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A vowel is a vowel: Generalizing newly-learned phonotactic constraints to new contexts

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Abstract

Adults can learn novel phonotactic constraints from brief listening experience. We investigated the representations underlying phonotactic learning by testing generalization to syllables containing new vowels. Adults heard consonant-vowel-consonant (CVC) study syllables in which particular consonants were artificially restricted to onset or coda position (e.g., */f/ is an onset, /s/ is a coda*). Subjects were quicker to repeat novel constraint-following (*legal*) than constraint-violating (*illegal*) test syllables whether they contained a vowel used in the study syllables (*training vowel*) or a new (*transfer*) vowel. This effect emerged regardless of the acoustic similarity between training and transfer vowels. Listeners thus learned and generalized phonotactic constraints that can be characterized as simple first-order constraints on consonant position. Rapid generalization independent of vowel context provides evidence that vowels and consonants are represented independently by processes underlying phonotactic learning.

Keywords

speech perception; phonological development; statistical learning; phonotactic learning; generalization

Phonotactic constraints describe how speech segments are combined in a language. For example, the /ŋ/ at the end of ‘sing’ never begins English words, though it can be word-initial in other languages. Alongside such categorical constraints, languages have probabilistic constraints: Some permissible sequences are more likely than others (e.g., Frisch, Pierrehumbert, & Broe, 2004; Kessler & Treiman, 1997; Lee & Goldrick, 2008). Implicit knowledge of these categorical and probabilistic constraints influences speech processing: Native speakers more readily perceive and produce sound sequences that are more probable in their language (e.g., Brown & Hildum, 1956; Pitt, 1998; Stemberger, 1990; Treiman, Kessler, Knewasser, Tincoff, & Bowman, 2000; Vitevitch, Armbrüster, & Chu, 2004).

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Cross-linguistic variability in phonotactic patterns suggests that these patterns are at least partly learned (e.g., Moreton, 2002; Wilson, 2006). Furthermore, evidence of sensitivity to probabilistic constraints suggests that phonotactic learning arises from ongoing experience with phonological sequences (Frisch et al., 2004). On this hypothesis, natural phonotactic knowledge is continually in flux. Each listening or speaking experience updates the phonological processing system, permitting adaptation to new phonotactic constraints, which then influence speech processing (Dell, Reed, Adams, & Meyer, 2000).

Consistent with this view, infants and adults quickly adapt to new phonotactic constraints within experiments (e.g., Chambers, Onishi, & Fisher, 2003; Dell et al., 2000; Finley & Badecker, 2009; Goldrick, 2004; Onishi, Chambers, & Fisher, 2002; Saffran & Thiessen, 2003; Seidl, Cristià, Bernard, & Onishi, 2009). For example, after listening to consonant-vowel-consonant (CVC) nonsense syllables (e.g., *fip*, *bas*) in which particular consonants were artificially restricted to syllable-initial (onset) position or syllable-final (coda) position (e.g., */f/ is an onset, /s/ is a coda*), adults were quicker to identify and repeat new syllables that were legal rather than illegal with respect to the newly-established constraints (Onishi et al., 2002).

This evidence that the phonological processing system continually adapts to new phonotactic constraints leaves open the question of precisely how the system represents these constraints. Here, we begin to address this question. Below we delineate two possible accounts of how the phonological processing system represents phonotactic constraints. These accounts lead to different predictions about the circumstances under which newly-learned phonotactic constraints should generalize to new contexts.

Two accounts of phonotactic learning

The experimental constraints mentioned above are easily described as simple constraints involving consonants and syllable-positions, such as */f/ is an onset*, or */s/ is a coda*. These are *first-order* constraints; they depend on no aspect of the linguistic context other than the segment and its position. However, adults and infants also learn *second-order* constraints in which consonant position depends on another feature of the syllable, such as an adjacent vowel as in */f/ is an onset if the vowel is /æ/, but a coda if the vowel is* /ɪ/ (Chambers, Onishi, & Fisher, submitted; Onishi et al., 2002; Warker & Dell, 2006).

One account of phonotactic learning would appeal to representations of individuated consonants and vowels (segments), disentangled from their contexts and linked with syllable positions. Theories of spoken word identification and phonotactic learning have typically invoked individuated phoneme units (at least for modeling convenience; Luce & Pisoni, 1998; McClelland & Elman, 1986; Norris, McQueen, & Cutler, 2000; Warker & Dell, 2006). On this account, first- and second-order constraints would be represented differently. First-order constraints could be stated as simple relationships between individuated consonants and syllable positions, while second-order constraints would require the maintenance of contextual information. As a result, first-order constraints such as */f/ is an onset* should generalize immediately to syllables containing vowels not presented during training.

Another account would appeal primarily to representations of sequences larger than a segment (e.g., Sumner & Samuel, 2007; see Vitevitch & Luce, 1999). Robust priming of consonant-vowel (CV) and vowel-consonant (VC) sequences could explain the learning of both first- and second-order constraints. On this account, first- and second-order constraints would be represented similarly. For example, rather than learning that */f/ is an onset*, subjects would learn that /f/ precedes the specific vowels experienced in training. Such representations would predict pervasive context effects, even for newly-learned first-order phonotactic constraints, and would limit generalization when syllables contain new vowels.

Questions about the participation of individuated segments and larger sequences in phonotactic learning do not imply a search for a single privileged representational unit for speech processing. Speech perception is flexible and context-sensitive, recruiting evidence from multiple time scales to identify linguistic elements at multiple linguistic levels (e.g., Goldinger & Azuma, 2003). Our research is guided by the hypothesis that phonotactic generalization can occur at multiple levels of phonological structure (e.g., features, segments, or combinations of segments), depending on the evidence presented to the learner.

Indirect evidence for the recruitment of individuated segments in phonotactic learning, as described in the first account, comes from language production experiments: Warker and Dell (2006) found that second-order constraints were learned more slowly than were first-order constraints. This suggests that second-order constraints are represented as more complex than first-order constraints, implicating a role for individuated segments in phonotactic learning, at least in language production. Here, we asked whether adults, when given evidence for first-order constraints, (1) learn abstract segment-based constraints such as */f/ is an onset*, or (2) learn restrictions on consonant position that are more tightly tied to the contexts in which those consonants appeared. We did so by testing generalization to new vowels.

The present research

In four experiments using a speeded-repetition task, adults heard CVC syllables exhibiting first-order consonant-position constraints. In a set of study syllables, each consonant was restricted to either onset or coda position, with assignment of consonants to syllable positions counterbalanced across subjects. Learning was assessed by measuring latency to repeat novel test syllables, half of which were *legal* and half *illegal* with respect to the experimental constraints. Half of the test syllables contained a vowel found in the study syllables (*training vowels*), while half contained a new, *transfer vowel*. Crucially, subjects received no evidence that the experimental constraints applied to syllables containing the transfer vowel, because half of the transfer-vowel syllables they encountered were legal and half were illegal.

For training-vowel test syllables, we expected a legality advantage in repetition latency, as found in previous studies (e.g., Onishi et al., 2002; Vitevitch & Luce, 2005). For transfer-vowel test syllables, we reasoned that the outcome would depend on the representations recruited for learning. If representations of individuated segments contribute substantially to phonotactic learning, then subjects should readily generalize first-order constraints to new vowel contexts. In contrast, if phonotactic learning in perception is dominated by more context-sensitive representations, these representations should reduce subjects' generalization of newly-learned first-order constraints to new vowel contexts.

Across experiments, we varied the similarity of the training and transfer vowels to probe how freely first-order constraints were generalized to new vowel contexts. In Experiments 1a and 1b, we began with a less demanding test of generalization, using training and transfer vowels that were relatively similar. In Experiments 2a and 2b, the training and transfer vowels were quite dissimilar, permitting a stronger test of the context-independence of first-order constraints. In all cases, we tested generalization outside the similarity space circumscribed by the training vowels. To illustrate, in Experiment 1a the training vowels were /æ/ (as in *tan*) and /ɛ/ (*ten*), and the transfer vowel was /ɪ/ (*tin*). These three vowels differ only in the feature height: /æ/ and /ɛ/ are low and mid vowels, respectively, and /ɪ/ is a high vowel. Generalization to a high vowel from low and mid training examples requires extrapolation beyond the region of vowel similarity space circumscribed by the training vowels. Extrapolation beyond the training space, and generalization without regard to the similarity between training and test contexts, are diagnostic of abstract representations (e.g., Marcus, 2001).

EXPERIMENTS 1A AND 1B

Experiment 1a tested generalization from the training vowels /æ/ and /ɛ/ to the transfer vowel /ɪ/. In Experiment 1b, the training vowels were /ɪ/ and /ɛ/, and the transfer vowel was /æ/. These vowels are distinct enough to differentiate English words, but share several features. All are lax (as opposed to tense), front, unrounded vowels, differing only in the feature height. If extrapolation to a new vowel is possible, we should find it in these experiments.

Method

Subjects—80 college-aged native English speakers reporting normal hearing (40 in each experiment) participated for course credit or a small payment. Data from 17 additional subjects were excluded due to error rates over 25% (3 in Experiment 1a, 1 in Experiment 1b) and experimenter error or equipment problems (6 in Experiment 1a, 7 in Experiment 1b).

Design—The key manipulation involved restricting particular consonants to particular syllable positions in study syllables, counterbalanced across subjects. We adopted a continuous study-test design: Stimulus syllables were organized into 7 blocks, with no boundary between blocks from the subjects' perspective. The experimental constraints were established and maintained by 25 study syllables presented in different random orders in each of the 7 blocks. 100 unique test syllables were presented, each occurring only once. Twenty test syllables were presented in each of the last 5 blocks, randomly intermixed with the study syllables. Crossing the factors legality (legal/illegal) and vowel-type (training-vowel/transfer-vowel) yielded 4 test-item types; 25 syllables of each type were presented, distributed evenly across the 5 testing blocks. Thus, each subject heard 275 syllables: 7 repetitions of the 25 study syllables, and 100 test items. Half of the test items were legal, half illegal; half of the test items contained a training vowel, and half contained the transfer vowel.

Materials—We selected two groups of five consonants that could not be differentiated by a small set of phonetic features (group-1: /b, f, k, m, t/; group-2: /p, s, g, n, tʃ/). For Experiment 1a, these were combined with the training vowels /æ/ and /ɛ/ to create two master sets of 50 syllables, one with group-1 onsets and group-2 codas (e.g., /bæp/), and one with the opposite assignment of consonants to positions (e.g., /pæb/). Each master list was divided into two 25-syllable subsets, with consonants and vowels distributed as evenly as possible across subsets. For each subject, one subset provided the study items (e.g., /bæp/, /bɛs/), the other subset from the same master list provided legal training-vowel test items (e.g., /bɛp/, /bæs/), and one subset from the opposing master list yielded illegal training-vowel test items (e.g., /pɛb/, /sæb/). The transfer-vowel test syllables were created by combining the two consonant groups with the transfer vowel /ɪ/ to produce two 25-syllable lists, one with group-1 onsets and group-2 codas (e.g., /bɪp/, /bɪs/), the other with the opposite pattern (e.g., /pɪb/, /sɪb/). Vulgar words were omitted; their place in the task was filled by additional training-vowel syllables containing the same consonants. Four lists were created such that across subjects, each training-vowel syllable occurred equally often as a study, a legal test, and an illegal test item; each transfer-vowel syllable occurred equally often as a legal and an illegal test item. A female native English speaker recorded the syllables[1].

The syllables were rearranged to create the materials for Experiment 1b, with the training vowels /ɪ, ɛ/ and the transfer vowel /æ/.

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[1] Syllables were recorded in random order by a female native English speaker in a sound-attenuated booth and digitized at 16 bits and 44.1 kHz. Multiple tokens of each syllable were recorded. Tokens faithfully reproducing the intended syllable were selected, then normalized to reduce amplitude differences. Appendix A presents summary statistics for the frequencies of F0 and the first 3 formants at the midpoint of each vowel, and the duration of each vowel.

In Experiment 1a, 37% of the training-vowel syllables and 33% of the transfer-vowel syllables were English words, as were 29% of training-vowel and 49% of transfer-vowel syllables in Experiment 1b. Preliminary analyses of response latencies revealed no interactions of lexical status with the factors of interest, *F*s < 2.02, *p*s > .16; we therefore collapsed across this factor. As found previously, when words and non-words are intermixed and the task does not require lexical access, lexical status does not strongly govern performance (Mirman, McClelland, Holt, & Magnuson, 2008; Onishi et al., 2002).

Procedure—Subjects were tested individually using PsyScope software and voice-activated response key (Cohen, MacWhinney, Flatt, & Provost, 1993). After hearing a syllable presented over headphones, subjects repeated it as quickly and accurately as possible. The experiment was self-paced, and took approximately 15 minutes.

Scoring—Repetition latencies were measured from stimulus offset to response onset. Audio recordings of each session were transcribed twice. Responses were excluded if both transcribers agreed there was a pronunciation error (M = 24.3 in Experiment 1a, 18.0 in Experiment 1b), if response latency was more than 200 ms before or 1500 ms after stimulus offset (M = 5.4 in Experiment 1a, 5.2 in Experiment 1b), or if the latency was more than 2.5 SD beyond each subject’s mean for a particular condition (M = 5.8 in Experiment 1a, 6.3 in Experiment 1b).

Results and Discussion

Table 1 shows repetition latencies for each Experiment, averaged across the five testing blocks; accuracy data are shown in Table 2. Two (legality) by 2 (vowel-type) ANOVAs were conducted for each response measure (latency, accuracy) for each Experiment (Table 3).

In both Experiments, latencies were reliably shorter for legal than illegal test syllables; this pattern held for both training- and transfer-vowel test syllables (Table 1). Vowel-type and legality did not interact. Repetition latencies were reliably slower for the transfer-vowel syllables in Experiment 1a, and for the training-vowel syllables in Experiment 1b. These vowel-type effects presumably reflect the durations of the stimulus syllables: Because repetition latencies were measured from stimulus offset, syllables with longer durations resulted in shorter latencies across all 4 Experiments (see Appendix A).

Paired t-tests (2-tailed) revealed the predicted legality advantage in Experiments 1a and 1b, respectively, both for training-vowel, $t(39) = 4.41$, $p < .001$; $t(39) = 3.75$, $p = .001$, and transfer-vowel syllables, $t(39) = 2.91$, $p = .006$; $t(39) = 2.52$, $p = .02$.

Repetition accuracy (Table 2) was numerically but not reliably higher for legal than illegal items, both for training- and transfer-vowel items. This trend confirms that the latency findings did not reflect a speed-accuracy trade-off. There were reliable effects of vowel-type on accuracy, favoring transfer-vowel items in Experiment 1a and favoring training-vowel items in Experiment 1b; both effects reflect a tendency for the vowel /æ/ to be repeated less accurately.[2]

Experiments 1a and 1b revealed spontaneous generalization of newly-learned first-order phonotactic constraints to syllables containing a new vowel. Subjects received no evidence

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[2] Higher error rates with /æ/ have been found in other datasets (e.g., Hillenbrand et al., 1995). Also, many subjects in our Experiments were probably speakers of the Northern Cities dialect, while our talker was not. In this dialect, /æ/ is changing, shifting closer to /ɛ/ in its formant values (Clopper, Pisoni, & de Jong, 2005). This dialect difference may have contributed to difficulty with /æ/. Nevertheless, the latency data in Table 1 show that subjects readily extended the new constraints to this vowel, in syllables repeated without errors.

that the constraints applied to syllables containing the transfer vowel; nonetheless, they responded more rapidly to legal than illegal syllables containing that vowel.

EXPERIMENTS 2A AND 2B

Experiments 1a and 1b tested generalization among relatively similar vowels. In Experiments 2a and 2b, we instituted a more demanding test of generalization. In Experiment 2a, the training vowels were /i/ (as in *teen*) and /ε/ (*ten*), while the transfer vowel was /u/ (*tune*). In Experiment 2b, the training vowels were /ɪ/ and /ε/, and the transfer vowel was /u/. In both experiments, the training and transfer vowels are quite dissimilar, and virtually never confused with one another under ordinary listening conditions. The training vowels /i/, /ɪ/ and /ε/ are front unrounded vowels; the transfer vowel /u/ is a back, rounded vowel. A legality advantage for these transfer-vowel test items would provide strong evidence that listeners extend first-order phonotactic constraints without regard to vowel similarity.

Method

Subjects—We tested 64 subjects (32 in each Experiment) from the same population tested in Experiments 1a and 1b. Data from 12 additional subjects were excluded due to high error rates (1 in Experiment 2a) and experimenter error or equipment malfunction (9 in Experiment 2a, 2 in Experiment 2b).

Materials—The syllables from Experiments 1a and 1b containing /ε/ and /ɪ/ were re-used; new syllables containing /i/ and /u/ were recorded by the same speaker. In Experiment 2a, 31% of the training-vowel syllables and 22% of the transfer-vowel syllables were words, as were 29% of the training-vowel and 22% of the transfer-vowel syllables in Experiment 2b. Preliminary analyses of response latencies again revealed no significant interactions involving lexical status[3]; we therefore collapsed over lexical status.

Scoring—Responses were excluded if they contained a pronunciation error ($M = 15.7$ in Experiment 2a, 11.8 in Experiment 2b), were early or late responses ($M = 5.2$ in Experiment 2a, 6.3 in Experiment 2b), or latency outliers ($M = 6.4$ in Experiment 2a, 5.8 in Experiment 2b).

Results and Discussion

Repetition latencies in both Experiments were reliably shorter for legal than for illegal test syllables (Table 1, Table 3). Latencies were also reliably shorter for transfer- than training-vowel items, reflecting the greater length of the transfer vowel /u/. Vowel-type did not reliably interact with legality, suggesting that the legality advantage was independent of the vowel context. Paired t-tests revealed legality advantages for both training-vowel syllables, $t(31) = 4.97$, $p < .001$; $t(31) = 4.10$, $p < .001$, and transfer-vowel syllables, $t(31) = 2.70$, $p = .01$; $t(31) = 2.18$, $p = .04$, in Experiments 2a and 2b, respectively.

Accuracy was also reliably higher for legal than for illegal test items (Table 2, Table 3). Accuracy tended to be higher for transfer-vowel (/u/) than training-vowel items; this effect was reliable in Experiment 2a. Vowel-type again did not interact with legality.

Despite the dissimilarity of the training and transfer vowels in Experiments 2a and 2b, subjects spontaneously generalized the newly-learned phonotactic constraints to syllables containing

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[3] The 3-way interaction of lexical status, vowel-type, and legality approached significance in Experiment 2b, $F(1,31) = 2.94$, $p = .096$. This trend reflected the fact that the transfer-vowel test items that were English words did not show a legality advantage. However, only a small proportion of the transfer-vowel syllables formed words, making this comparison difficult to evaluate; we also found no such trend in Experiment 2a, in which the same transfer-vowel syllables were presented.

the transfer vowel. Thus, although adults can learn second-order constraints in which consonant position depends on an adjacent vowel (e.g., Dell et al., 2000; Onishi et al., 2002; Warker & Dell, 2006), they also generalize first-order phonotactic constraints to syllables containing different vowels.

Combined Analyses: Experiments 1a through 2b—We combined the data from all four Experiments to determine whether the time-course of the legality advantage differed for training- and transfer-vowel test items. Mean latencies by test-item type and test block (Figure 1) show that the legality advantage was quite stable across blocks for both training- and transfer-vowel test items. This pattern suggests that the first-order phonotactic constraints created by the study syllables were quickly learned, and solidly in place by the beginning of the first testing block. Furthermore, we found no evidence that the effect of legality depended on whether the test syllable contained training or transfer vowels, even as evidence accrued across blocks that the transfer-vowel syllables did not honor the first-order phonotactic constraints created by the study items.

Converging evidence: Other measures—Rapid generalization of first-order phonotactic constraints to new vowel contexts suggests that the learning in these experiments recruited representations of individuated segments. However, we need to consider the possibility that these results depended on the task we used. Speeded repetition has a strong sequential component. The stimulus syllable is extended in time, and subjects respond as quickly as possible. In principle, repetition latency might more strongly reflect processing of the beginnings of syllables; if so, our results might reflect this measure's insensitivity to non-initial sounds.

We can rule out the strongest form of this concern based on prior results. In previous experiments, speeded-repetition latencies revealed sensitivity to second-order constraints in which consonant-position depended on the vowel in CVC syllables (Onishi et al., 2002), and to harmony constraints involving consonants in non-stimulus-initial syllables (Koo, 2007). Thus, latencies in our task are sensitive to aspects of the test items beyond the initial consonant. Nevertheless, a weaker form of this objection might be considered. To the extent that stimulus processing is not complete by speech onset (e.g., Kello, Plaut, & MacWhinney, 2000), repetition latencies could be more sensitive to the legality of early segments, with response durations reflecting the legality of later segments. To ensure that such a latency/duration trade-off did not mask effects of vowel context in our task, we analyzed response durations. We also analyzed coda consonant accuracy to seek converging evidence for sensitivity to restrictions on coda consonants.

Response durations: We measured response durations for Experiment 2b (see Appendix B) because this experiment offered the most dramatic differences between training and transfer vowels. Response durations did not vary with legality, either for training-vowel, $M(SE)$: Legal = 428(11) ms, Illegal = 425(9) ms, or transfer-vowel items, Legal = 448(9) ms, Illegal = 453 (11) ms. A vowel-type by legality ANOVA revealed no effect of legality, $F < 1$, and no interaction of vowel-type and legality, $F(1,30) = 2.41$, $p = .13$. There was an effect of vowel-type, $F(1,30) = 164.91$, $p < .001$, reflecting the longer duration of the transfer-vowel (/u/) syllables.

The absence of a legality effect on response durations makes sense. In tasks such as ours that do not involve special inducements for fast responding, higher-level constraints such as phonotactic legality tend to affect response latency but not duration (e.g., Kello et al., 2000). Crucially, we again found no interaction of legality and vowel-type, supporting our contention that subjects robustly generalized first-order phonotactic constraints to new vowel contexts.

Coda Accuracy: For coda consonants in test syllables repeated without vowel errors, production accuracy was high, with means ranging from .93 to .99 per condition across experiments. Nevertheless, in each Experiment, coda accuracy was reliably higher for legal than illegal items, *F*s > 6.85, *p*s < .05. As in the latency analyses, vowel-type and legality did not interact, *F*s < 1.46, *p*s > .23. These findings suggest that subjects learned coda as well as onset restrictions in this task, and generalized them to new vowel contexts.

GENERAL DISCUSSION

Listening or speaking experience leads to the learning of new phonotactic constraints (e.g., Dell et al., 2000; Goldrick, 2004; Goldrick & Larson, 2008; Onishi et al., 2002; Warker & Dell, 2006). We investigated the representations underlying this learning by testing generalization to new vowels. Four experiments documented rapid generalization of newly-learned first-order phonotactic constraints to syllables containing new vowels. Listeners were quicker to repeat syllables that adhered to the experimental constraints than those that did not. This legality advantage emerged for training- and transfer-vowel syllables, regardless of the similarity of the training and transfer vowels.

The abstract nature of these rapidly-learned phonotactic constraints implies that consonants are easily separable from adjacent vowels in the representations underlying phonotactic learning. As noted earlier, representations of speech at multiple time scales and multiple degrees of detail influence speech processing (e.g., Dahan & Magnuson, 2006). The abstractness of first-order phonotactic learning documented here strongly suggests that context-independent segment-sized units play a functional role in phonological sequence learning.

This conclusion supports Warker and Dell's (2006) explanation for the difficulty of learning second-order constraints in which consonant position depends on an adjacent vowel. In their computational model of phonotactic learning, second-order constraints were harder because the model relied on individuated representations of consonants and vowels. Such representations make it easy to represent and generalize phonotactic patterns at the level of the segment, independent of the local context, and thereby make it harder to learn new patterns that *are* dependent on that context.

This conclusion is also consistent with other evidence for the separability of consonants and vowels in implicit learning. For example, listeners readily tracked transitional probabilities between non-adjacent consonants across varying vowels (e.g., Newport & Aslin, 2004); this required them to detach consonants from the adjacent vowels. Further evidence comes from rapid adaptation in speech production. Speakers adjusted their vowel productions when given distorted auditory feedback; this adaptation generalized to contexts in which the relevant vowels were adjacent to new consonants (Houde & Jordan, 1998).

In natural languages, phonotactic constraints exist at multiple levels of phonological structure (e.g., Pierrehumbert, 2003). Some constraints are best described as applying to the syllable positions of individual segments, others to featurally-defined classes of segments, and still others to combinations of these. If phonological sequence learning in adults is continuous with the creation of a phonological grammar, then new learning from brief experience should be similarly flexible as to the units underlying learning. Previous experiments have shown that both adults and infants can learn second-order constraints in which consonant position depends on the adjacent vowel (e.g., Onishi et al., 2002; Seidl et al., 2009, Warker & Dell, 2006). The present findings, by establishing spontaneous generalization of first-order phonotactic constraints to new vowel contexts, make clear that adults can also learn phonotactic constraints at the level of the segment, disentangled from the segment's context. Such findings testify to the flexibility of implicit learning about speech (see also Kraljic & Samuel, 2006). The ongoing adaptation of the phonological-processing system involves encoding phonotactic constraints flexibly, at multiple levels of linguistic detail. What is learned, and how it is generalized, depends on the nature of the evidence provided.

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Appendix A

Mean Formant Values at midpoint (Hz) and Duration (ms) for Vowels in Experiments 1a Through 2b , as measured using Praat (Boersma & Weenink, 2008)

Phoneme	F0 (Hz)	F1 (Hz)	F2 (Hz)	F3 (Hz)	Duration (ms)
æ	228	847	1913	2875	264
ε	242	759	1967	2946	183
I	248	535	2038	2859	169
i	248	389	2396	3181	203
u	254	408	1223	2565	207

Appendix B: Procedure for Measuring Response Durations, Experiment 2b

Syllables were segmented based on visual information in the waveform and spectrograph displays using Praat (Boersma & Weenink, 2008), supplemented by auditory information. Segmentation criteria depended on segmental composition, and were chosen to permit maximum uniformity of measurement despite variability in subject responses. Syllable onsets were marked: at the release of the oral closure for plosive (/b/, /p/, /g/, /k/, /t/) or affricate (/t ʃ /) onsets, at the start of voicing for nasal onsets (/m/, /n/), and at the start of frication (as shown in the spectrograph) for fricative onsets (/f/, /s/). Syllable endings were marked at the release of oral closure for plosive codas, at the end point of voicing for nasal codas, and at the end point of the turbulent noise produced by frication for fricative or affricate codas. These measurements were made for all responses to test items for 31 of the 32 subjects in Experiment 2b; durations for one subject could not be measured. Trials were omitted from analyses using the same criteria described for the latency analyses; an additional 29 trials were omitted due to local noise preventing accurate measurement. The responses of three randomly-selected subjects were independently measured by a second coder; the two sets of measurements were very similar (n = 294, Pearson r = .93, median absolute difference = 6 ms).

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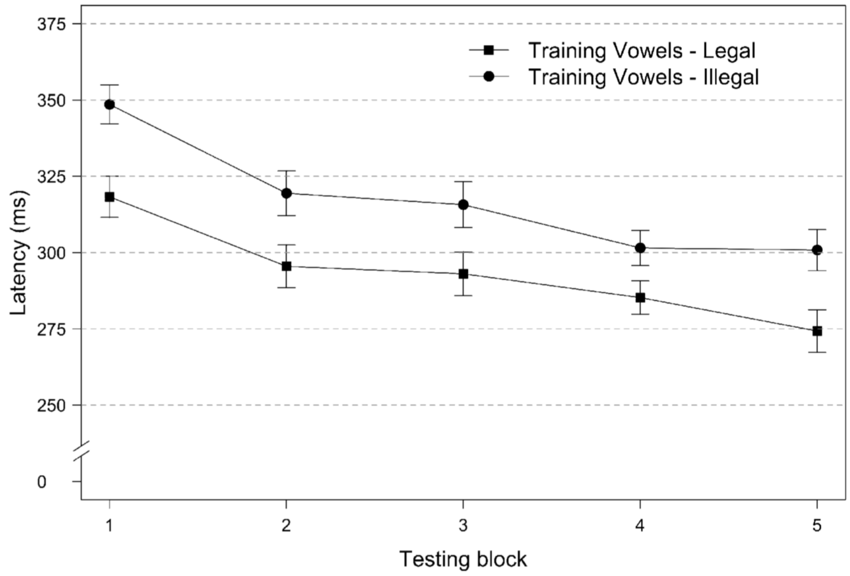
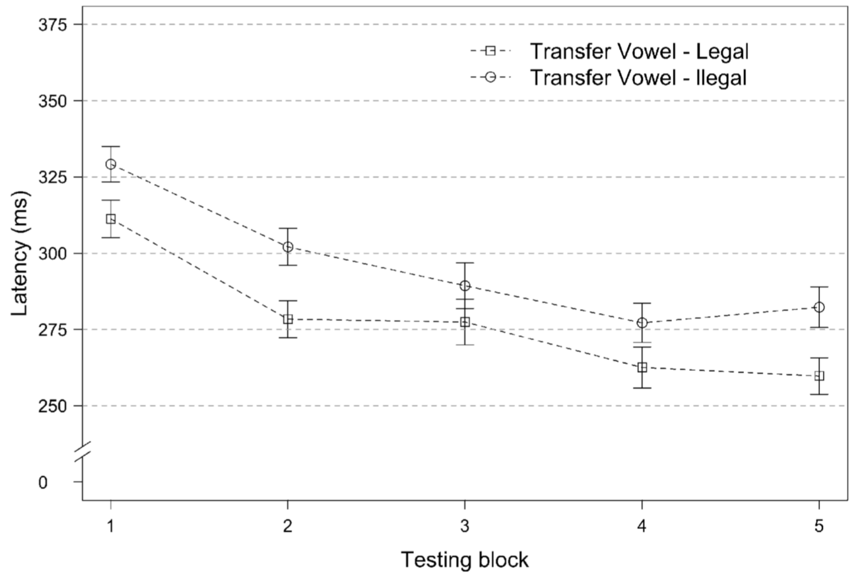


a. Training-vowel test items



b. Transfer-vowel test items

Figure 1.

Mean repetition latencies (ms) by legality and testing block for training-vowel (panel a) and transfer-vowel (panel b) test trials, averaged across Experiments 1a through 2b. Error bars represent 95% inferential confidence intervals (Tryon, 2001). A 4 (Experiment) by 5 (block) by 2 (vowel-type) by 2 (legality) ANOVA with Experiment as a between-subjects factor, revealed no main effect of Experiment, *F*(3,140) = 1.67, *p* = .18, a main effect of legality, *F* (1,140) = 72.15, *p* < .001, a main effect of block, *F*(4,560) = 26.60, *p* < .001, reflecting speeding up across blocks, but no vowel-type by legality interaction, *F*(1,140) = 2.49, *p* = .12, and no interactions involving testing block and legality, *F*s < 1.14, *p*s > .33. The only other significant effects in the combined analysis were an interaction of block by experiment, *F*(12,560) = 2.18,

$p = .01$, reflecting variation in the degree to which latencies decreased across blocks in different experiments, a main effect of vowel-type, $F(1,140) = 81.90$, $p < .001$, and an interaction of vowel-type by experiment, $F(3,140) = 31.03$, $p < .001$, reflecting the variation in the direction of the effect of vowel-type across experiments, as discussed in the text.

Table 1

Mean (SE) Repetition Latency (ms) by Legality and Vowel-Type for Experiments 1a Through 2b

	Training Vowels	Transfer Vowels	Study Items	Training-Vowel Test Items			Transfer-Vowel Test Items		
				Legal	Illegal	Legality Advantage	Legal	Illegal	Legality Advantage
Expt. 1a	/æ, ε /	/ɪ/	303 (23)	309 (22)	332 (21)	23	322 (21)	343 (23)	21
Expt. 1b	/ɪ, ε /	/æ/	290 (18)	294 (17)	314 (18)	20	286 (19)	299 (18)	13
Expt. 2a	/i, ε /	/u/	288 (17)	288 (16)	317 (17)	29	256 (19)	275 (17)	19
Expt. 2b	/ɪ, ε /	/u/	273 (21)	276 (20)	301 (20)	25	238 (21)	254 (19)	16

Table 2

Mean (SE) Proportion Correct Responses by Legality and Vowel-Type for Experiments 1a Through 2b

			Study Items	Training-Vowel Test Items			Transfer-Vowel Test Items		
	Training Vowels	Transfer Vowel		Legal	Illegal	Legality Advantage	Legal	Illegal	Legality Advantage
Expt. 1a	/æ , ε /	/ɪ/	.91 (.012)	.90 (.009)	.88 (.012)	.02	.96 (.006)	.95 (.008)	.01
Expt. 1b	/ɪ, ε /	/æ/	.95 (.009)	.94 (.008)	.91 (.011)	.03	.88 (.018)	.87 (.017)	.01
Expt. 2a	/i, ε /	/u/	.94 (.009)	.96 (.008)	.92 (.013)	.04	.97 (.008)	.95 (.008)	.02
Expt. 2b	/ɪ, ε /	/u/	.96 (.010)	.96 (.009)	.94 (.011)	.02	.97 (.008)	.96 (.008)	.01

Table 3

Analysis of Variance Results, Experiments 1a Through 2b

Results from Legality (legal, illegal) by Vowel-Type (training, transfer) ANOVAs with repetition latency and accuracy as dependent measures for Experiments 1a through 2b.

		Dependent Measure	
	Effect	**Response Latency**	**Accuracy**
Expt. 1a	Legality	$F(1,39) = 18.25^{***}$	$F(1,39) = 2.92$
	Vowel-Type	$F(1,39) = 4.71^{*}$	$F(1,39) = 49.29^{***}$
	Legality by Vowel-Type	$F(1,39) < 1$	$F(1,39) < 1$
Expt. 1b	Legality	$F(1,39) = 15.56^{***}$	$F(1,39) = 2.38$
	Vowel-Type	$F(1,39) = 10.54^{**}$	$F(1,39) = 10.94^{**}$
	Legality by Vowel-Type	$F(1,39) = 1.63$	$F(1,39) < 1$
Expt. 2a	Legality	$F(1,31) = 22.48^{***}$	$F(1,31) = 11.60^{**}$
	Vowel-Type	$F(1,31) = 122.69^{***}$	$F(1,31) = 7.00^{**}$
	Legality by Vowel-Type	$F(1,31) = 1.61$	$F(1,31) = 1.92$
Expt. 2b	Legality	$F(1,31) = 15.47^{***}$	$F(1,31) = 4.73^{*}$
	Vowel-Type	$F(1,31) = 61.23^{***}$	$F(1,31) = 2.96$
	Legality by Vowel-Type	$F(1,31) < 1$	$F(1,31) < 1$

Note.

$^{*}p < .05$;

$^{**}p < .01$;

$^{***}p < .001$