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Brief article

Learning phonotactic constraints from brief auditory experience

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Abstract

Three experiments asked whether phonotactic regularities not present in English could be acquired by adult English speakers from brief listening experience. Subjects listened to consonant–vowel–consonant (CVC) syllables displaying restrictions on consonant position. Responses in a later speeded repetition task revealed rapid learning of (a) first-order regularities in which consonants were restricted to particular positions (e.g. [bæp] not *[pæb]), and (b) second-order regularities in which consonant position depended on the adjacent vowel (e.g. [bæp] or [pIb], not *[pæb] or *[bIp]). No evidence of learning was found for second-order regularities in which consonant position depended on speaker's voice. These results demonstrated that phonotactic constraints are rapidly learned from listening experience and that some types of contingencies (consonant–vowel) are more easily learned than others (consonant–voice). © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Speech processing is guided by phonotactic regularities that determine what sound sequences are possible. For example, English speakers learn the legal positions of English phonemes (e.g. the [ng] in "sing" can end words but not begin them) and legal structures of English syllables (e.g. "strengths" has the syllable structure CCCVCCC, which most languages prohibit). These regularities are facts about English–Vietnamese which allows word-initial [ng] and Japanese which forbids syllables with a structure heavier than CVC. Therefore, these regularities must be learned.

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Phonotactic regularities influence phoneme identification (Massaro & Cohen, 1983; Pitt, 1998), speech errors (Fromkin, 1971; Stemberger, 1990), syllabification (Donselaar, Kuijpers, & Cutler, 1999; Smith & Pitt, 1999), word segmentation (McQueen, 1998; Norris, McQueen, Cutler, & Butterfield, 1997), and novel word perception (Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). They are also learned early: 9-month-old infants listen longer to phonotactically legal (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993) or phonotactically frequent syllables (Jusczyk, Luce, & Charles-Luce, 1994), and use phonotactic probabilities to segment speech (Mattys & Jusczyk, 2001).

How are phonotactic regularities acquired? To learn subsyllabic regularities such as "no initial [ng]", speech sound representations must permit abstraction across contexts. However, not all context information can be lost, because English also has restrictions on phoneme co-occurrence (e.g. Kessler & Treiman, 1997). For example, long vowels (e.g. [aU] in "council") in some word positions can only be followed by sonorants or fricatives (Harris, 1994). To detect such second-order patterns, each sound's context must be represented. Consequently, phonological learning requires representations that function flexibly, allowing abstraction while maintaining more detailed contextual information.

Research on auditory word priming has yielded evidence for flexible representations of spoken words in both preschoolers and adults. Each listening experience added perceptual information to the word identification system that was used abstractly to identify word or syllable types but also included token-specific details (e.g. Chambers, Fisher, & Church, 1999; Fisher, Hunt, Chambers, & Church, in press). Similar findings indicating flexible representations of speech in both preschoolers and adults suggest that the same implicit learning mechanisms operate continuously throughout development.

If speech representations change with each listening experience and can be used flexibly across development, then phonotactic knowledge could emerge from the accumulation of incremental changes due to repeated experience perceiving words. If so, mere listening should alter the phonotactic expectations that guide speech processing for children and for adults. Word-level knowledge emerges in just this way in both 8-month-olds and adults: brief listening experience established word-like units defined by high syllable-to-syllable transitional probability in the exposure set (Saffran, Aslin, & Newport, 1996; Saffran, Newport, & Aslin, 1996).

Dell, Reed, Adams, and Meyer (2000) found rapid phonotactic learning in speech production. They embedded novel phonotactic regularities in nonsense syllables that speakers repeated during four experimental sessions. The speakers' errors quickly came to reflect the experiment's phonotactic restrictions, even for errors resulting in syllables outside the practice set. This suggested that speakers acquired more than a syllable inventory – speaking practice induced subsyllabic learning.

Dell et al. (2000) attributed the phonotactic regularity of their speakers' errors to the tuning of the production system by recent utterances. However, practice saying native-language words is probably not the major source of a 9-month-old's detailed phonotactic knowledge. Nine-month-olds babble, but not until about 10 months is there a shift toward native-language phoneme targets (e.g. de Boysson-Bardies & Vihman, 1991). Listening, not speaking, must create infants' sensitivity to native-language phonotactic regularities.

The present experiments asked whether adults could acquire new phonotactic regularities from listening practice. In Experiment 1, subjects listened to syllables in which some consonants (e.g. [b]) were syllable-initial (onsets) and others (e.g. [p]) were syllable-final (codas). Subjects later repeated previously heard (studied) syllables (e.g. [bæp]) and two kinds of unstudied syllables – items that followed (legal, e.g. [bæn] or [mIp]) or violated (illegal, e.g. [næb] or [pIm]) the experimental constraints. If subjects learned phonotactic regularities from brief listening experience, they should be quicker to identify and repeat unstudied legal than illegal syllables.

2. Experiment 1

2.1. Method

2.1.1. Subjects

Forty University of Illinois students who spoke English as their first language and reported no hearing problems received course credit or cash payment for participation.

2.1.2. Materials

The key manipulation involved restricting particular consonants to particular syllable positions in studied lists, counterbalanced across subjects. Two groups of consonants that could not be differentiated by a single phonetic feature or set of features were selected (group 1: [b, k, m, t]; group 2: [p, g, n, ch]). These were combined to create two 16 syllable-frame sets – one with group 1 consonants as onsets and group 2 consonants as codas (e.g. [b_p]), and one with the opposite assignment (e.g. [p_b]). To increase the number and phonetic variety of syllables, [f] and [s] were combined with the other consonants and themselves, adding four frames with [f] as onset, four with [s] as coda, and one [f_s] frame to each set, for a total of 25 frames per set. Each set was divided into two subsets (of 12 and 13 frames), such that if one subset was studied, the other subset would be legal but unstudied at test. The two subsets exhibiting the opposite constraint would be illegal at test. Each of the four syllable-frame subsets was filled with the vowels [æ] and [I], resulting in four study lists with 24 or 26 items. Vulgar words (e.g. [pIs]) were replaced by syllables with the same consonants but the other vowel ([pæs]). Syllables were recorded by a female native English speaker. The same tokens were used in study and test.

Subjects studied one of the lists and were tested on all four lists (98 syllables). Every syllable containing consonants from group 1 or 2 appeared in every cell of the design (studied, unstudied legal, unstudied illegal) across subjects.

2.1.3. Procedure

Ten subjects were randomly assigned to each of the study lists and tested using PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993). Subjects heard through headphones their study list syllables presented four to six times each in a random order (for a total of 120 or 130 items), and rated clarity of articulation. After a distractor task (28 two-digit addition problems), subjects listened to and repeated the test items “as quickly as possible without making errors” into a microphone attached to a voice-activated response key.

2.1.4. Scoring

Recordings of the repetition test were transcribed. Errors (consonant errors or exchanges of [æ] and [I]) were few (M = 3.0 per subject) and were excluded from further analysis. Reaction times were measured from stimulus offset to response onset. Responses more than 250 ms before or 1500 ms after stimulus offset were eliminated (M = 0.5), as were responses 2 SD beyond each subject's mean (M = 4.2).

The first 18 of the randomly-ordered test items were considered practice and not analyzed. The 80 remaining items were averaged by condition to create three scores per subject: studied (M = 18.6 items), unstudied legal (M = 18.9), and unstudied illegal (M = 37.1).

Due to the method of stimulus construction English words comprised 49%, 46%, and 47% of the test items in Experiments 1, 2, and 3, respectively. Preliminary analyses including lexical status as a factor revealed no main effects or interactions (all $F < 1.46$, all $P > 0.24$) in any of the experiments; therefore, this factor is not analyzed further. Apparently, at least in this task in which words and non-words were freely mixed, lexical status had no effect on the phonotactic learning that we measured.

2.2. Results and discussion

Legal syllables were repeated more quickly than illegal ones ($t(39) = 2.03$, $P < 0.05$; Table 1). Studied syllables were not repeated reliably faster than legal syllables ($t(39) = 1.28$, $P = 0.21$). Several minutes of listening to syllables exhibiting consonant position constraints influenced repetition of unstudied syllables that either followed or violated those constraints.

Since the test included as many illegal as legal items, we expected the advantage of legal over illegal items to diminish during testing. Dividing the results into two equal blocks shows the observable decrease in the legality advantage (Fig. 1). Block and legality did not interact reliably ($F(1, 39) = 1.15$, $P = 0.29$), even though there was a trend for a reliable legality advantage in Block 1 ($t(39) = 1.81$, $P < 0.08$) that was clearly gone in Block 2 ($t(39) < 1$). The difference between studied and legal items did not reliably change across blocks ($F(1, 39) = 2.51$, $P = 0.12$).

3. Experiment 2

In Experiment 1, listeners learned new consonant position restrictions, but naturally

Table 1
Average (SD) response time in milliseconds by condition for Experiments 1–3

Experiment	Studied	Legal	Illegal	
			1st order	2nd order
1	336 (131)	341 (132)	350 (128)	–
2	368 (146)	372 (142)	–	382 (146)
3	333 (117)	343 (122)	–	347 (119)

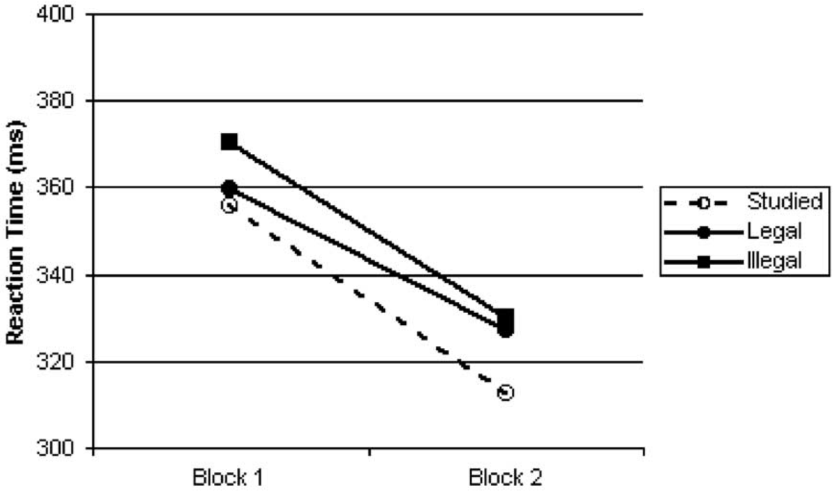

Fig. 1. Results from Experiment 1 divided into two blocks of trials.

occurring phonotactic constraints often involve more complex sound interactions. Experiment 2 examined second-order constraints. Adults heard syllables in which consonant positions depended on adjacent vowels; thus, [b]s might be onsets and [p]s codas with the vowel [æ], but these positions would be reversed with the vowel [I]. If listeners could learn that consonant positions depended on vowels, they should again be faster to repeat constraint-following than constraint-violating test items. Attending to position alone would lead to no difference in speed of repetition because each constrained consonant appeared equally often as onset and coda in each study list.

3.1. Method

3.1.1. Subjects

Forty subjects from the same population as Experiment 1 participated. One additional subject with more than 25% error was eliminated.

3.1.2. Materials

The syllables of Experiment 1 were recombined to create study lists in which consonant position depended on the vowel. Each subject heard both groups of consonants in both syllable positions during the study, but group 1 consonants were always onsets and group 2 consonants codas for one vowel, while the reverse held for the other vowel. Two different tokens of each syllable appeared in each study list, one spoken by a female (from Experiment 1) and the other by a male (two voices were used for consistency with Experiment 3). Vulgar words were eliminated since substituting the alternate vowel would violate the consonant–vowel contingencies. Consequently, study lists contained either 48 or 50 items. The test included all four study lists (194 items) plus 36 filler syllables not studied by any subject; the 230 test items were divided into two lists of 115 items.

3.1.3. Procedure

Ten subjects were assigned to each of the four study lists; five of each received test list 1 and five received test list 2. The procedure was as in Experiment 1 except that study lists were rated seven times each.

3.1.4. Scoring

Transcription and scoring were as in Experiment 1. Errors (M = 7.4 per subject), early and late responses (M = 0.8), and outliers (M = 4.6) were excluded.

The first 15 of the test items were considered practice and not analyzed. The 100 remaining items, excluding filler syllables, were averaged by condition to create three scores per subject: studied (M = 19.3 items), legal (M = 18.9), and illegal (M = 38.3).

3.2. Results and discussion

Legal syllables were repeated more quickly than illegal syllables that violated the experimental second-order constraints ($t(39) = 2.39$, $P < 0.05$; Table 1). Studied syllables were not repeated reliably faster than legal syllables ($t(39) = 1.26$, $P = 0.22$). Several minutes of listening to syllables with consonant–vowel contingencies influenced repetition of unstudied syllables that either followed or violated the second-order constraints.

Again, the effect of the experimental phonotactic regularities waned during the test. Dividing the results into two equal blocks shows the reliable interaction of block and legality ($F(1, 39) = 4.47$, $P < 0.05$; Fig. 2). The legality advantage was reliable in Block 1 ($t(39) = 2.63$, $P < 0.05$) but gone by Block 2 ($t(39) < 1$). The difference between studied and legal items did not change across blocks ($F(1, 39) = 1.15$, $P = 0.29$).

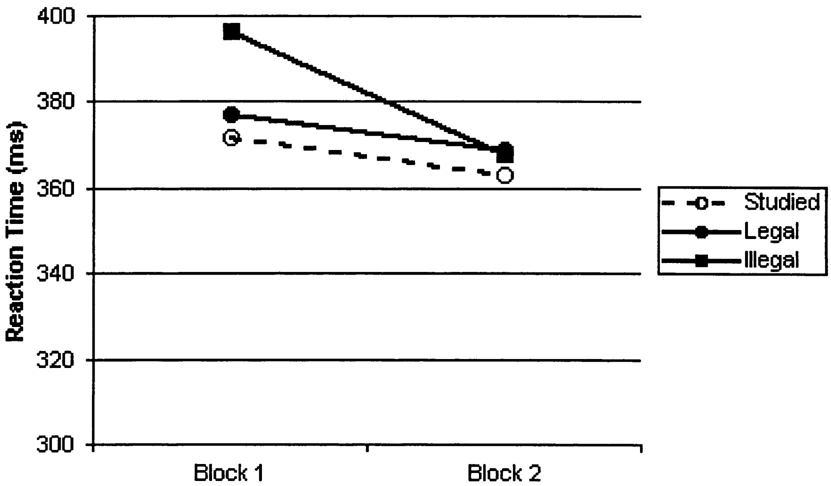

Fig. 2. Results from Experiment 2 divided into two blocks of trials.

4. Experiment 3

In Experiment 2, listeners learned consonant–vowel constraints that applied to two voices. However, token-specific details (including voice) can affect spoken word identification (e.g. Church & Schacter, 1994; Goldinger, 1996; Nygaard & Pisoni, 1998). In Experiment 3, consonant position depended on the speaker's voice; thus, [b]s were onsets for one speaker but codas for another. This contingency is formally no more complex than the vowel contingency of Experiment 2 but might be more difficult to learn since phonotactic regularities are not ordinarily specific to particular voices.

4.1. Method

4.1.1. Subjects

Forty subjects from the same population as Experiment 2 participated. Two additional subjects with more than 25% error were eliminated.

4.1.2. Materials

The syllables from Experiment 2 were rearranged to create study lists with voice-contingent consonant positions. Each subject heard both groups of consonants in both syllable positions during the study, but group 1 consonants were always onsets and group 2 consonants codas for one voice, while the reverse contingency held for the other voice. Vowels in vulgar words were replaced with the alternate vowel. Each study list contained 50 items. Test items included all four study lists (200 items) plus 36 filler syllables not studied by any subject. The syllables were divided into two 118-item test lists.

4.1.3. Procedure

The procedure was the same as in Experiment 2.

4.1.4. Scoring

Transcription and scoring were as in Experiment 2. Errors (M = 6.4 per subject), early and late responses (M = 0.9), and outliers (M = 5.3) were excluded.

The first 18 of the test items were considered practice and not analyzed. The 100 remaining items were averaged by condition to create three scores per subject: studied (M = 19.6 items), unstudied legal (M = 18.7), and unstudied illegal (M = 19.3). These scores excluded filler syllables and studied syllables that changed voice from study to test. The latter violated the voice contingency, but as studied syllables should accrue some repetition advantage; therefore, we had no clear prediction for these items.

4.2. Results and discussion

Listeners failed to detect the voice-dependent consonant restrictions (Table 1). Legal syllables were not repeated reliably faster than illegal syllables ($t(39) < 1$). However, studied syllables were repeated more quickly than unstudied syllables (legal and illegal combined; $t(39) = 2.47$, $P < 0.05$), demonstrating implicit memory for the studied items. Though Experiments 2 and 3 had equivalently complex contingencies, two voices, and the same amount of training, the consonant–vowel but not the consonant–voice contingency was learned.

5. General discussion

Languages have regularities in their legal sound sequences which guide language processing. The current experiments showed that new sequencing constraints can be acquired through listening to CVC syllables. Within minutes, listeners became sensitive to novel phonotactic regularities. Adults more quickly repeated unstudied syllables that followed rather than violated the experimentally-imposed first-order constraints on consonant position (Experiment 1) and second-order constraints in which consonant position depended on the adjacent vowel (Experiment 2). The current findings of first- and second-order learning parallel the evidence from language production (Dell et al., 2000). However, listeners failed to learn contingencies between consonant position and speaker's voice (Experiment 3).

These findings bolster the claim that speech sound representations are flexible (e.g. Fisher et al., in press). Listeners abstracted across syllables to learn that consonants were restricted to particular positions (Experiment 1). Listeners also learned about consonant positions relative to vowels, keeping track of context information while abstracting across syllables (Experiment 2). The present research also showed that speech representations are flexible in another way. Although the subjects were adult native English speakers, they rapidly acquired novel phonotactic regularities through listening experience. Each encounter with spoken language appears to add perceptual information to the language processing system, with the accumulation of these changes resulting in the abstraction of phonotactic regularities.

Similarly, infants learn sequences of whole syllables and perhaps even smaller units. After listening to four three-syllable sequences randomly concatenated in a 2-minute stream, 8-month-old infants listened longer to isolated "part-words" of low transitional probability than to the now-familiar "words" from training (Aslin, Saffran, & Newport, 1998). Additionally, listening to nonsense words from a densely-packed lexical neighborhood led 9-month-olds to treat a novel nonsense word from that neighborhood as familiar (Hollich & Luce, 2001), suggesting that the infants generalized across syllables. Together, the adult and infant studies begin to demonstrate the continuity of phonological learning across development.

The ability to detect sequential regularities is neither particular to language nor to humans. Infants learn musical sequences (Saffran, Johnson, Aslin, & Newport, 1999), and tamarin monkeys find "words" in syllable streams (Hauser, Newport, & Aslin, 2001). Similar implicit learning principles operate within many domains, from face identification (e.g. Althoff & Cohen, 1999) to keyboard digit-entering (Poldrack, Selco, Field, & Cohen, 1999) to sentence production (Chang, Dell, Bock, & Griffin, 2000).

If implicit learning is domain general, why did subjects not learn the voice contingency in Experiment 3? Though similar mechanisms operate across perceptual domains, representations within each domain constrain learning. Word recognition benefits less from repetition when the voice changes from study to test (e.g. Goldinger, 1996; Schacter &

Church, 1992; Sheffert, 1998), suggesting that voice information is retained in representations used to identify words. Yet evidence also suggests that voices and words are represented separately. For example, amnesic patients (who show word priming) do not show reduced priming for repeated words when the voice changes, unlike normal controls (Schacter, Church, & Bolton, 1995). Schacter and his colleagues argued for episodic links between voice and word representations rather than a unitary representation. Consistent with this episodic binding view, our results suggest that representations for word recognition make it more difficult to link voices than vowels with consonant position regularities.

Interesting questions about the nature of phonotactic learning are raised by these findings. First, how abstract was the learning? Consonant–vowel transitions contain considerable information about phoneme identity, and useful estimates of phonotactic probabilities rely on diphone frequencies as well as position-sensitive phoneme frequencies (Bailey & Hahn, 2001). In both Experiments 1 and 2, subjects generalized to new syllables but may have done so by learning specific phoneme transitions instead of a general rule such as, "[b]s are onsets". Would adults also generalize to tokens with new transitions? Second, are some transitions more important than others? For example, co-occurrence restrictions in English are stronger between vowels and codas than between onsets and vowels (Kessler & Treiman, 1997). Ongoing studies in our laboratory are addressing these questions and exploring how the internal structure of spoken word representations makes some sequencing regularities easier to learn.

We began by asking how phonotactic regularities are acquired. The present findings suggest that phonotactic regularities are learned through a life-long sensitivity to sequential patterns in perceptual experience. This claim is consistent with other findings of the continuity of implicit learning about speech from infancy through adulthood (Church & Fisher, 1998; Fisher et al., in press; Saffran, Aslin, & Newport, 1996; Saffran, Newport, & Aslin, 1996). To make good on this claim, of course, we must extend the present design to children. Ongoing studies with preschoolers and infants explore how subsyllabic learning might work throughout development and yield a method for exploring the structure of spoken word representations across the course of acquisition. The current studies indicate that knowledge about phonology is neither all-or-none nor static but instead results from the incremental tuning and flexible use of speech sound representations. Investigation of this tuning in both children and adults will allow us to explore how children gradually learn the phonotactic regularities of their language and how adults continually adapt to their language environment.

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