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Running head**:** Second-order phonotactic constraint learning in French-speaking adults

Quick learning of novel vowel-consonant conjunctions within the mature speech production system – a commentary on Dell, Kelley, Bian and Holmes (2019)

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Abstract

This is a commentary on a review article by Dell, Kelley, Bian, and Holmes (2019), "Tuning the blueprint: how studies of implicit learning during speaking reveal the information processing components of the production system", doi: 10.1080/23273798.2019.1613553. The authors describe limitations for what can be learned in the *mature* language production system. In particular, they demonstrate how adult speech slowly adapts to novel vowel-contingent phonotactic constraints. A connectionist framework is proposed for which variability in learning outcomes may be explained by the availability of hidden units as a function of early linguistic experience. Here, we enclose data from French-speaking adults in which *rapid* phonotactic constraint learning of vowel-consonant conjunctions could be observed. The data fit within their proposal for hidden units in a connectionist model, where hidden units can be variously accessible, and suggest that not only maturation but also linguistic knowledge may affect how language learning abilities evolve throughout life.

Key words: speech production, implicit learning, speech errors, phonotactics, hidden units

Speech errors tend to obey underlying constraints of the spoken language and therefore reveal the speaker's unconscious knowledge of the constraints that govern their language (Fromkin, 1971). This knowledge includes phonotactics, i.e. constraints that determine allowable sound combinations and locations of phonemes within a syllable. For instance, native English speakers will seldom slip the sound /ŋ/ to an onset position of a word because this does not exist in the English spoken language. The speech production system is flexible and can adapt to novel constraints rapidly. In 2000, Dell and colleagues asked participants to recite written sequences of syllables (e.g. *hes feng nek tem*) at a fast pace, in time with a metronome to elicit speech errors involving consonant movements (i.e., speech slips, e.g. ***hef seng)*** (Dell et al., 2000). They measured how often consonants erroneously moved to the same *versus* opposite syllable position to which it was presented, as a measure of implicit knowledge of the constraints. Some consonants were constrained to a particular syllable position (i.e., onset or coda) in accordance to the spoken language (e.g., in English, /ŋ/ always appears at coda while /h/ always appears at onset). Other consonant positions appeared unrestricted, also consistent with the spoken language (e.g., In English, /f/, /m/, /n/, and /s/, /k/, /t/ appear both at onset and coda). Two of these unrestricted consonants appeared restricted within the setting of the experiment (e.g., /k/ always appeared at onset while /t/ always appeared at coda or vice versa). Dell and colleagues observed that participants' speech errors mirror these experimentally-induced constraints after only limited exposure (< 96 trials), indicating *rapid* implicit learning of novel phonotactic constraints (Dell et al., 2000). However, the mature speech production system appears less flexible when adapting to novel vowel-contingent *second-order* constraints, such as /k/ appears at onset and /t/ as coda when the vowel is /i:/ and vice-versa when the vowel is /a/. For these second-order constraints, sleep-dependent consolidation is necessary for learning to emerge

during speech production (Anderson & Dell, 2018; Gaskell et al., 2014). Consolidation seems less important for the immature speech production system . In 2017, we exposed Dutch-speaking children (9-year-olds) and adults to a speech error task that was adapted to the Dutch language (Smalle et al., 2017). We found that while learning only appeared from the second training day (i.e., after a period of sleep) in adults, similar to previous work, children already started learning on the first training day. This shows that the immature production system does not depend on consolidation periods for learning to appear and, thus, can more efficiently (i.e., rapidly) adapt to novel vowel-contingent second-order rules. The rapid time course for phonotactic constraint learning in children compared with adults supports a critical-period hypothesis for language acquisition (Lenneberg, 1967). Age of acquisition effects for the phonological aspects of language production are indeed very robust in everyday life, as evidenced by the typical foreign accents in late learners (Newport et al., 2001).

Recently, Dell and colleagues proposed a novel connectionist framework to explain circumstances for *rapid* implicit linguistic learning, such as found in children but not in adults (Dell et al., 2019). They argue that limitations for rapid learning arise from variations in the availability of hidden units that can detect and code for the conditional vowel-consonant conjunctions. Conditional vowel-consonant conjunctions, such as '/f/ must be an onset *if* the vowel is /a/ but a coda if the vowel is /o/', are largely irrelevant for the task of syllabification, i.e. the task whereby phonemes are implicitly assigned to syllable positions before their articulation in natural speech (at least in some languages, Dell et al., 2019). In English, as well as in Dutch, for instance, consonants are usually allowed in onset and/or coda positions *regardless of* which vowel is used. Dell et al. (2019) argue that while children might still code for such contingencies, the hidden units eventually become *backgrounded* when the system further matures. As a result,

sleep is needed for Dutch -and English-speaking adults, but not for children, to offset these weights again and bring online the hidden units that are required for representing the context sensitivity of the vowel within the experimental setting (Dell et al., 2019).

Here, we present data from French-speaking adults in which *rapid* implicit linguistic learning of novel vowel-consonant conjunctions could nevertheless be observed. The data-set contains a replication (in French) of Smalle et al., (2021) and was originally not designed for the purpose of this commentary. It is part of a larger project on the role of the cognitive system in novel language learning (in which we argue that late-developing cognitive-control abilities suppress implicit learning processes that are relevant for language, and thereby explain age-related sensitivities in language acquisition. In the original study, Smalle et al., 2021, we exposed Dutch-speaking adults to the Dutch variant of the phonotactic constraint paradigm similar to our previous developmental work (Smalle et al., 2017), under either depleted or non-depleted cognitive control conditions. We observed that the cognitively depleted adults showed the strongest learning effects. Moreover, they showed learning already on the first day of training without any need for sleep. This is similar to what we observed earlier with Dutch-speaking children (Smalle et al., 2017). Together, these findings indicate that the higher-order and mature cognitive system interferes with implicit learning processes that are important for early language acquisition. As part of the project, we aimed to replicate this finding with French-speaking adults. As expected, we found strong learning effects from early on in the training in the cognitively depleted adults, but also, and this was quite unexpected, as we will show next, in the control adults.

Methods

Participants

Thirty-six native French-speaking participants from the French part of Belgium (average age = 21 years, range = 18-25 years, 8 males, 14 left-handed), were recruited for the experiment. One participant was excluded from data-collection due to equipment failure. None of the participants reported a history of neurological and/or developmental disorders and they all reported normal sleep quality during the month preceding the experiment. The participants were randomly assigned to three groups. In two groups, participants performed a cognitively challenging dual working-memory task prior to training under high cognitive load conditions (n = 11; Group 1) or low cognitive load conditions (n = 12; Group 2). For more details on the task and procedure used, we refer to the original study, Smalle et al., 2021. In Group 3, no cognitively depleting task was performed prior to training and thus this group will act as our test case in the present commentary. Informed consent was obtained prior to the experiment and debriefing took place afterwards. The experiment was approved by the ethics committee of the Psychological Sciences Research institute at the Université catholique de Louvain (reference: Projet2017-27).

Materials and procedure

The main focus for the current commentary concerns our replication of the speech error task as used in Dell et al., (2000). All participants were trained on novel phonotactic constraints across two consecutive days with an intervening night of sleep. On each day, participants received a set of 96 sequences with four syllables (i.e. consonant-vowel-consonant) adapted to the French spoken language (i.e., *lox [lɔks] rot [rɔt] kof [kɔf] bos [bɔs]*). The participants were asked to repeat the syllables in time with a metronome, first slowly at a rate of 1 syllable/sec and

then 3 times fast without pause at a rate of 2.53 syllables/sec. In total, eight consonants were used to construct the syllables sequences on each trial, with each consonant appearing once per sequence. Two consonants (i.e., /b/ and /x/) were always presented at onset and coda position similar to the French spoken language, i.e. language-wide positional constraints. Four consonants (i.e., /r/, /s/, /k/, /f/) appeared equally at onset or coda position and thus were *unrestricted*, in accordance with the French spoken language. Two consonants appeared *restricted* within the setting of the experiment (i.e., /l/ and /t/) while they appear unrestricted in the spoken language. Their syllable position depended on a medial French vowel */ɔ/* or */ə/* that alternated across sequence trials. For half of the participants, /l/ appeared at onset and /t/ appeared at coda when the vowel was */ɔ/,* and vice versa when the vowel was */ə/*; for the remaining participants, the inverse was true. The rule was not told to the participants. The sequences were randomly generated by a program that was made available to us by the Gary S. Dell research group. Letter combinations that resulted in existing words were avoided. All sequences were printed in 80-point bold Courier New and white font and appeared in one line on a screen with a black background on each trial. Responses were digitally recorded using an USB microphone.

Results

All speech errors involving consonant movements were transcribed from the recordings and either coded as ‘same-position’ or ‘other-position’. This was coded separately for type of restriction (i.e., language-wide, experiment-wide or unrestricted). For more details on the coding scheme and examples, we refer to Smalle et al. (2021). Transcription was done independently by two native French speakers and blind to the conditions of the participants. The first coder, who helped in data-collection, transcribed all audio-files, i.e. a total of 80640 syllables. The second

coder who was unfamiliar with the task and experiment was asked to doubly transcribe audio-files from 10 participants, randomly chosen from the sample. For the 23040 syllables doubly transcribed (i.e., 29% of the total syllables), the two coders agreed (99.9% agreement rate) on the presence and nature of 904 errors and on the absence of errors on 22119 syllables. The coding of the first coder was not changed.

As predicted, slips involving language-wide consonants always adhered to the position (i.e., 100% same-position, SE = 0, based on a total of 1064 errors across groups and days). The key measure is whether the rate at which errors maintain their syllable position (i.e., proportion of same-position error) is higher for experimentally restricted consonants than for unrestricted consonants. This would be evidence that novel phonotactic constraints have been acquired within the experiment (see Smalle et al., 2021). The contrast between the experimentally restricted and unrestricted condition was tested by using nonparametric Wilcoxon's matched pair-tests. As can be derived from Table 1, learning was reliably present on both training days, as expected in Groups 1 and 2, replicating Smalle et al. (2021) for the French language, but interestingly also in Group 3, the control group (our group of interest). Individual data for learning effects on the first training day are shown in in tables in a supplementary file, and show robust learning across almost all individuals. We additionally carried out a hierarchical logistic regression analysis on the constrained slips (i.e. experimentally restricted versus unrestricted) comparing the factor of Day (1 or 2) in Group 3, our test case. The analysis included participants as random intercept and a slope for restrictedness. This revealed a significant effect of Restrictedness, indicating learning (i.e., $\beta = 0.77$, $z = 3.99$, $X^2(1) = 15.9$, $p < .001$), but no evidence for overnight consolidation (i.e., Day x Restrictedness: $\beta = 0.009$, $z < 1$, $X^2(1) < 1$).

Table 1. Percentage of same-position errors of unrestricted and experimentally restricted consonants.

	Unrestricted	SE	Restricted	SE	*Z*	*p*
Group 1						
Day 1	73.5	3.2	91.8	1.7	*2.80*	*.005***
Day 2	78.3	2.1	88.2	3.5	*2.09*	*.037**
***N* Errors**	**1094**		**426**			
Group 2						
Day 1	74.9	3.2	97.1	5.0	*2.94*	*.003***
Day 2	74.3	5.6	97.3	1.0	*2.94*	*.003***
***N* Errors**	**1025**		**363**			
Group 3						
Day 1	66.1	5.7	92.1	3.0	*2.63*	*.009***
Day 2	77.8	2.4	93.9	2.1	*2.95*	*.003***
***N* Errors**	**810**		**311**			

Note: "*N* Errors" provides the number of slips of the relevant consonant type, that is, the denominator for the percentage of "same-position" errors in the Unrestricted and Restricted condition; * $p < .05$, ** $p < .01$.

Discussion

In a sample of French-speaking adults, we observed rapid acquisition of novel second-order phonotactic constraints independently of sleep. This finding is opposed to what is widely observed in work with Dutch-speaking and English-speaking adults, where learning appears slowly after an offline and sleep-dependent consolidation period (Anderson & Dell, 2019). Although these findings were unexpected, they can be fitted within the recent framework proposed by Dell et al. (2019), by assuming exceptional, language-specific circumstances in which conditional vowel-consonant conjunctions *remain* important for the mature speech production system. French as a spoken language could be such an exception: In French, open syllables are preferred even when this is inconsistent with the written system (Fagyal et al., 2006). For instance, though the final letter of *petit* (French word for *small*) is a consonant, it is silent and therefore the final sound is a vowel *[pəti:]*. This however is not always the case and sometimes syllables are produced with a closing consonant, similar to its written format. For instance, the two-syllable word *avec* (French word for *with*) ends in a closed sound *[avək]*. This variability in open or closed syllables usually depends on the preceding adjacent vowel: when the vowel is "low" or "open" (i.e., the sound is produced with the tongue far from the roof of the mouth, such as in *pâtes [pat], vol [vɔl], sept [sət];* French words for *pasta, flight and seven,* resp.) closed syllables are preferred. In contrast, when the vowel is "high" or "closed" (i.e., tongue touching the roof of the mouth, such as in *trop [tro], nez [ne], six [si:];* French words for *too much, nose and six,* resp.), open endings are preferred. This effect is referred to as *the law of position* in Fagyal et al. (2006) [1]. As such, the nature of vowels, particularly by tongue height, is

[1]The effect is specific to rimes and does not affect the pronunciation of consonants across syllables or words. For instance, the larger phrase *petit lit ('small bed')* would be produced as /*pəti:li:/*.

highly informative for syllabification processes in French speech, unlike in Dutch or English speech where vowels are not very important. It is proposed in Dell et al. (2019) that learners create a mini-grammar, i.e. a sort of copy of the native language network, on which they can do further training within the experiment. This mini-grammar is supposed to inherit the hidden-unit resources that detect and code for complex second-order constraints of the main spoken grammar. These resources can be available or not available (i.e., nonexistent) depending on the role that they play in the main spoken grammar, and as such determine whether the new rule in the experiment will be learned or not. We argue here that hidden units that code for vowel-consonant conjunctions should be *foregrounded (*i.e. salient and accessible)*,* rather than *backgrounded* in the French production system, irrespective of its maturational state (Dell et al., 2019). As a consequence, in French-speaking adults, novel vowel-contingent second-order rules, such as '/f/ is an onset if the vowel is /a/ but a coda if the vowel is /o/', can be rapidly learned without the need for sleep, as can be observed in our present data-set.

It is indisputable that language-learning outcomes become worse the later in life the acquisition occurs. However, there are circumstances in which some adults are still able to learn well and attain native-like proficiency (e.g., Birdsong & Molis, 2001). Today, it is still difficult to explain why most but not all adults have difficulties learning a novel language, especially with respect to its phonological properties. We believe that language-learning outcomes can differ as a function of at least two independent factors, namely the learner's maturational state of his/her cognitive system (as shown in Smalle et al., 2021) *but also* the learner's prior linguistic knowledge. This second factor involves *entrenchment* of one's first and main spoken language, which supports learning that is consistent with this language system, while making novel learning that is inconsistent with this knowledge more difficult. French-speaking adults may not

have *backgrounded* the hidden units that code for vowel-consonant contingencies in their spoken language as opposed to Dutch or English-speaking adults because such contingencies remain important in French natural speech. Therefore, rapid acquisition is achieved in a novel experimental setting where such hidden units are required. Dutch-speaking and English-speaking adults, in contrast, first have to offset the weights of these units again, i.e. foreground them, before they can adapt to the novel experimental context. This takes time and presumably requires overnight consolidation. The idea that the availability of hidden units plays a role in the time course of second-order constraint learning is further evidenced by studies that report *no* learning, even not after sleep, in conditions where syllable positions depend on irrelevant or extra-linguistic properties such as speech rate (Warker et al., 2008) or tone (Bian & Dell, 2019). Altogether, findings from our lab suggest that both the state of the cognitive system as well as one's main spoken language plays a major role in the effectiveness and/or time course of language acquisition. We believe that the connectionist model proposed by Dell et al. provides a good account for individual variabilities in novel language acquisition outcomes throughout life, in that both maturation and the spoken language itself play a role in how fast a speaker can adapt to novel phonotactic constraints.

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