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Investigating the Retention and Time-Course of Phonotactic Constraint Learning From Production Experience

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Abstract

Adults can rapidly learn artificial phonotactic constraints such as /f/ *only occurs at the beginning of syllables* by producing syllables that contain those constraints. This implicit learning is then reflected in their speech errors. However, second-order constraints in which the placement of a phoneme depends on another characteristic of the syllable (e.g., if the vowel is /æ/, /f/ occurs at the beginning of syllables and /s/ occurs at the end of syllables but if the vowel is /I/, the reverse is true) require a longer learning period. Two experiments question the transience of second-order learning and whether consolidation plays a role in learning phonological dependencies. Using speech errors as a measure of learning, Experiment 1 investigated the durability of learning, and Experiment 2 investigated the time-course of learning. Experiment 1 found that learning is still present in speech errors a week later. Experiment 2 looked at whether more time in the form of a consolidation period or more experience in the form of more trials was necessary for learning to be revealed in speech errors. Both consolidation and more trials led to learning; however, consolidation provided a more substantial benefit.

Keywords

phonotactic learning; implicit learning; consolidation

Every language has underlying constraints, known as phonotactics, specifying where phonemes can be placed in syllables and whether particular combinations of phonemes are permitted or not. For example, in English, /ŋ/ only occurs at the end of a syllable in the coda position (e.g., sing) but never at the beginning of a syllable in the onset position (e.g., ngis). Evidence suggests phonotactics are learned early in life as infants track distributional information about phonemes from language input using an implicit statistical learning mechanism (Aslin, Saffran, & Newport, 1998; Maye, Werker, & Gerken, 2002; Saffran, Newport & Aslin, 1996). Moreover, the ability to learn phonotactic constraints continues into adulthood. Both infants and adults can learn artificial constraints, such as /s/ only appearing as a syllable onset, after hearing syllables exhibiting that constraint, and they can generalize those newly learned constraints to novel items (Chambers, Onishi, & Fisher, 2003; Onishi, Chambers, & Fisher, 2002). Adults can also learn similar artificial constraints by producing syllables containing those constraints (e.g., Dell, Reed, Adams, & Meyer, 2000; Goldrick, 2004; Taylor & Houghton, 2005; but see Finn & Hudson Kam, 2008, for evidence that first language phonotactics can interfere with the learning of new phonotactic patterns).

Although it is clear that learning occurs in these artificial constraint studies, several questions remain about the nature of the learning. The experiments presented here focus on two main questions: The first is whether the phonotactic learning that results from recent production experience is transient, that is, whether it, like natural-language phonotactics, lasts much longer than the experimental sessions that demonstrate it. The second is whether consolidation, which has been shown to play a role in forming associative relationships, also plays a role in forming the associations necessary to learn more complex phonotactic constraints.

Phonotactic Learning from Production Experience

In experiments assessing the learning of phonotactic patterns from production experience, acquisition is measured by looking at speech error patterns. Speech errors have two properties that make them well suited for measuring phonotactic learning. The first is that speech errors preserve the phonotactics of a language, a phenomenon known as the phonotactic regularity effect (Fromkin, 1971). For example, if a surfer intends to say “hang ten” but errs, “ngang ten” is an unlikely slip. The second is that when phonemes move in error, they tend to stick to their original syllable position; a phoneme in an onset position is more likely to move to the onset position of another syllable than to a coda position. This is known as the syllable position effect (Nootheboom, 1969). For example, “tang ten” is a more likely slip for “hang ten” than “hat ten.” However, the phonotactic regularity effect exerts a stronger pull over errors than the syllable position effect; phonological errors obey their native language phonotactics nearly 100% of the time (Stemberger, 1990), but only stick to their original syllable position about 77% of the time (Vousden, Brown, & Harley, 2000).

Dell et al. (2000) developed an experimental paradigm utilizing the difference between these two error effects to test phonotactic learning in production. If participants experience a new phonotactic pattern in which a particular phoneme is restricted to a particular syllable position and are able to learn it, this learning should affect their speech errors. When the restricted phoneme moves in error, it should move to a syllable position consistent with the newly learned pattern, that is, the errors should exhibit a phonotactic regularity effect. If participants did not learn the new phonotactic pattern, their errors should be unaffected by it, but should still exhibit a syllable position effect. Participants performed a tongue twister-like task designed to induce phonological errors. Once a day for four days, they quickly repeated 96 sequences of four consonant-vowel-consonant (CVC) syllables. Each sequence contained the same vowel (/ /) and the same eight consonants (/h, ŋ, f, s, k, g, m, n/). Importantly, the syllable positions of the eight consonants were constrained in each sequence. *Language-restricted constraints* concerned the distribution of the phonemes /h/ and /ŋ/: /h/ only appeared as an onset and /ŋ/ only appeared as a coda as dictated by English language phonotactics. *Experiment-restricted constraints* concerned the distribution of two other consonant phonemes. Specifically, throughout the experiment, /f/ and /s/ were restricted such that /f/ only appeared as an onset and /s/ only appeared as a coda (or the reverse). The remaining consonant phonemes (/k, g, m, n/) were *unrestricted* and could appear as either an onset or a coda. Here is an example of how two sequences looked:

hes fek meng gen
heng ges kem fen

The resulting speech errors were then scored for whether moving phonemes retained their original syllable position, e.g., a phoneme in an onset position moved to an onset position in the next syllable, or whether they moved to a different syllable position, e.g., an onset moved to a coda position. As expected, the *language-restricted* phonemes (/h/ and /ŋ/) demonstrated the phonotactic regularity effect; slips of these phonemes moved to the same

syllable position 100% of the time. Slips involving the *unrestricted* phonemes (/k, g, m, n/) demonstrated the (weaker) syllable position effect and stuck to their original position only 68% of the time. The question of interest was whether the errors involving the *experiment-restricted* phonemes (/f/ and /s/) would behave more like the language-restricted phonemes or the unrestricted phonemes. Errors involving the experiment-restricted phonemes moved to the same position 98% of the time. Thus, participants' errors adhered to the new phonotactic constraint embedded in the sequences. This adherence appeared on the first day of testing, suggesting that this learning happens quite rapidly.

Further demonstrations using this paradigm found that learning occurs at both the segmental and the featural level (Goldrick, 2004), that learning is modulated by phonotactic probability (Goldrick & Larson, 2008), and that learning is abstract enough to generalize to novel syllables (Dell et al., 2000; Warker & Dell, 2006; Warker, 2009; but see Warker, Xu, Dell, & Fisher, 2009, for evidence that the phonotactics of syllables that are *heard* but not said sometimes do not impact speech errors). In addition, Taylor and Houghton (2005) investigated the time course of learning by switching the artificial constraint halfway through the experimental session. Participants began reciting sequences with the constraint /f/ is an onset and at the session's midpoint, the constraint switched to /f/ is a coda. Their speech errors began reflecting the new constraint after repeating only nine sequences with that constraint. These results confirmed that this type of phonotactic learning occurs very rapidly.

Thus far, the experimental phonotactic patterns have been constraints in which a particular phoneme's location in a syllable depends only on syllable position, or first-order constraints. However, not all natural phonotactics follow this form. In many languages, what syllable position a phoneme appears in depends on another property of the syllable, including adjacent and even nonadjacent phonemes. For example, in English, what phonemes can occur at the beginning of a syllable as part of a consonant cluster depends on the identity of other phonemes in the cluster; /sl/ and /dr/ are perfectly good onset clusters but /dl/ and /sr/ are not. This type of constraint is known as a second-order constraint.

A series of experiments tested the learnability of second-order constraints from production experience in adults and found an important distinction between the time course of first-order and second-order constraint learning. Using the speech error paradigm, Warker and Dell (2006) gave participants a constraint where phoneme position in a syllable depended on the identity of an adjacent vowel - if the vowel is /æ/, /k/ is an onset and /g/ is a coda, but if the vowel is /ɪ/, /g/ is an onset and /k/ is a coda. Each sequence contained the same vowel (either /æ/ or /ɪ/) and eight consonants (/h, ɲ, f, s, k, g, m, n/). As before, /h/ and /ɲ/ were constrained by English phonotactics, two phonemes (/k/ and /g/) were experimentally restricted, and the rest were unrestricted. Participants recited 96 sequences three times each for four days, and their subsequent errors were coded for movements to the same syllable position or to a different syllable position. When experiment-restricted phonemes (henceforth referred to as restricted phonemes) moved in error, they retained their original syllable positions more often (86% of the time) than unrestricted phonemes (75% of the time), indicating that second-order constraints between adjacent elements can be learned. However, the learning rate was much slower than in the first-order constraint studies; speech errors did not begin to reflect learning until the second day of testing.

A similar data pattern was found for learning dependencies between nonadjacent linguistic elements. These experiments used sequences containing four CVCVC disyllables where the syllable position of a restricted phoneme depended on the medial phoneme. For example, if the medial phoneme is /v/, /k/ is an onset and /g/ is a coda but if it is /b/, /g/ is an onset and /k/ is a coda (Warker & Dell, 2006, Experiment 2; Warker, Dell, Whalen, & Gereg, 2008).

Restricted phonemes moved to the same syllable positions more often than unrestricted phonemes, and this effect did not show up in the errors until the second day of testing. When the results from all second-order constraint experiments are combined (see Figure 1), a clear pattern emerges. There is no second-order influence on speech errors on the first day of testing after experiencing 96 sequences, but there is a significant influence on speech errors on each of the remaining days. The experiments investigating second-order constraint learning between adjacent and nonadjacent syllable elements suggest that second-order constraint learning is not nearly as rapid as first-order constraint learning. Participants either need more exposure to learn the contextual associations between syllable elements and phoneme position, or the learning process requires additional time, that is, a consolidation period.

A Model of Phonotactic Learning

Taken together, the first- and second-order constraint learning studies are informative about what type of phonotactic information can or cannot be learned from experience producing items that follow a particular phonotactic pattern. However, they do not say much about the mechanisms used to learn those constraints, particularly when it comes to second-order constraints and the delayed appearance of learning. A three-layer feed forward connectionist network created by Warker and Dell (2006) suggests possible mechanisms involved in learning first- and second-order constraints from production (see Figure 2). The model is designed to simulate human performance in a first-order and second-order constraint learning task.

In line with connectionist learning theories, the model supposes that experiences are represented in weighted links in a layered network of processing units or nodes. It applies this principle to the mapping from input phonemes to an output in which phonemes are assigned to their syllable positions. When the model experiences a set of syllables that exhibit a particular phonotactic constraint such as the English language constraint that /h/ is always an onset, its weights, and consequently its outputs, come to reflect that constraint. An output that corresponds to an illegal /h/-coda becomes largely impossible, i.e., the activation of an output node for /h/-coda is near zero regardless of what input the model receives. The model also accounts for the learning time discrepancy between first- and second-order constraints because the second-order constraints can be thought of as *self-interfering*. For a first-order constraint (e.g., /f/ is always an onset), when the system receives an /f/, it is always in the onset position, and so the connections between /f/ and the onset position are continually reinforced and are strengthened quite rapidly. When the system needs to output an /f/ in speech, it is then biased to occur in an onset position. With a second-order constraint (e.g., /f/ is an onset if the vowel is /ae/ but a coda if the vowel is /I/), a restricted phoneme occurs as both an onset and a coda, and as a result, the connections between /f/ and onset position as well as /f/ and coda position are both strengthened. When the system tries to produce an /f/, both the onset and coda position are vying for the phoneme. The system must overcome this interference by learning the association between the vowel and the phoneme's syllable position by way of the hidden units in the model. The development of these contextual associations in the hidden units requires a greater number of learning trials. Similar to the behavioral data, the model learns the first-order constraints quickly, but only learns the second-order constraints after the model has received a greater number of trials.

The model makes two key assumptions. One, it assumes that the same network that initially learned English phonotactics is also used to learn the experimental phonotactics. Two, it assumes that the expression of learning for a particular kind of constraint is related only to the number of trials experienced. The experiments presented here provide data that challenge these assumptions. These data address how time, consolidation, and number of

trials contribute to the learning and retention of new second-order phonotactic patterns and provide important constraints that must be applied to future models of adult phonotactic learning from production experience.

The model's assumption that the same network architecture that learns one's native language phonotactics also learns new phonotactic constraints implies that the network is highly sensitive to recent experience, an implication that is consistent with these kinds of models (e.g., McCloskey & Cohen, 1989). This suggests that the model, and by extension our phonological system, is continually learning new information about the distribution of phonemes in a language by constantly updating its connection weights in response to new experiences. If those new experiences involve exposure to syllables that contain different phonotactic constraints, then the model will learn the new constraints and, in the process, overwrite the older constraints because it uses the same units, connections, and learning principles for natural phonotactics and for the experimental phonotactics. As a consequence, without continuous exposure to syllables exhibiting the experimental constraints, the experimentally learned patterns will not be retained. To put it another way, as soon as participants leave the laboratory, they experience phonotactic patterns that conflict with their newly learned experimental ones. This everyday life experience with normal English syllables will eventually overwrite the learning that took place in the laboratory, and as a result, participants' speech errors will no longer reflect the experimental phonotactic patterns.

On the other hand, it is possible that the experimental phonotactics will be retained by participants once they leave the laboratory just as natural language phonotactics are retained across different situations. The learning in these experiments is the result of an implicit learning process. Participants have little to no awareness of the learning process or the products of learning, and there is no difference in speech error patterns between participants who were explicitly informed of the constraints beforehand and those who were not informed (Dell et al., 2000; Reber, 1967; Warker & Dell, 2006). Some implicit learning effects can be quite long-lasting (Cleeremans, Destrebecqz, & Boyer, 1998; for review, see Seger, 1994). In a variety of implicit learning paradigms, including artificial grammar learning tasks, serial reaction time tasks, and sequence learning tasks, evidence of learning reappears days, weeks, and even years later when participants return to the experimental context to perform the same task or a very similar task (Allen & Reber, 1980; Reber, 1992; Kolers & Ostry, 1974). Applying these results to the current phonotactic learning paradigm leads to the prediction that the experimental learning should persist over time, even if participants do not continually experience saying syllables that contain those constraints. The learning should still be reflected in speech errors if participants return to the laboratory and perform the same task again. Although such a finding would be consistent with the implicit learning literature, it would require a modification to the phonotactic learning model. The model, as currently configured, is highly responsive to recent experience at the expense of retaining older experience.

The model's assumption that learning is based only on the number of trials experienced implies that second-order constraint learning is delayed because a greater number of syllables adhering to that pattern need to be experienced than for first-order constraint learning. In the behavioral studies, learning appears in speech errors after the first day of testing, that is, after participants have said 96 sequences. If the model's assumption is true, second-order learning should appear in speech errors on the first day of testing if participants experience a greater number of trials in a single testing session. However, it is important to note that another way of describing the behavioral data is that participants' errors do not reveal evidence of learning until the second *day* of testing. In addition to having produced 96 sequences by that point, participants have also experienced several

hours awake and several hours asleep in between testing sessions. It is possible that consolidation, the solidifying of memories and experience into a more permanent, stable form during offline processing or during sleep, is needed before second-order constraint learning is exhibited (Squire, Knowlton, & Musen, 1993).

The idea that consolidation benefits performance has been circulating since Jenkins and Dallenbach (1924) reported that participants who slept performed better on a memory test than those who did not. Since then, the beneficial effects of consolidation during sleep have been found in visual discrimination tasks (Stickgold, James, & Hobson, 2000), auditory skill learning tasks (Fenn, Nusbaum, & Margoliash, 2003; Gaab, Paetzold, Becker, Walker, & Schlaug, 2004) and procedural motor learning tasks (Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002; however, see Keisler, Ashe, & Willingham, 2007, and Rickard, Cai, Rieth, Jones, & Ard, 2008, for a different interpretation). Evidence also suggests that sleep contributes to language learning tasks, including word learning in a second language (De Koninck, Lorrain, Christ, Proulx, & Coulombe, 1989) and in one's native language (Dumay, Gaskell, & Feng, 2004; Dumay & Gaskell, 2005). Spindle activity and slow wave sleep, in particular, have been shown to play a role in word learning (Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010).

Consolidation may also impact the learning of associative information (Walker, 2009). Fifteen-month old infants who listened to artificial language utterances containing dependencies between nonadjacent syllables generalized the pattern on a later test if they had napped after the initial learning session than if they had not (Gomez, Bootzin, & Nadel, 2005; Hupbach, Gomez, Bootzin, & Nadel, 2009). Similarly, Ellenbogen, Hu, Payne, Titone, & Walker (2007) found that consolidation during sleep and during offline processing contributes to relational memory performance. Participants learned pairs of items ($A > B$, $B > C$, ..., $E > F$), which unbeknownst to the participants also conformed to the hierarchy $A > B > C > D > E > F$. Compared to participants tested 20 minutes after learning, participants tested 12 hours later were able to correctly make inferential judgments about novel pairs ($A > C$); participants who slept during those 12 hours showed an additional advantage when judging more distant relationships in the hierarchy. In the current phonotactic learning experiments, learning a second-order constraint also requires learning associative information. The time between testing sessions or periods of sleep may allow the associations between vowel and syllable position to form and lead to the expression of the experimental constraint in speech errors when participants return the next day.

Overview of Present Experiments

Two experiments directly tested the model's assumptions about the durability of second-order learning and the reason for the delay in second-order learning. Experiment 1 asked whether participants' speech errors would still reflect learning of a second-order constraint if participants return to the same experimental context and perform the same task a week after their initial exposure to the constraint. If the model is correct, the effect of learning on speech errors a week later should be greatly diminished if not eliminated. Once participants leave the laboratory, they hear and say many different utterances in English that have a different phonological distribution than the sequences they recited in the experiment. Saying these new patterns should interfere with the phonological learning from the experiment, and the experimental constraints should then be unlearned (as in the experiment by Taylor & Houghton, 2005, where reversing the constraints on the distribution of the experiment-restricted phonemes quickly shifted the error pattern). On the other hand, if second-order phonotactic learning in the laboratory involves a similar degree of context specificity and durability as some other implicit learning phenomena, that learning should be revealed when the same experimental task is performed again, even after a long delay.

Experiment 2 investigated why it takes longer for second-order learning to manifest itself in speech errors than first-order learning. Experiment 2 was intended to determine whether this delay in learning is because participants need more trials or a consolidation period. Participants were divided into four groups and experienced a second-order constraint embedded in a total of 192 sequences spread out over one or two days. If more experience is needed to overcome the self-interfering effect, learning should appear in speech errors when participants experience more sequences (e.g., more than the usual 96 sequences) in a single testing session. On the other hand, if a consolidation period is needed, participants should not benefit from more trials in a single testing session. Learning should only be reflected in speech errors when participants return to the laboratory for a second day, regardless of how many sequences were recited during their first session.

Experiment 1

Thus far, none of the second-order constraint experiments using speech errors as a measure of learning have directly tested the retention of phonotactics learned from experience. It clearly persists for at least a day. In experiments where participants return to the lab for four consecutive days, learning appears on the second day and on the remaining testing days. Experiment 1 investigated whether the learning would still influence speech errors a week after participants first experienced sequences containing a second-order constraint. This was tested by comparing the speech errors of participants who performed the task for three consecutive days to the speech errors of participants who performed the task for two consecutive days and one day a week later.

If the implicit learning mechanisms involved in second-order phonotactic learning produce long-lasting learning, participants' speech errors should still reflect second-order constraints in a session a week later in the Week-Later Group. (From previous work, it can be expected that the constraint will still influence speech errors on Day 3 in the Consecutive Days Group). If the learning does not persist in the Week-Later Group, that would suggest the model is correct in assuming that the learning is detrimentally affected by experience speaking other phonological patterns outside of the laboratory context.

Method

Participants—Twenty-four native English-speaking students from the University of Illinois at Urbana-Champaign received \$24 for participating in three testing sessions that took place on three separate days. Participants were randomly assigned to two different groups. Half of the participants were in the Consecutive Days Group, which required participating on three consecutive days, and half were in the Week-Later Group, which required participating on two consecutive days and one day a week after the first day of participation. Within each Group, one-third of the participants experienced /f/ and /s/ as the restricted phonemes, one-third experienced /k/ and /g/ as the restricted phonemes, and the remaining third experienced /m/ and /n/ as the restricted phonemes.

Materials—Participants received a set of 96 sequences, composed of 4 CVC syllables, on each day. The vowels in the four syllables alternated by sequence and were either /æ/ or /I/. Each sequence contained eight consonants (/h, ŋ, f, s, k, g, m, n/) that were distributed within the sequence as onsets and codas. Half of the participants in the /f/-/s/ condition experienced the constraint: if the vowel is /æ/, /f/ is an onset and /s/ is a coda but if the vowel is /I/, /s/ is an onset and /f/ is a coda. The other half experienced the opposite assignment of /f/ and /s/. In the /k/-/g/ condition, half received if the vowel is /æ/, /k/ is an onset and /g/ is a coda but if the vowel is /I/, /g/ is an onset and /k/ is a coda and the other half received /k/ and /g/ in the opposite assignment. In the /m/-/n/ condition, half experienced if the vowel is /æ/, /m/ is an onset and /n/ is a coda but if the vowel is /I/, /n/ is

an onset and /m/ is a coda and the other half experienced /m/ and /n/ in the opposite positions. Two CVC syllables were excluded from the sequences because they created offensive words in English.

A computer program randomly generated three sets of 96 sequences for each participant, one for each day of participation. The sequences for the Consecutive Days Group and the Week-Later Group were matched such that Participant 1 in the Consecutive Days Group received the same sequences as Participant 1 in the Week-Later Group. An example of four sequences for a participant in the /f/-/s/ condition follows:

has kan fang gam
gif nik sim hing
fam hang kag nas
sin gif mik hing

The sequences were presented on a computer screen one at a time and alternated between /æ/-sequences and /ɪ/-sequences.

Procedure—Participants repeated each sequence three times aloud without pause in time to a metronome set at 2.53 beats/second and advanced to the next sequence at their own pace by pressing the space bar. There were two practice sequences before each session began. All sessions were digitally recorded.

Results

Participants' repetitions were transcribed for errors involving the movement of onsets and codas. Errors were scored for whether they moved to the same syllable position or a different position depending on what syllable position a phoneme moved to when it slipped. An error was classified as *same-position* if the phoneme maintained its original syllable position when it moved, i.e., a phoneme that was originally an onset slipped to another onset position. An error was classified as *different-position* if the phoneme did not maintain its original syllable position when it moved, i.e., a phoneme that was originally an onset slipped to a coda position. For example, if the intended sequence was *has kan fang gam* but the participant actually recited *kas han fas gak*, the errors were classified as follows: There is one same-position error involving language-restricted phonemes since the onset /h/ moved from *has* to *han*. There is one same-position error involving restricted phonemes since the coda /s/ moved from *has* to *fas*. There is one same-position error involving unrestricted phonemes since the onset /k/ moved from *kan* to *kas*, and one different-position error involving unrestricted phonemes since the onset /k/ moved from *kan* to *gak*. The percentage of errors for each type of constraint (language-restricted, restricted, and unrestricted) was then tallied. Cutoff errors (e.g., *k...has*) were included but errors containing phonemes other than the original eight (e.g., /b/) or undistinguishable phonemes were not included.

To determine the reliability of the error transcriptions, a naive second coder transcribed a subset of the recordings, and the two transcriptions were compared. There was an overall agreement rate of 97.5%, meaning that of the 5760 syllables both coders transcribed, they agreed that there was no error on 5211 syllables and on the presence and nature of 405 errors. When only considering agreement on the errors that the primary coder found, this conditionalized agreement rate is 84.4%. Both measurements of reliability are similar to those found in previous studies.

Consecutive Days Group Results—Errors involving the language-restricted phonemes (/h/ and /ŋ/) formed same-position errors 100% of the time on all three testing days ($SE = 0$, based on 615 total errors). Based on the results from previous second-order constraint

experiments (Warker & Dell, 2006; Warker et al., 2008), planned contrasts looking at whether the percentage of errors involving restricted phonemes that moved to the same position was greater than the percentage of errors involving unrestricted phonemes that moved to the same position were done for each testing day using the normal approximation of the nonparametric Wilcoxon Signed-Ranks test. The expectation was that there should be no difference in percentages on Day 1 but that the percentage of same-position restricted errors should be greater than the percentage of same-position unrestricted errors on Days 2 and 3. The planned contrasts between the restricted and unrestricted same-position percentages use a one-tailed p-value since the effect of learning is predicted in one direction (restricted > unrestricted), and any other outcome is interpreted as the absence of learning. Interactions involving restrictedness with other factors are tested use two-tailed p-tests since there is potential interest in any form of the interaction.

Table 1 contains the number of restricted and unrestricted errors made on each day. On Day 1, the mean same-position percentage for restricted errors was 76.8 ($SE = 4.72$), which was not significantly different from the mean same-position percentage for unrestricted errors ($M = 73.2$, $SE = 3.42$; Wilcoxon $Z = .69$, $p = .25$). On Day 2, the mean same-position percentage for restricted errors ($M = 94.0$, $SE = 2.46$) was significantly greater than the same-position percentage for unrestricted errors ($M = 67.5$, $SE = 2.88$; Wilcoxon $Z = 3.04$, $p < .01$). This was also the case on Day 3. Restricted errors involved moves to the same syllable position 92.5% of the time ($SE = 2.81$) whereas unrestricted errors involved moves to the same syllable position 77.1% of the time ($SE = 2.84$; Wilcoxon $Z = 2.47$, $p < .01$). See Figure 3 for a summary. These results demonstrate that participants learned the experiment-restricted constraint present in their sequences and that this learning expressed itself in their speech errors. As expected, the learning did not appear until the second day of testing and was still present on the third day of testing.

Week-Later Group Results—Errors involving the language-restricted phonemes (/h/ and /ŋ/) were same-position errors 100% of the time on all three testing days ($SE = 0$, based on 719 total errors).

Table 1 contains the number of restricted and unrestricted errors made on each day. Three planned contrasts between restricted and unrestricted errors (one for each day) were tested. As in the Consecutive Days Group, there should be no evidence of learning on Day 1, but it should appear on Day 2 with a greater same-position percentage for restricted than unrestricted errors. On Day 8, if the learning is subject to interference from English, this effect should diminish or be eliminated. On Day 1, the mean same-position percentage for restricted errors was 79.6 ($SE = 4.35$), which was not significantly different from the mean same-position percentage for unrestricted errors ($M = 74.5$, $SE = 3.87$; Wilcoxon $Z = 1.08$, $p = .14$). On Day 2, the mean same-position percentage for restricted errors ($M = 88.5$, $SE = 4.27$) was significantly greater than the same-position percentage for unrestricted errors ($M = 74.7$, $SE = 3.89$; Wilcoxon $Z = 1.94$, $p = .026$). This was also the case on Day 8. Restricted errors were same-position errors 93.6% of the time ($SE = 2.40$) whereas unrestricted errors were same-position errors 74.1% of the time ($SE = 3.91$; Wilcoxon $Z = 2.49$, $p < .01$). See Figure 4 for a summary. Thus, evidence of learning appeared in speech errors on Day 2 as expected, but it also appeared a week later on Day 8. In addition, a Mann Whitney U test on the difference between restricted and unrestricted same-position percentages found no significant difference between Day 3 of the Consecutive Days Group and Day 8 of the Week-Later Group, an indication that the learning effect that reappeared on Day 8 in the Week-Later Group was not detectably different from the one that appeared on Day 3 in the Consecutive Days Group ($U = 85$, $p = .24$).

Discussion

In both groups, participants learned the second-order constraint from experience producing syllables containing that constraint. This learning revealed itself in their speech errors, but, as predicted, not until the second day of testing, providing yet another demonstration that second-order constraint learning develops more slowly than first-order constraint learning. However, the main goal of this experiment was to determine the transience of this second-order learning once it appears by testing one group for three consecutive days and one group a week later. For participants who came in for three consecutive days, learning was still present in speech errors on the third day of testing, as expected. Moreover, for those that came in a week later, their speech errors still exhibited the learning a week after they were first exposed to the experimental constraint and that learning was just as strong on the eighth day as it was on the second day of testing. The model from Warker and Dell (2006) would predict that learning should quickly be overwritten by phonological patterns experienced outside of the laboratory and be much less in evidence after a week. Contrary to that prediction, the constraint learning was long-lasting and apparently resistant to interference outside of the laboratory. These results coincide with other findings from the implicit learning literature; participants appear to be learning a phonotactic pattern that, presumably, becomes encapsulated with the experimental task and context.

Experiment 2

Experiment 1 demonstrated that second-order constraint learning does not appear in speech errors until the second day, and more importantly, it showed that this learning is retained for at least seven days. What mechanisms are responsible for creating this slow but long-lasting learning? By definition, the second-order constraints are more complex than the first-order constraints because they require participants to make an association between syllable position and a linguistic context such as vowel identity (Experiment 1; Warker & Dell, 2006; Warker et al., 2008). Learning this association involves overcoming the self-interference that naturally arises from the nature of the constraint. (The mapping is like the logical XOR function often discussed as a motivator for hidden units in connectionist models.) This interference seems to slow the learning process in some manner.

What do participants need in order to master this interference and demonstrate second-order learning? One clue can be found by determining at what point in previous second-order experiments learning first appeared in speech errors. To do this, I combined the mean same-position percentages for restricted and unrestricted errors on Day 1 and Day 2 across all previous experiments (i.e., the Consecutive Days Group and the Week-later Group from Experiment 1; Experiments 1 and 2 from Warker & Dell, 2006; and Experiment 1 from Warker et al., 2008) to see when the same-position percentage for restricted errors becomes significantly greater than the same-position percentage for unrestricted errors. In each experiment, participants ($N = 56$) recited 96 sequences on the first day of testing and 96 sequences on the second day. The 96 sequences from each day were broken down into halves, or two sets of 48 sequences, to more precisely determine when evidence of learning began to manifest itself in speech errors. The combined mean same-position percentages for restricted and unrestricted errors and standard errors are shown in Table 2.¹ On Day 1, there was no significant difference in same-position percentages between restricted and unrestricted errors during the first 48 sequences (Wilcoxon $Z = .75$, $p = .23$) or during the second set of 48 sequences (Wilcoxon $Z = .16$, $p = .44$). However, learning does appear

¹In the second half of Day 1, there were three empty data cells for the restricted errors because three subjects did not make any errors involving restricted consonants. There were also two empty data cells for restricted errors in the first half of Day 2 and one empty cell in the second half of Day 2 for the same reason. All empty data cells were estimated for analyses using the mean for restricted errors for the appropriate half.

immediately on the second day. There is a significant difference between restricted and unrestricted same-position percentages during the first half of Day 2 (Wilcoxon $Z = 3.28$, $p < .01$) and the second half (Wilcoxon $Z = 5.31$, $p < .01$). This suggests that participants must say at least 96 sequences before learning is revealed. As the model from Warker and Dell (2006) assumes, perhaps second-order constraints just require more trials than first-order constraints do.

However, evidence of learning shows up in full force at the start of the second testing day, suggesting that something more than experience, perhaps consolidation, may be behind it. Experiment 2 aimed to see whether more experience or a consolidation period is required for second-order learning to emerge in speech errors by varying how many sequences participants say on the first day of testing before they return the next day for a second testing session. All participants recite the same total number of sequences typically experienced in two sessions in this paradigm (192 sequences). Here, those 192 sequences are broken down into 4 sets of 48 sequences each. Participants either recite 48 sequences, 96 sequences, 144 sequences, or 192 sequences on the first day of testing. Then, all participants save the group that recited 192 sequences return the next day to recite their remaining sequences, so that all groups receive a total of 192 sequences. If the number of trials is all that matters, then learning should first appear in speech errors when more than enough trials (presumably more than 96 trials) are recited in one sitting. On the other hand, if consolidation coupled with experience plays a role in the expression of learning, then evidence of learning should first appear in speech errors when participants return to the lab on the second day of testing.

Method

Participants—Twenty-four native English-speaking students from the University of Illinois at Urbana-Champaign were paid for participating. Participants were divided into 4 groups of 6 participants each. Within each Group, one-third of the participants were in a restricted /f/-/s/ condition, one-third in a restricted /k/-/g/ condition, and one-third in a restricted /m/-/n/ condition.

Materials—A set of 192 sequences composed of 4 CVC syllables was generated for each participant. The sequences were created as in Experiment 1 and presented to participants on a computer monitor in the same fashion.

Procedure—Participants recited each sequence three times without pause at 2.53 syllables/second in time to a metronome and advanced to the next sequence at their own pace. Depending on which group the participant was assigned to, the participant repeated all 192 sequences in one session or in two sessions spread out over two days. Group A received 48 sequences on Day 1 and 144 sequences on Day 2. Group B received 96 sequences on Day 1 and 96 sequences on Day 2. Group C received 144 sequences on Day 1 and 48 sequences on Day 2. Group D received 192 sequences on Day 1. The first set of 48 sequences is referred to as Session 1, the second as Session 2, the third as Session 3, and the fourth as Session 4. All sessions were digitally recorded. Each testing day began with two practice sequences.

Results

Errors were scored as in Experiment 1. Testing for reliability of the error transcription yielded an overall agreement rate of 98.6% and a conditionalized agreement (based on 246 errors) of 93.1%.

Table 3 contains the number of restricted and unrestricted errors made during each session for each group. The results were then combined across Groups depending on whether the participants' sessions took place on the first day or the second day. Table 4 contains the

breakdown of same-position percentages for restricted and unrestricted errors for each of the four sessions within each group.² When they slipped, language-restricted phonemes (/h/ and /ŋ/) retained their original syllable position 100% of the time in all four groups in all four sessions ($SE = 0$, based on 1119 errors). The mean restricted and unrestricted same-position percentages and standard errors across the Groups are presented in Figure 5. As in previous experiments, planned contrasts were used to determine if learning occurred. For the first 48 sequences recited, none of the participants ($N = 24$) had had a consolidation period yet and, as expected, there was no difference in the same-position percentages between restricted and unrestricted errors (Wilcoxon $Z = 1.26$, $p = .11$). For Session 2, six of the participants had a consolidation period prior to reciting their sequences and 18 had not. Those with a consolidation period produced significantly more same-position restricted errors than unrestricted errors (Wilcoxon $Z = 1.78$, $p = .038$) whereas participants who had not did not (Wilcoxon $Z = -.68$, wrong direction). For Session 3, twelve participants had a consolidation period and 12 had not. Those with a consolidation period showed a significantly higher percentage of same-position restricted errors than unrestricted errors (Wilcoxon $Z = 2.11$, $p = .017$), and those that had not did not (Wilcoxon $Z = .35$, $p = .36$). For Session 4, 18 of the participants had a consolidation period and 6 had not. Once again, those participants that did produced significantly more same-position restricted errors than unrestricted errors (Wilcoxon $Z = 2.92$, $p < .01$), but those participants that had not did not (Wilcoxon $Z = 1.21$, $p = .11$) although the difference between restricted and unrestricted errors was in the right direction. Overall, the combined results suggest that consolidation, possibly during sleep since testing sessions took place the next day, led to more rapid learning of the second-order constraint.

To confirm the suspected interaction between restrictedness and consolidation, the data were analyzed using a hierarchical logistic regression model. The dependent variable was Position, or whether phonemes moved to the same position or different position. Subject was a random effect, and there were three predictor variables, or fixed effects. The predictor variables were Restrictedness, which referred to whether a particular error was restricted or unrestricted, Consolidation, which referred to whether or not a participant had a consolidation period before the session, and Session, which referred to the session that the errors originated in, 1, 2, 3, or 4. Several different models were tested. The best fitting model was one that included Session, an interaction between Restrictedness and Consolidation, and a separate slope for the effect of Restrictedness for each subject³. The output for the fixed effects is shown in Table 5. There was a main effect of Session - the odds of being a same-position error for each successive block of 48 sequences were higher by a factor of 1.19. This indicates that there is a tendency for both restricted and unrestricted phonemes to move to the same syllable position with each session as the experiment progresses. In addition, there is a main effect of Restrictedness such that the odds of being a same-position error if a restricted phoneme was involved were higher by a factor of 2.16. There was no main effect of Consolidation. Most importantly, there was a significant interaction between Restrictedness and Consolidation such that the odds of producing a same-position restricted error increased by a factor of 2.61 if the participant had a consolidation period before a testing session.

²The results of Session 1 for Group D are anomalous given previous research using this paradigm. Usually, no evidence of learning is found during the first 48 sequences; however, here, learning seems to appear in Session 1. One possible explanation for this anomaly is that error rates and patterns vary greatly among participants, and in this case, the participants may have been particularly variable. For example, Session 1 has an unusually low same-position percentage for unrestricted errors. In Groups A, B, and C, this value averaged 73.7% ($SE = 4.72$) for Session 1. In Group D, this value was uncharacteristically lower, 44.3% ($SE = 8.86$), leading to a significant difference.

³The model was fitted using the statistical program, R. The categorical predictor variables, Restrictedness and Consolidation, were coded using effects coding to test for main effects rather than simple main effects (Barr, 2008). The best fitting model in R notation was Position ~ Session + Restrictedness * Consolidation + (1 + Restrictedness | Subject).

When determining the best fitting model, a hierarchical logistic regression model was ran that also included an interaction between Session and Restrictedness to see if producing more sequences resulted in a greater same-position difference between restricted and unrestricted errors. However, the interaction was not significant (estimated coefficient = $-.11$, $SE = .15$, $z = -.74$, n.s.), and this more complex model was not a significantly better fit ($\chi^2(1) = .54$, $p = .46$).

Discussion

Overall, the results point to consolidation playing a role in the expression of second-order constraint learning, and they do not support the assumption of the Warker and Dell (2006) model that what matters is solely the number of trials. Participants who had test sessions on a second day displayed evidence of learning in their errors, regardless of how many sequences they produced on the first day, and participants who were tested only on the first day showed little evidence of learning. This suggests that the consolidation period allowed for the association between vowel and syllable position to form, and that that association then became available to the participants as soon as they resumed the experimental task. The finding that consolidation aided in acquisition of phonological patterns is consistent with previous findings that a consolidation period aids in the acquisition of novel words (Dekonnick et al., 1989; Dumay & Gaskell, 2005; Dumay et al., 2004; Fenn et al., 2003; Tamminem et al., 2010) and syllable patterns (Gomez et al., 2006).

As operationalized here, consolidation presumably occurred during the time between testing sessions. It is natural to hypothesize that this is happening when participants were sleeping. However, consolidation may also occur during any break from the task regardless of how that break is spent. This possibility is discussed further in the General Discussion. Another issue that remains is the hint of a learning effect during Session 4 in the group that experienced no consolidation period. Although the difference is not significant, the percentage of same-position restricted errors is numerically greater than the percentage of same-position unrestricted errors, suggesting that there may be a difference there that this experiment did not have the power to detect. An additional experiment replicated this condition (Group D) with twice as many participants to provide more power.

Twelve participants recited 192 sequences containing a second-order constraint in a single testing session. Participants' speech errors were transcribed, coded, and analyzed in sessions of 48 sequences each (Session 1, 2, 3, and 4, respectively) as in Experiment 2. Planned contrasts were used to test whether experiment-restricted phonemes resulted in a greater percentage of same-position errors than unrestricted phonemes. The mean same-position percentages for each session are given in Figure 6⁴. There was no significant difference in same-position percentages between experiment-restricted and unrestricted errors in Session 1 (restricted: $M = 71.5\%$, $SE = 8.26$, 97 errors; unrestricted: $M = 71.4\%$, $SE = 4.84$, 223 errors; Wilcoxon $Z = .53$, $p = .3$), Session 2 (restricted: $M = 66.5\%$, $SE = 8.65$, 109 errors; unrestricted: $M = 65.1\%$, $SE = 4.21$, 252 errors; Wilcoxon $Z = .69$, $p = .25$), or Session 3 (restricted: $M = 74.3\%$, $SE = 8.29$, 102 errors; unrestricted: $M = 76.7\%$, $SE = 2.84$, 237 errors; Wilcoxon $Z = -.60$, wrong direction). However, there was a significant difference in the same-position percentage of restricted errors ($M = 82.4\%$, $SE = 4.26$, 116 errors) and unrestricted errors ($M = 71.6\%$, $SE = 3.36$, 248 errors) during the last 48 sequences, i.e., Session 4 (Wilcoxon $Z = 2.02$, $p = .022$). Thus, the second-order constraint did not begin influencing speech errors until participants had experienced at least 144 sequences. These results imply that more experience may be sufficient to learn a second-order constraint and

⁴In Session 1, there was one empty data cell for the restricted errors because one subject did not make any errors involving restricted consonants. There was also one empty data cell for restricted errors in Session 3 for the same reason. Both empty data cells were estimated for analyses using the mean for restricted errors for the appropriate session.

that consolidation may not be the only mechanistic route by which learning emerges. However, the effect of a consolidation period is much stronger than the effect of number of trials experienced. Thus, although more experience may create some second-order learning when there is no consolidation period, consolidation is clearly the more powerful factor.

General Discussion

These experiments investigated two aspects of phonotactic learning, durability and consolidation, using a paradigm that reveals the learning of second-order phonotactic constraints in speech-error patterns. Experiment 1 retested participants a week after they first demonstrated learning of the constraint. The model of phonotactic learning by Warker and Dell (2006) predicted that second-order learning should not appear in speech errors after a week because the intervening language experience would overwrite the experimental learning. However, Experiment 1 clearly showed the opposite. Errors reflected the second-order constraints immediately upon return to the laboratory, suggesting that the mechanisms involved in second-order phonotactic learning produce learning that is resistant to interference outside the laboratory. Experiment 2 explored the general finding that learning is considerably slower for second-order constraints than first-order ones. Does second-order learning just need more experience (more learning trials) or more time (a consolidation period)? The model explains the effect solely in terms of experience. Experiment 2 found that consolidation was by far the major factor, although an additional follow-up found that, when there was no consolidation period, participants needed to experience 144 sequences before some evidence of learning appeared in their errors.

What are the implications of Experiment 1's finding that learning is long-lasting? First, they square with other findings in the implicit learning literature (e.g., learning persists over time when the same, or a highly similar, task is performed, Cleeremans et al., 1998; Dienes & Berry, 1997) and suggest that the learning is tightly linked to the experimental context, and hence is relatively immune to interference from outside it. This means that the model's assumption of completely shared network resources for English and the experimental situation is wrong. More generally, this result actually raises the unappealing possibility that artificial-grammar learning experiments do not have that much to do with real language, or at least with real language learning.

Although the artificial situation clearly is more separated from the natural linguistic knowledge than the model assumes, I would dispute the idea that the natural and artificial are largely unrelated. Instead, it is proposed that models of artificial linguistic learning must be reconceived to include a mechanism that accounts for the associative learning that takes place between the experimental context and the artificial linguistic properties, in this case, the phonological distribution of the restricted and unrestricted phonemes. One way to realize this is through the creation of a mini-model that is a copy of the original phonotactic learning model and is specific to the experiment. This notion is borrowed from a proposal by Nielson and Wilson (2008) to account for our ability to learn the characteristics of specific speakers or accents.⁵ Suppose that there is a general language model of English phonotactics that implicitly learned by picking up on the distributions of sounds in the language from experience. This general language model would include the constraints that /h/ is always an onset and that /ŋ/ is always a coda as well as the other phonotactic constraints of English. Presumably, this is what a large idealized version of the Warker and Dell (2006) model would know after it is trained for a long time on English syllables. When placed in an experimental setting, a smaller copy of this model that is specific to the experiment is

⁵In the case of accent adaptation, Nielson & Wilson (2008) propose that every one has a general model of English and when one encounters a different accent, a subset of this general model is formed that adheres to properties of that particular accent.

created that uses the same learning mechanisms as the general language model to acquire phonotactics. This copy inherits the phonotactic constraints from the general language model, such as /ŋ/ can only be a coda, (hence explaining the 100% same-position slips of /h/ and /ŋ/) and, as it experiences new syllables with new phonotactic constraints, its connection weights change accordingly. These new changes are restricted to the copy and are thus linked to the experimental conditions. When the model experiences those experimental conditions again, the copy is activated and the second-order constraints reappear in the model's output just as second-order learning reappeared in participants' speech errors when they returned to the experimental situation. One way to think about this copy is that it is learning the features of the experimental condition *that are not true of the general model*, sort of like interaction terms in hierarchical regression models. Since a real brain would not want to have many full-fledged copies lying around, it might be best to think of these copies as containing only the information that is not predictable from the general model (see Nielson & Wilson, 2008, for a Bayesian treatment of this hierarchical approach).

The model's second assumption was that second-order constraint learning is slower because more experience, and only more experience, is needed to overcome the self-interfering effect. Although a follow-up to Experiment 2 confirmed that more experience does lead to the appearance of the learned constraint in speech errors, the main findings of Experiment 2 suggest that consolidation is more influential than number of trials, at least under the conditions of the experiment. In Experiment 2, a consolidation period occurred during the break between testing sessions when participants spent some time sleeping and some time going about their daily business. This period, I propose, solidified the associations between vowel identity and syllable position. Although consolidation occurs while awake and while asleep and it is possible that awake and sleep time may provide different benefits, many researchers investigating the role of consolidation have primarily focused on the benefits that arise during sleep (e.g., Walker et al., 2002).

However, sleep may not be solely responsible for these learning benefits. Rickard et al. (2008) conducted a reanalysis of several studies that claimed sleep enhanced motor learning and found that this effect did not remain when factors such as time of day, fatigue, or task exhaustion were controlled for. Their reanalyses suggested that sleep may help to safeguard information from forgetting rather than to enhance existing learning. The possibility that factors such as time of day and exhaustion may account for performance enhancements previously attributed to sleep also emerges for implicit sequence learning tasks (Keisler, Ashe, & Willingham, 2007). Factors such as these were not controlled for in Experiment 2, and so it is possible participants may be benefiting from consolidation as a result of time passing or sleep or because they were fatigued and received a break from the task. However, it seems unlikely that relief from exhaustion can completely account for the results of Experiment 2. In the speech error paradigm, learning is measured by looking at the change in the pattern of errors rather than performance enhancements. Although one may make more errors when fatigued at the end of a testing session, the errors that are made will still follow phonotactic patterns. The error patterns seen in Experiment 2 suggest that the associations between vowel identity and syllable position are being established during the period between testing sessions, and not that already established learning is being enhanced between testing sessions because it had been suppressed by exhaustion. Regardless of whether sleep is necessary between testing sessions, the consolidation period provides a substantial benefit to the expression of second-order constraint learning in speech errors. This period enables associative sound patterns to be learned and incorporated into future productions despite a very short exposure period to those patterns.

Additionally, the results of Experiment 2 do not support the model's assumption that the appearance of second-order learning in speech errors depends entirely on the number of

experienced trials. Rather, these data, in combination with the growing literature on the role of consolidation, demonstrate that the passage of time contributes to the expression of learning. One way this could be incorporated into the model is by associating consolidation with the hidden units, the intermediate layer between the input and output layers that the model uses to learn the association between vowel identity and syllable position for a particular phoneme in second-order constraints (see Figure 2). It may be that the hidden units take time to develop or to come online in the model and that this growth occurs during a consolidation period.

The experiments presented here used artificial constraints to investigate the implicit learning of phonological patterns from speech production experience in adults. Using artificial constraints to study learning in the laboratory has advantages and disadvantages. It allows for more control over precisely what information is being learned and how that information is being learned. It also allows for the isolation of certain factors that may modulate the learning process and for the investigation of their influence in greater detail. However, the primary disadvantage of using artificial constraints in the laboratory is that the learning that results from these studies is often limited to the specific experiment. Those conclusions are interesting in their own right because they provide information about the cognitive learning process in a given situation. But, ideally, the conclusions would also extend to similar learning situations outside the laboratory.

The methods and conclusions from these production studies do have some implications for the acquisition of natural language phonotactics and the importance of experience in language learning. Even though artificial constraints are used, these experiments clearly show learning within the speech production system, suggesting that the speech production system is quite flexible, even in adults. The speech production system adapts to recent experience and continually updates itself to match those new experiences (even if those new experiences contain errors, Humphreys, Menzies, & Lake, 2010). When evidence from production constraint learning studies is combined with evidence from perception constraint learning studies in which the perception system also responds adaptively to experimental constraints (Chambers et al., 2003; Onishi et al., 2002), it suggests that the conclusions from these studies about adapting to experience are not limited to the production or the perception system but to the language processing system as a whole. Although, at this point, it is unclear why the production system needs more experience or a consolidation period to acquire the second-order constraints but the perception system (in adults, at least) does not. This difference may arise because of the way learning is measured in production. The possibility that second-order learning happens at an earlier time point from production experience but is not revealed in speech errors until later cannot be ruled out.

Lastly, these experiments provide information about the properties of learning that arise through experience and the mechanisms involved in that learning process. The finding that second-order learning persists over extended time intervals supports the notion that natural language phonotactics may be learned from experience and that experience-driven learning can be long-lasting. As one begins to learn the phonological patterns of a language, that learning should persist over time so that one can draw on previous learning experiences when facing a situation requiring the use of those phonological patterns in the future. After all, it would be cognitively inefficient to have to relearn a language's phonotactics every time that language is encountered in the future. The finding that both more practice and consolidation lead to second-order learning suggests that there are multiple routes for acquiring more complex phonological dependencies from experience. Learning through practice necessarily requires one to have more first-hand experience reciting a particular phonotactic pattern whereas learning through consolidation allows one to have less first-hand experience but necessitates time away from the task and may involve a period of sleep.

This adds to the growing body of literature showing that consolidation aids in associative learning and demonstrates that consolidation also benefits experience-driven language learning.

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References

- Allen R, Reber AS. Very long term memory for tacit knowledge. *Cognition*. 1980; 8:175–185. [PubMed: 7389287]
- Aslin RN, Saffran JR, Newport EL. Computation of conditional probability statistics by human infants. *Psychological Science*. 1998; 9:321–324.
- Barr DJ. Analyzing 'visual word' eyetracking data using multilevel logistic regression. *Journal of Memory and Language*. 2008; 59:457–474.
- Chambers KE, Onishi KH, Fisher C. Infants learn phonotactic regularities from brief auditory experiences. *Cognition*. 2003; 87:B69–B77. [PubMed: 12590043]
- Cleeremans A, Destrebecqz A, Boyer M. Implicit learning: News from the front. *Trends in Cognitive Science*. 1998; 2:406–415.
- De Koninck J, Lorrain D, Christ G, Proulx G, Coulombe D. Intensive language learning and increases in rapid eye movement sleep: Evidence of a performance factor. *International Journal of Psychophysiology*. 1989; 8:43–47. [PubMed: 2584082]
- Dell GS, Reed K, Adams D, Meyer A. Speech errors, phonotactic constraints, and implicit learning: a study of the role of experience in language production. *Journal of Experimental Psychology: Learning, Memory, & Cognition*. 2000; 26:1355–1367.
- Dienes Z, Berry D. Implicit learning: Below the subjective threshold. *Psychonomic Bulletin and Review*. 1997; 4:3–23.
- Dumay N, Gaskell MG. Do words go to sleep? Exploring consolidation of spoken forms through direct and indirect measures. *Behavioral and Brain Sciences*. 2005; 28:69–70.
- Dumay, N.; Gaskell, MG.; Feng, X. A day in the life of a spoken word. *Proceedings of the Twenty-Sixth Annual Conference of the Cognitive Science Society*; Mahwah, NJ: Lawrence Erlbaum Associates; 2004. p. 339-344.
- Ellenbogen JM, Hu PT, Titone D, Payne JD, Walker MP. Human relational memory requires time and sleep. *PNAS*. 2007; 104:7723–7728. [PubMed: 17449637]
- Fenn KM, Nusbaum HC, Margoliash D. Consolidation during sleep of perceptual learning of spoken language. *Nature*. 2003; 425:614–616. [PubMed: 14534586]
- Finn AS, Hudson Kam CL. The curse of knowledge: First language knowledge impairs adult learners' use of novel statistics for word segmentation. *Cognition*. 2008; 108:477–499. [PubMed: 18533142]
- Fromkin VA. The non-anomalous nature of anomalous utterances. *Language*. 1971; 47:27–52.
- Gaab N, Paetzold M, Becker M, Walker M, Schlaug G. The influence of sleep on auditory learning. *Neuroreport*. 2004; 15:731–734. [PubMed: 15094486]
- Goldrick M. Phonological features and phonotactic constraints in speech production. *Journal of Memory and Language*. 2004; 51(4):583–604.
- Goldrick M, Larson M. Phonotactic probability influences speech production. *Cognition*. 2008; 107:1155–1164. [PubMed: 18096149]
- Gomez RL, Bootzin RR, Nadel L. Naps promote abstraction in language-learning infants. *Psychological Science*. 2006; 8:670–674. [PubMed: 16913948]
- Humphries KR, Menzies H, Lake JK. Repeated speech errors: Evidence for learning. *Cognition*. 2010; 117:151–165. [PubMed: 20801433]

- Hupbach A, Gomez RL, Bootzin RR, Nadel L. Nap-dependent learning in infants. *Developmental Science*. 2009; 12:1007–1012. [PubMed: 19840054]
- Jenkins JG, Dallenbach KM. Obliviscence during sleep and waking. *American Journal of Psychology*. 1924; 35:605–612.
- Keisler A, Ashe J, Willingham DT. Time of day accounts for overnight improvement in sequence learning. *Learning and Memory*. 2007; 14:669–672. [PubMed: 17911369]
- Kolers PA, Ostry DJ. Time course of loss of information regarding pattern analyzing operations. *Journal of Verbal Learning and Verbal Behavior*. 1974; 13:599–612.
- Maye J, Werker JF, Gerken L. Infant sensitivity to distributional information can affect phonetic discrimination. *Cognition*. 2002; 82:B101–111. [PubMed: 11747867]
- McCloskey, M.; Cohen, NJ. Catastrophic interference in connectionist networks: The sequential learning problem. In: Bower, GH., editor. *The psychology of learning and motivation: Volume. Vol. 24*. Academic Press; San Diego: 1989. p. 109-165.
- Nielsen, K.; Wilson, C. A hierarchical bayesian model of multi-level phonetic imitation. In: Abner, Natasha; Bishop, Jason, editors. *Proceedings of the 27th West Coast Conference on Formal Linguistics*; Somerville, MA: Cascadilla Proceedings Project; 2008. p. 335-343.
- Nooteboom, SG. The tongue slips into patterns. In: Sciarone, AG.; Van Essen, AJ.; Van Raad, AA., editors. *Nomen: Leyden studies in linguistics and phonetics*. Mouton; The Hague: 1969. p. 114-132.
- Onishi K, Chambers K, Fisher C. Learning phonotactic constraints from brief auditory experience. *Cognition*. 2002; 83:B13–B23. [PubMed: 11814489]
- Reber AS. Implicit learning of artificial grammars. *Journal of Verbal Learning and Verbal Behavior*. 1967; 6:855–863.
- Reber AS. The cognitive unconscious: An evolutionary perspective. *Consciousness and Cognition*. 1992; 1:93–133.
- Rickard TC, Cai DJ, Rieth CA, Jones J, Ard MC. Sleep does not enhance motor sequence learning. *Journal of Experiment Psychology: Learning, Memory, and Cognition*. 2008; 34:834–842.
- Saffran JR, Newport EL, Aslin RN. Word segmentation: The role of distributional cues. *Journal of Memory & Language*. 1996; 35:606–621.
- Seger CA. Implicit learning. *Psychological Bulletin*. 1994; 115:163–196. [PubMed: 8165269]
- Squire LR, Knowlton B, Musen G. The structure and organization of memory. *Annual Review of Psychology*. 1993; 44:453–95.
- Stemberger JP. Wordshape errors in language production. *Cognition*. 1990; 35:123–157. [PubMed: 2354610]
- Stickgold R, James L, Hobson JA. Visual discrimination learning requires sleep after training. *Nature Neuroscience*. 2000; 3:1237–1238.
- Tamminem J, Payne JD, Stickgold R, Wamsley EJ, Gaskell MG. Sleep spindle activity is associated with the integration of new memories and existing knowledge. *The Journal of Neuroscience*. 2010; 30:14356–14360. [PubMed: 20980591]
- Taylor CF, Houghton G. Learning artificial phonotactic constraints – time course, durability, and relationship to natural constraints. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2005; 31:1398–1416.
- Vousden JI, Brown GDA, Harley TA. Serial control of phonology in speech production: A hierarchical model. *Cognitive Psychology*. 2000; 41:101–175. [PubMed: 10968924]
- Walker MP. The role of sleep in cognition and emotion. *The Year in Cognitive Neuroscience*. 2009; 1156:168–197.
- Walker MP, Brakefield T, Morgan A, Hobson JA, Stickgold R. Practice with sleep makes perfect: sleep-dependent motor skill learning. *Neuron*. 2002; 35:205–211. [PubMed: 12123620]
- Warker, JA. Unpublished doctoral dissertation. University of Illinois at Urbana-Champaign; 2009. Investigating the mechanisms behind phonotactic learning from recent production experience.
- Warker JA, Dell GS. Speech errors reflect newly learned phonotactic constraints. *Journal of Experimental Psychology: Learning, Memory, & Cognition*. 2006; 32:387–398.

- Warker JA, Dell GS, Whalen CA, Gereg S. Limits on learning phonotactic constraints from recent production experience. *Journal of Experimental Psychology: Learning, Memory, & Cognition*. 2008; 34:1289–1295.
- Warker JA, Xu Y, Dell GS, Fisher C. Speech errors reflect the phonotactic constraints in recently spoken syllables, but not in recently heard syllables. *Cognition*. 2009; 112:81–96. [PubMed: 19398099]

Figure 1.

Mean same-position percentages and standard errors of restricted and unrestricted errors for the combined results from Warker & Dell (2006) and Warker et al. (Experiment 1, 2008).

Figure 2.
Architecture of phonotactic learning connectionist model from Warker & Dell (2006).

Figure 3. Mean same-position percentages and standard errors of restricted and unrestricted errors for Consecutive Days Group in Experiment 1.

Figure 4. Mean same-position percentages and standard errors of restricted and unrestricted errors for Week-Later Group in Experiment 1.

Figure 5.

Mean same-position percentages and standard errors of restricted and unrestricted errors in Experiment 2 combined across Groups. Each session refers to a set of 48 recited sequences.

Figure 6.
Mean same-position percentages and standard errors of restricted and unrestricted errors in the follow up to Experiment 2.

Table 1

Number of Same-Position and Different-Position Errors in Experiment 1

	<u>Restricted</u>		<u>Unrestricted</u>		<u>Total</u>
	Same	Different	Same	Different	
Consecutive Days Group					
Day 1	129	50	338	142	659
Day 2	164	13	248	130	555
Day 3	121	9	241	86	457
Week-Later Group					
Day 1	155	47	313	121	636
Day 2	130	17	227	86	460
Day 3	177	10	260	97	544

Table 2

Mean Same-Position Percentages for Restricted and Unrestricted Errors in Previous Experiments

	Restricted	SE	Unrestricted	SE
Day 1				
1st Half	78.1	2.74	75.9	1.89
2nd Half	80.3	2.21	80.2	2.58
Day 2				
1st Half	89.9	1.94	79.0	2.40
2nd Half	93.8	1.26	76.8	1.89

Note. N = 56

Table 3

	48 Sequences				96 Sequences				144 Sequences				192 Sequences			
	Restricted		Unrestricted		Restricted		Unrestricted		Restricted		Unrestricted		Restricted		Unrestricted	
	Same	Diff	Same	Diff	Same	Diff	Same	Diff	Same	Diff	Same	Diff	Same	Diff	Same	Diff
Group A	43	11	88	25	39	7	79	54	60	11	71	46	43	3	88	49
Group B	43	15	69	28	22	9	62	28	21	6	51	18	38	4	86	24
Group C	39	9	67	27	34	11	55	15	32	12	65	31	36	4	54	18
Group D	20	5	39	38	33	12	66	29	27	5	71	28	19	5	68	21

Table 4

Mean Same-Position Percentages of Errors for Each Session of 48 Sequences in Each Group

Group	Session	Restricted	SE	Unrestricted	SE	Statistics
A	1	79.9	10.34	78.8	3.31	$Z = .11, p = .46$
	2 [^]	81.7	7.74	59.8	4.12	$Z = 1.78, p = .038$
	3 [^]	84.8	5.17	59.8	7.69	$Z = 2.2, p = .014$
	4 [^]	92.5	5.5	67.6	10.24	$Z = 1.47, p = .071$
B	1	62.7	11	71.3	9.94	$Z = -.11, \text{wrong direction}$
	2	55	14.03	74.8	7.92	$Z = -.73, \text{wrong direction}$
	3 [^]	80.5	11.87	73.8	2.97	$Z = .94, p = .17$
	4 [^]	88.9	4.26	74.3	7.52	$Z = 2.02, p = .022$
C	1	76.9	8.4	71	10.49	$Z = .11, p = .46$
	2	69.7	15.4	84.1	6.17	$Z = -.94, \text{wrong direction}$
	3	75.4	10.04	81.4	5.27	$Z = -.52, \text{wrong direction}$
	4 [^]	94.4	3.56	75.5	8.33	$Z = 1.75, p = .04$
D	1	75	12.9	44.3	8.86	$Z = 2.00, p = .023$
	2	74.8	9.94	69.3	6.94	$Z = .52, p = .30$
	3	82.5	10.67	72.1	5.16	$Z = 1.37, p = .086$
	4	85.4	7.11	77.6	7.35	$Z = 1.21, p = .11$

Note. Statistics represent planned comparisons between the mean same-position percentage for restricted and unrestricted errors.

[^] indicates that the session took place on the second day of testing, presumably after consolidation occurred.

Table 5

Summary of Fixed Effects Output from Hierarchical Logistic Regression Model, in Experiment 2

Predictors	Estimated Coeff.	SE	z-value
Intercept	0.79	0.199	3.98 *
Session	0.17	0.061	2.84 *
Restrictedness	0.77	0.239	3.24 *
Consolidation	-.005	0.181	-0.03
Restrictedness *Consolidation	0.96	0.288	3.33 *

* *Note.* indicates significance ($p < .01$)