally recorded using a head-mounted microphone and a computer-built  
202 recorder.

203

### Results

204 Before analysis, speech errors were transcribed from the digital recordings. Consonants that  
205 moved position in a particular sequence were either coded as same-position or other-position, depending  
206 on the position they moved to. For the experiment-wide consonants, this was coded with respect to the  
207 medial vowel within the sequence-trial and the restriction that the participant was experiencing (i.e. “tiek-  
208 keut” or “kiet-teuk”). For example, if the target sequence is *kieng nief siet hiem* and a participant (who is  
209 experiencing the “kiet-teuk” restriction) recited this sequence as ***hieng tief nies kiem***; five errors would be  
210 coded (in bold): One same-position error for the language-wide constraint (i.e., /h/ switched from onset to  
211 another onset), one other-position error for the experiment-wide constraint (i.e., /t/ switched from coda to  
212 onset), one same-position error for the unrestricted constraint (i.e., /n/ switched from one onset to another  
213 onset), one other-position error for the unrestricted constraint (i.e., /s/ switched from onset to coda), and  
214 one same-position error for the experiment-wide constraint (i.e., /k/ switched from onset to another onset).  
215 For cutoff errors (e.g., *s...keut*), only the first uttered consonant was coded. Substitutions (i.e., consonants  
216 that were replaced by other new consonants) and omissions or indistinguishable phonemes were not  
217 included for analysis. A second coder who was blind to the manipulations and the aim of the study  
218 transcribed 12 sessions (randomly distributed across group and training day) in order to test for inter-rater

219 reliability. Overall, coding reliability was very good: For the 18 432 syllables that were doubly  
220 transcribed, both coders agreed there was no error on 17 760 syllables and on the presence and nature of  
221 414 errors. The agreement was 98.6%. For those syllables in which the original coder found an error (512  
222 errors), the conditionalized agreement rate was 75%. These values are comparable to previous studies  
223 (e.g., Warker et al., 2008). Therefore, the original coding of the first coder was not changed.

224 To measure the effect of novel phonotactic learning, the same analyses were used as in Dell  
225 (2000), Warker and Dell (2006) by using non-parametric Wilcoxon matched pair tests. We were  
226 specifically interested in the percentage of same-position slips for experiment-wide versus unrestricted  
227 consonants on each day/training session (see also, Warker and Dell, 2006). The percentage of same-  
228 position slips for the experiment-wide consonants should be significantly above that of the unrestricted  
229 consonants, if learning occurs.

230 **Children.** The language-wide constraints were never violated: children's errors containing /h/  
231 and /ŋ/ were legal 100% of the time (SE = 0, based on a total of 926 errors). The raw number same-  
232 position and different-position errors on each day for both the experiment-wide and unrestricted  
233 consonants can be found in Table 1. On the first day, there was already evidence for learning (**Day 1**,  $Z =$   
234  $-2.98$ ,  $p = .003$  with only 1 of 12 participants having a mean difference in the unexpected direction)<sup>2</sup>. The  
235 effect was significant on all subsequent days (**Days 2-4**,  $Z = -3.06$ ,  $p = .002$ ; separately per day, **Day 2**,  $Z$   
236  $= -2.98$ ,  $p = .003$  with 1 participant in the wrong direction; **Day 3**,  $Z = -2.76$ ,  $p = .006$  with 1 participant in  
237 the unexpected direction; and **Day 4**,  $Z = -2.82$ ,  $p = .005$  with 2 participants in the wrong direction).  
238 Additionally, a Mann Whitney U test was performed to test for differences between the informed and  
239 uninformed children. Overall, the learning effect was not significantly different between groups ( $Z = -$   
240  $1.54$ ,  $p = .12$ ; nor for each day separately,  $ps > .05$ ). Finally, the 96 sequences from day 1 were broken  
241 down into four sets of 24 sequence trials to more precisely determine when learning began to manifest  
242 itself in speech errors. Although there was no significant difference for the first 24 sequences (i.e., **1-24**,  $Z$   
243  $= -1.61$ ,  $p = .11$ ), the restricted constraints were picked up significantly in the subsequent sequences (i.e.,

244 **25-48**,  $Z = -2.16$ ,  $p = .031$ ; **49-72**,  $Z = -2.67$ ,  $p = .008$ ; **73-96**,  $Z = -3.06$ ,  $p = .002$ ). The pattern of speech  
245 errors during the first day is visualized in Figure 1.

246 **Adults.** The language-wide constraints were never violated: adult's errors containing /h/ and /ŋ/  
247 were 100% legal (SE = 0, based on a total of 354 errors). The raw number of same-position and different-  
248 position errors that were made on each day, for both the experiment-wide and unrestricted consonants, are  
249 reported in Table 2. On the first day, there was no significant difference between experiment-wide and  
250 unrestricted errors (**Day 1**,  $Z = -.80$ ,  $p = .42$  with 4 of 12 participants having a mean difference in the  
251 unexpected direction). However, the difference emerged on the subsequent days (**Days 2-4**,  $Z = -2.3$ ,  $p =$   
252  $.019$ ; separately per day, **Day 2**,  $Z = -1.96$ ,  $p = .05$  with 2 participants in the unexpected direction; **Day 3**,  
253  $Z = -.11$ ,  $p = .92$  with 3 participants in the wrong direction; **Day 4**,  $Z = -2.19$ ,  $p = .028$  with 1 participant  
254 in the wrong direction)<sup>3</sup>. Additionally, a Mann Whitney U-test was performed to test for differences  
255 between informed and uninformed adults. Overall, the learning effect was not significantly different  
256 between groups (i.e., across all days,  $Z = -.943$ ,  $p = .35$ ). In a further analysis, the second day for which  
257 the learning effect appeared (i.e., sequences 97 to 192) was broken down in four sets of 24 sequence trials  
258 to more precisely determine when learning began to manifest itself in speech errors during this session.  
259 The analysis revealed a learning effect that emerged significantly from the second quartile of sequence-  
260 trials: **97-120**,  $Z = -1.60$ ,  $p = .11$ ; **121-144**,  $Z = -2.67$ ,  $p = .008$ ; **145-168**,  $Z = -2.25$ ,  $p = .024$ ; **169-192** set,  
261  $Z = -2.81$ ,  $p = .005$ ). The pattern of speech errors revealing learning during the second day and across  
262 other days is visualized in Figure 2.

263 **Group comparison.** To further investigate child-adult differences for phonotactic constraint  
264 learning early in training, a hierarchical logistic regression model was fit to the speech-error data on Day  
265 1, using the lme4 package in R (R Development Core Team, 2011). The dependent variable was Position,  
266 or whether phonemes move to the same or different position. There were two predictor variables or fixed  
267 effects, i.e., Restrictedness (experiment-wide vs. unrestricted) and Age Group (Children vs. Adults).  
268 Maximal inclusion of random slopes for the within-participants variables (i.e.,  $1+ \text{Restrictedness} | \text{ppn}$ )

269 was strived for (Barr, Levy, Scheepers, & Tily, 2013). However, due to convergence issues, the random  
270 slope for restrictedness was dropped from the model, and only a random slope for subject was included.  
271 The p-values were calculated using Wald-z. The analysis revealed a significant two-way interaction  
272 between Restriction and Group ( $\beta=1.23$ ,  $SE=.44$ ,  $z = 2.79$ ,  $p<.01$ ), as well as an effect of Restriction ( $\beta=-$   
273  $1.50$ ,  $SE=.19$ ,  $z= -7.89$ ,  $p<.001$ ). Planned comparisons showed a significant phonotactic learning score for  
274 the children ( $\beta=-1.5$ ,  $SE=.19$ ,  $z=-7.89$ ,  $p<.001$ ) but not for the adults ( $\beta=-.027$ ,  $SE=.40$ ,  $z=-.69$ ,  $p=.90$ ).  
275 The same-position percentage for the unrestricted condition was higher for the adults than for the children  
276 ( $\beta = 1.37$ ,  $SE=.31$ ,  $z=4.3$ ,  $p<.001$ ).

### 277 **General Discussion**

278 The current study demonstrated that both children and adults were able to pick up complex (second-order)  
279 phoneme combination rules. Speech errors for the experimentally-constrained consonants violated their  
280 original syllable position less often than for the unrestricted consonants, indicating that children and  
281 adults acquired implicit knowledge of the experimentally restricted phonotactics through exposure, above  
282 and beyond what can be explained by a syllable-position effect. Importantly, the speech error data  
283 revealed a different time course for phonotactic learning in children than in adults, with children showing  
284 evidence for learning already on the first day. We elaborate on these findings below.

285 First, and this was the focus of the current study, nine-year old children learned a set of second-  
286 order phonotactic constraints by producing novel word-forms containing that constraint. Remarkably, and  
287 in contrast to what has been observed with adults in previous studies, learning revealed itself in speech  
288 errors already on the first day of learning. When the first day was broken down into four sets of 24  
289 sequences, results showed that the learning effect appeared reliably after an exposure of 24 sequences.  
290 This indicates that children are rapid learners of novel phonotactics and do not need a large amount of  
291 sequence trials (including a consolidation period involving sleep) as was found in adults (Warker, 2013;  
292 Warker et al., 2008).

293           Second, an additional group of Dutch-speaking adults were exposed to the same set of second-  
294 order phonotactic constraints. Similar to what has been found in previous studies with English speaking  
295 adults, but in contrast to what we observed with the children in the current study, the adults showed a  
296 learning effect that emerged only from the second day of training. When the second day was broken down  
297 into four sets of 24 sequences, results demonstrated a significant effect above the unrestricted constraints  
298 from the second quartile of trials. In other words, adults learned the same phonotactic constraints after  
299 much more exposure to 120 trials. One must immediately consider, however, that the same-position  
300 percentage for the unrestricted condition was surprisingly high in our group of adults, i.e., 87.4%. This is  
301 about 11% higher than in previous adult studies (Warker and Dell, 2006), and about 14% higher than  
302 what we observed in our children. The high syllable-position effect in adults could be explained by the  
303 fact that the to-be-recited sequences contain four non-words, for both the children and the adult group.  
304 This means that adults are reciting sequences that are two to three items below their working memory  
305 span ( $M_{\text{forward span}} = 6$ ,  $SD = .81$ ) while this is not true for children (who perform conform their working  
306 memory span,  $M_{\text{forward span}} = 4.8$ ,  $SD = .37$ ). The bimodal (written and spoken) stimulus sequence  
307 presentation in the current study, in contrast to previous studies in adults where the sequences were  
308 presented in a written mode only, could have further strengthened the adult's advantage for sequence-  
309 specific position labeling within each trial

310           As far as we know, no previous studies have investigated children's time course of speech errors  
311 in phonotactic constraint paradigm. In contrast with speed of learning, there has however been some work  
312 investigating the strength of learning across groups. In 2014, Samara and Caravolas compared school-  
313 aged children with adults when learning graphotactic constraints (Samara & Caravolas, 2014). In their  
314 study, 7 years old children and adults were exposed to written sequences of three letters (e.g., "des") that  
315 contained consonants constrained to a particular position (first-order), or depending on the vowel (second-  
316 order). After exposure to 144 (short exposure) or 288 (long exposure) trials, and a short distraction task,  
317 participants were tested for legality judgment on a set of novel strings. Signal detection analyses showed

318 that both children and adults were sensitive to the two types of constraints but strength of learning was  
319 higher in adults than in children. Interestingly however, when existing words were removed from the  
320 stimulus set, children performed as accurately as adults. Moreover, reaction times analysis showed that  
321 adults were not faster than children in responding to test items that contained the complex constraints. So  
322 even though the 7-years-old children have just begun to receive formal literacy instruction, they show  
323 comparable acquisition of the constraints as adults after a relatively short exposure of 144 trials. The  
324 current study was not designed for directly comparing the strength of learning in children and adults as  
325 this needs a different approach that controls for baseline differences in the syllable-position effect. The  
326 current study was able to demonstrate that children have an early time course for learning novel phoneme  
327 combination rules through speech production and are able to implicitly pick up the rule already on the  
328 first day of training. However, because of the significant baseline differences for the unrestricted  
329 constraints, we need to be cautious in making strong conclusions about potential child-adult differences  
330 without additional research.

331 A third observation is that both children and adults appear to learn implicitly. Even though half of  
332 the participants were told of the imposed constraints beforehand, the extent of learning was similar  
333 between instruction groups. This illustrates that primarily an implicit learning mechanism underlies  
334 performance in the constraint paradigm in both groups, and that speech errors denote a reliable measure  
335 of implicitly acquired knowledge.

336 We conclude that the apparently early time course for learning novel experimentally-induced  
337 phonotactics in children, provides some intriguing insights into child superiorities in some aspects of  
338 language learning. It is widely accepted that children, before they reach adolescence, are faster in picking  
339 up certain novel linguistic patterns than adults, in particular for phonology (Newport et al., 2001). They  
340 do not need years of practice before mastering a native-like tongue compared with adults (Johnson &  
341 Newport, 1989; Lenneberg, 1967). According to some researchers, implicit learning theories can provide  
342 more insight in the sensitive period debate (e.g., Dekeyser & Larson-Hall, 2005; Lichtman, 2016; Paradis,

2009; Ullman, 2001). The current study corroborates the hypothesis that developmental trajectories for some aspects of language learning, such as phonology, have its basis in implicit learning abilities. Additional research that investigates implicit learning performance for linguistic materials (such as phonotactic constraint learning via speech errors) across multiple sessions and developmental age cohorts is needed to explore these assumptions further. It is important to acknowledge that the results in the current study are restricted to a small set of consonants (/t/ and /k/). Although, we do not have strong reasons to assume that the effects found in the current study are not generalizable to other consonants (e.g. Warker, 2013; Warker & Dell, 2015), further research is recommended to take different consonants into account.

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437 **Table 1.** Number of consonant movements (i.e., same-position and different-position) obtained from the  
 438 children.

	Experiment-wide			Unrestricted			Learning (%)
	same- position	different- position	% same	same- position	different- position	% same	
<b>Day 1</b>	314	39	89	456	260	64	25**
<b>Day 2</b>	250	8	97	367	127	74	23**
<b>Day 3</b>	269	21	93	417	216	66	27**
<b>Day 4</b>	260	8	97	314	188	63	34**

439 \*\* $p < .01$

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450 **Table 2.** Number of consonant movements (i.e., same-position and different-position) obtained from the  
 451 adults.

	Experiment-wide			Unrestricted			Learning (%)
	same- position	different- position	% same	same- position	different- position	% same	
<b>Day 1</b>	85	10	89	193	29	87	2
<b>Day 2</b>	55	2	96	149	18	89	7*
<b>Day 3</b>	50	3	94	116	12	91	3
<b>Day 4</b>	30	1	97	96	17	85	12*

452 \* $p < .05$

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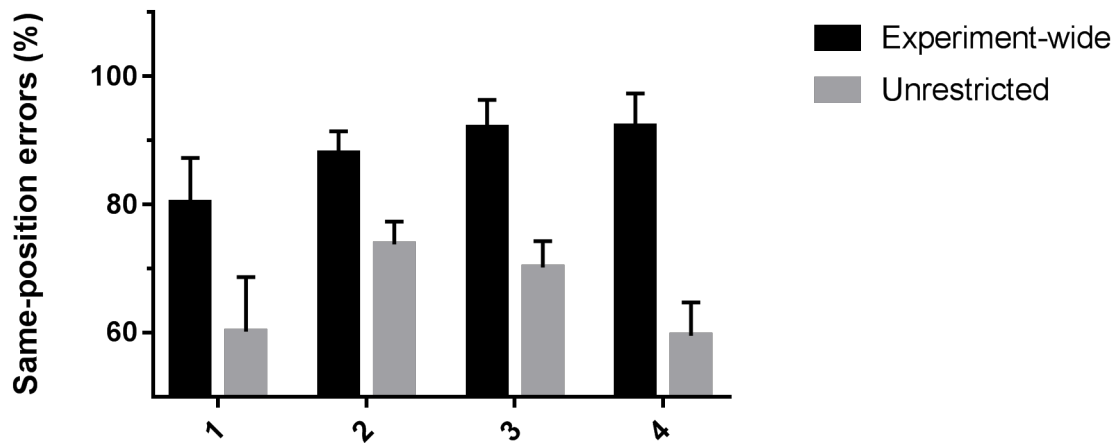
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464 **Figure 1.** Mean legality (same-position) percentages and standard errors across the four sets of 24 trial465 sequences in **day 1** in the group of children.

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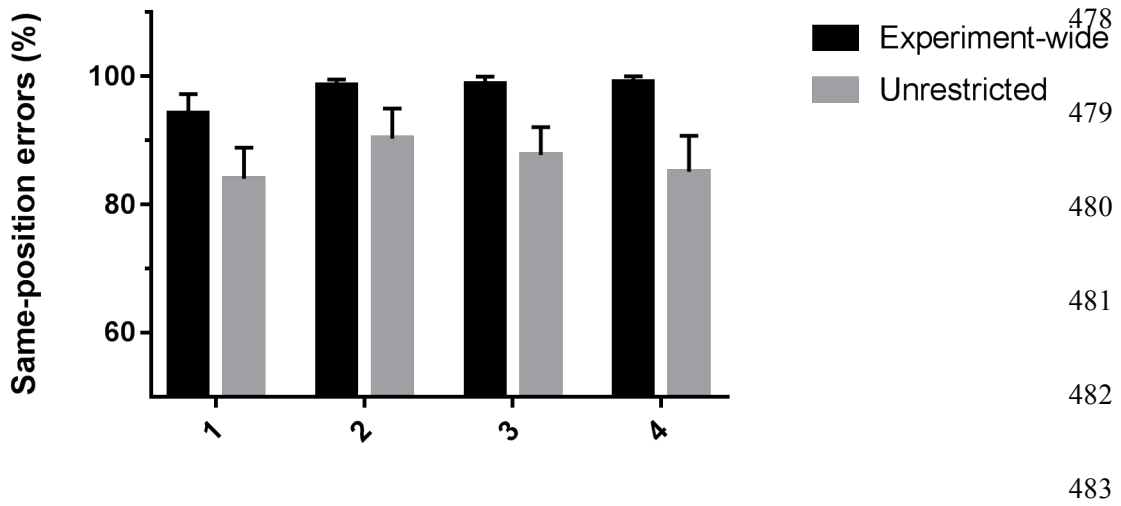
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484 **Figure 2.** Mean legality percentages and standard errors across the four sets of 24 trial sequences in **day 2**  
485 in the group of adults.

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<sup>1</sup>We avoided the vowels /ae/ and /I/ that were used in Dell et al. (2000) and in Warker and Dell (2006) as 1) the vowel /ae/ does not exist in the Dutch spoken language, and 2) the vowels /I/ or /ae/ or, alternatively, the most similar vowel /a/, resulted in too many existing words in the Dutch language during sequence generation.

<sup>2</sup>On the first day, there were two empty data cells, one for the experiment-wide errors and one for the unrestricted errors because there was one child who did not make any errors involving the experiment-wide and unrestricted consonants. As in Warker (2013), these empty data cells were estimated for analyses using the mean for experiment-wide errors and unrestricted errors for that day respectively.

<sup>3</sup>On the fourth day, there were four empty data cells for the restricted errors and one empty data cell for the unrestricted errors because four participants did not make any errors involving the restricted (or unrestricted consonants). As in Warker (2013), all empty data cells were estimated for analyses using the mean for the restricted (or unrestricted) errors for the appropriate day.