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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 nief 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 /øː/ 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

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

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

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

The key aspect of the paradigm concerns the contrast between errors involving the experiment-wide constraints and those involving the unrestricted consonants (see, for instance, Dell et al., 2000). For the unrestricted consonants, the percentage of errors that are "same-position" provides a baseline measure of the extent to which a participant's speech errors preserve their syllable position within a trial. This is also called the syllable-position effect (Dell et al., 2000; Fromkin, 1971; Warker et al., 2008). For experiment-wide consonants, the key question is whether the percentage of errors that is legal (i.e., same-position movements) *rises significantly above* this unrestricted baseline rate. This would be evidence that new phonotactic constraints have been acquired and significantly influence production (errors) in the longer term. In other words, the difference between experiment-wide and unrestricted same-position percentages is described as the phonotactic learnings score (with positive values suggesting that phonotactic learning has taken place). It thus reflects implicit learning of the novel experiment-induced constraint that cannot solely be explained by correctly labeling the syllable positions within the recited sequence (i.e., the syllable-position effect).

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

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

There has been some relevant work within the comprehension domain showing that young infants are able to learn (and generalize) novel second-order phonotactic constraints quickly after a short auditory exposure to a small set of input exemplars (e.g., Chambers, Onishi, & Fisher, 2003; Gerken & Knight, 2015). However, experiments testing children's ability to learn novel phonotactics through speech production are entirely missing. In the current study, we were interested in investigating children's ability to rapidly pick up novel phonotactic constraints by looking at their speech errors. With this aim, and with respect to Janacsek's developmental findings on implicit learning skills, we tested a group of nine-year-old children on Dell's phonotactic constraint paradigm. The main focus of the study concerned the time course of the phonotactic learning patterns in the speech error data of the children. A group of Dutch-speaking adults was also tested to see whether the (slowly developing) speech error patterns for second-order constraints found in previous studies could be replicated in a group of Dutch speaking adults. All participants returned to the lab on four consecutive days for production of sequences of CVC syllables that were constrained with language-wide, experiment-wide and unrestricted consonants. Similar to previous work, half of the participants were informed about the constraints and half were told nothing about the crucial manipulations. This was done to investigate whether phonotactic learning indeed develops under incidental learning conditions, which would indicate that it is not dependent on explicit information and therefore on implicit statistical learning (Warker & Dell, 2006).

Method

Participants

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

Materials

Each participant received a set of 96 sequences on each day. Each sequence contained four novel word-forms of the structure CVC (e.g., *kieng nief siet hiem*). In total, eight different consonants (i.e., /k/, /ŋ /, /n/, /f/, /s/, /t/, /h/ and /m/) were used. Each consonant appeared once per sequence. These consonants belonged to three different constraint groups: language-wide (/h/, /ŋ/), experiment-wide (/t/, /k/), and unrestricted (/m/, /n/, /f/, /s/). The vowels were either /i/ (as in the English word “deep” or the Dutch word “fiets”) or /øː/ (as in the Dutch word “deur”)[1], and this alternated between sequence-trials. This means that half of the trials contained sequences with solely /i/ vowels and half with solely /øː/ vowels. All sequences were constructed so that in each sequence /h/ was always an onset and /ŋ/ was always a coda in accordance to Dutch phonotactics. The consonants in the unrestricted groups appeared both as coda and as onset throughout the experiment (also in accordance to Dutch phonotactics). The consonants appeared equally often at both positions across the entire experiment. The positions of the consonants in the experiment-wide groups are unrestricted in the Dutch language but appeared restricted within the setting of the experiment. Half of the participants experienced the experiment-wide constraint */t/ is an onset and /k/ is a coda if the vowel is /i/; /k/ is an onset and /t/ is coda if the vowel is /øː/.* We call this the “tiek-keut” restriction. The other half of the participants experienced the reverse constraint. We call this the “kiet-teuk” restriction.

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

Procedure

Half of the participants were first informed about the experiment-wide constraints. This was done step-by step using a Powerpoint presentation. Each experiment-wide constraint was accompanied by two examples, one that followed and one that violated the constraint. The children and adults in the uninformed condition were not informed about the constraints. After task instructions, all participants were presented with four practice sequences to familiarize themselves with the task. Participants first heard the sequence once (together with the visual presentation on the screen), and were then asked to recite the sequences in time with a metronome. They first recited the sequence slowly at a rate of one syllable per second (in time with the metronome) and subsequently repeated this sequence three times without pause at a faster rate of 2.53 syllables per second (in time with the metronome). The sequence remained on the screen until reciting was finished. In total, one set of 96 sequences was completed per day. Each session was digitally recorded using a head-mounted microphone and a computer-built recorder.

Results

Before analysis, speech errors were transcribed from the digital recordings. Consonants that moved position in a particular sequence were either coded as same-position or other-position, depending on the position they moved to. For the experiment-wide consonants, this was coded with respect to the medial vowel within the sequence-trial and the restriction that the participant was experiencing (i.e. "tiek-keut" or "kiet-teuk"). For example, if the target sequence is *kieng nief siet hiem* and a participant (who is experiencing the "kiet-teuk" restriction) recited this sequence as ***h**ieng **t**ief **n**ie**s** **k**iem*; five errors would be coded (in bold): One same-position error for the language-wide constraint (i.e., /h/ switched from onset to another onset), one other-position error for the experiment-wide constraint (i.e., /t/ switched from coda to onset), one same-position error for the unrestricted constraint (i.e., /n/ switched from one onset to another onset), one other-position error for the unrestricted constraint (i.e., /s/ switched from onset to coda), and one same-position error for the experiment-wide constraint (i.e., /k/ switched from onset to another onset). For cutoff errors (e.g., *s…keut*), only the first uttered consonant was coded. Substitutions (i.e., consonants that were replaced by other new consonants) and omissions or indistinguishable phonemes were not included for analysis. A second coder who was blind to the manipulations and the aim of the study transcribed 12 sessions (randomly distributed across group and training day) in order to test for inter-rater reliability. Overall, coding reliability was very good: For the 18 432 syllables that were doubly transcribed, both coders agreed there was no error on 17 760 syllables and on the presence and nature of 414 errors. The agreement was 98.6%. For those syllables in which the original coder found an error (512 errors), the conditionalized agreement rate was 75%. These values are comparable to previous studies (e.g., Warker et al., 2008). Therefore, the original coding of the first coder was not changed.

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

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

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 errors during the first day is visualized in Figure 1.

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

Group comparison. To further investigate child-adult differences for phonotactic constraint learning early in training, a hierarchical logistic regression model was fit to the speech-error data on Day 1, using the lme4 package in R (R Development Core Team, 2011). The dependent variable was Position, or whether phonemes move to the same or different position. There were two predictor variables or fixed effects, i.e., Restrictedness (experiment-wide vs. unrestricted) and Age Group (Children vs. Adults). Maximal inclusion of random slopes for the within-participants variables (i.e., 1+ Restrictedness| ppn) was strived for (Barr, Levy, Scheepers, & Tily, 2013). However, due to convergence issues, the random slope for restrictedness was dropped from the model, and only a random slope for subject was included. The p-values were calculated using Wald-z. The analysis revealed a significant two-way interaction between Restriction and Group (β=1.23, SE=.44, z = 2.79, p<.01), as well as an effect of Restriction (β=-1.50, SE=.19, z= -7.89, p<.001). Planned comparisons showed a significant phonotactic learning score for the children (β=-1.5, SE=.19, z=-7.89, p<.001) but not for the adults (β=-.027, SE=.40, z=-.69, p=.90). The same-position percentage for the unrestricted condition was higher for the adults than for the children (β = 1.37, SE=.31, z=4.3, p<.001).

General Discussion

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

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

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

As far as we know, no previous studies have investigated children's time course of speech errors in phonotactic constraint paradigm. In contrast with speed of learning, there has however been some work investigating the strength of learning across groups. In 2014, Samara and Caravolas compared school-aged children with adults when learning graphotactic constraints (Samara & Caravolas, 2014). In their study, 7 years old children and adults were exposed to written sequences of three letters (e.g.,"des") that contained consonants constrained to a particular position (first-order), or depending on the vowel (second-order). After exposure to 144 (short exposure) or 288 (long exposure) trials, and a short distraction task, participants were tested for legality judgment on a set of novel strings. Signal detection analyses showed that both children and adults were sensitive to the two types of constraints but strength of learning was higher in adults than in children. Interestingly however, when existing words were removed from the stimulus set, children performed as accurately as adults. Moreover, reaction times analysis showed that adults were not faster than children in responding to test items that contained the complex constraints. So even though the 7-years-old children have just begun to receive formal literacy instruction, they show comparable acquisition of the constraints as adults after a relatively short exposure of 144 trials. The current study was not designed for directly comparing the strength of learning in children and adults as this needs a different approach that controls for baseline differences in the syllable-position effect. The current study was able to demonstrate that children have an early time course for learning novel phoneme combination rules through speech production and are able to implicitly pick up the rule already on the first day of training. However, because of the significant baseline differences for the unrestricted constraints, we need to be cautious in making strong conclusions about potential child-adult differences without additional research.

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

We conclude that the apparently early time course for learning novel experimentally-induced phonotactics in children, provides some intriguing insights into child superiorities in some aspects of language learning. It is widely accepted that children, before they reach adolescence, are faster in picking up certain novel linguistic patterns than adults, in particular for phonology (Newport et al., 2001). They do not need years of practice before mastering a native-like tongue compared with adults (Johnson & Newport, 1989; Lenneberg, 1967). According to some researchers, implicit learning theories can provide 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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Table 1. Number of consonant movements (i.e., same-position and different-position) obtained from the children.

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

**$p < .01$

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

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

*$p < .05$

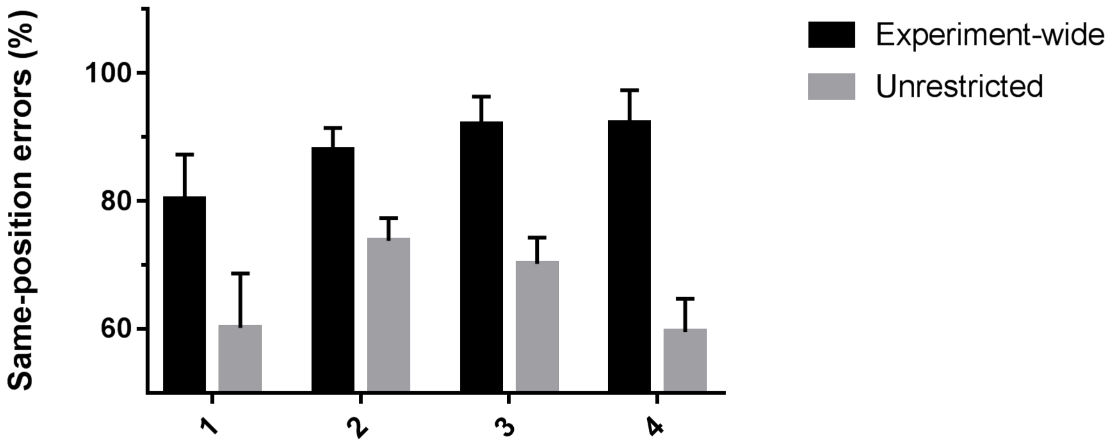

Figure 1. Mean legality (same-position) percentages and standard errors across the four sets of 24 trial sequences in **day 1** in the group of children.

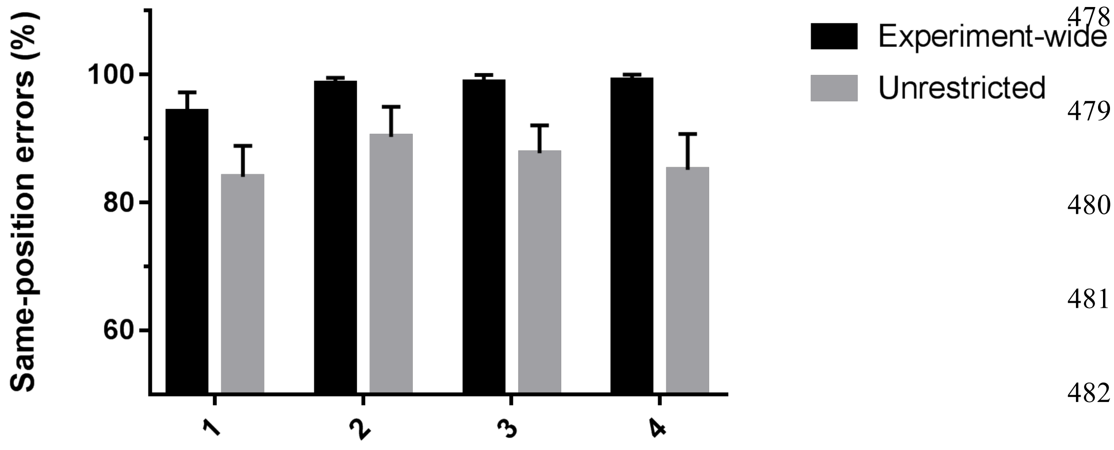

Figure 2. Mean legality percentages and standard errors across the four sets of 24 trial sequences in **day 2** in the group of adults.

Footnotes

[1]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.

[2]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.

[3]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.