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An onset is an onset: Evidence from abstraction of newly-learned phonotactic constraints

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ABSTRACT

Phonotactic constraints are language-specific patterns in the sequencing of speech sounds. Are these constraints represented at the syllable level (*ng* cannot begin syllables in English) or at the word level (*ng* cannot begin words)? In a continuous recognition-memory task, participants more often falsely recognized novel test items that followed than violated the training constraints, whether training and test items matched in word structure (one or two syllables) or position of restricted consonants (word-edge or word-medial position). E.g., learning that *ps* are onsets and *fs* codas, participants generalized from ***pef*** (one syllable) to ***putvif*** (two syllables), and from ***putvif*** (word-edge positions) to *bu**fp**ak* (word-medial positions). These results suggest that newly-learned phonotactic constraints are represented at the syllable level. The syllable is a representational unit available and spontaneously used when learning speech-sound constraints. In the current experiments, an onset is an onset and a coda a coda, regardless of word structure or word position.
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Introduction

Languages vary in the sound sequences they allow (phonotactics) and language users make use of this information; phonotactic knowledge affects online speech processing and facilitates word learning (e.g., McQueen, 1998; Storkel, 2001). For instance, when learning labels for new objects, even 12-month-old English-learning infants preferentially accept word forms that are phonotactically legal in English (e.g., ***pl**ok*) over those that are phonotactically illegal (e.g., ***pt**ak*; MacKenzie, Curtin, & Graham, 2012). Thus, constraints are learned early. But what is the linguistic unit over which these phonotactic constraints are represented? Is *plok* a better label because *pl* starts other words of similar structure (i.e., one-syllable words such as ***pl**um*), because *pl* starts other words of varied structures (e.g., words such as ***pl**um*, ***pl**enty*, ***pl**asticine*), or because *pl* starts other syllables regardless of their position in the word (e.g., ***pl**um*, *com**pl**ain*, *du**pl**icate*)? The representations underlying phonotactic learning will have consequences for later generalization. For example, if what matters is the position within the word, then learning at a word edge (as in ***pl**enty*) should not generalize to word medial positions (as in *com**pl**ain*). If what matters is position within a syllable, then learning at word edge should transfer to word medial positions as long as position in the syllable (e.g., syllable initial) remains the same (e.g., ***pl**enty* and *com**pl**ain* but not *di**pl**omat*, where *pl* crosses a syllable boundary).

Just as listeners have access to multiple structural units during speech perception (e.g., phoneme, syllable; Goldinger & Azuma, 2003), it may be that listeners also have access to multiple structural units for representing phonotactic knowledge. Listeners may represent and generalize phonotactic patterns at the level of the syllable, where a syllable can be thought of as having initial (onset) and final (coda) positions. Thus, a constraint such as '*f* is an onset' would be represented as a generalizable fact about

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syllables (i.e., *f* can start syllables) regardless of the word position and independent of the structure of the word (e.g., word-initial constraints, such as '*f* is an onset' in ***f**action*, should readily generalize to word-medial position, as in *con**f**er,* as long as syllable position is maintained). Alternatively, phonotactic patterns may be represented at the level of words (e.g., Steriade, 1999). If so, a constraint such as '*f* is word-initial' would be represented as a generalizable fact about words (i.e., *f* can start words), and may not generalize to other word positions (e.g., the pattern learned from ***f**action* provides no direct information about *con**f**er*), though it might generalize to other word structures as long as word position was maintained (e.g., ***f**og, **f**urniture*).

For phonotactic constraints to be represented at the level of the syllable, the syllable must be a structural unit available to the learner. The following sections review (1) evidence in support of the syllable as a unit of representation, (2) evidence suggesting the need for other units of representation, and (3) evidence suggesting words as one possible alternative unit of representation, then present the current experiments in which generalization of newly-learned phonotactic constraints was used to explore whether underlying representations seem to be syllable-based, word-based, or seem to depend on both levels.

Evidence in support of the syllable as a unit of representation

Several lines of work support the view that syllables are useful units of representation. First, syllable-level representation of phonotactics would be in accord with linguistic accounts that aim to describe the possible words of a language as legal combinations of the possible syllables of that language, thus treating syllables as one of the structural units of sound patterns (see Goldsmith, 2011, for a review). Indeed, although restrictions on the consonant clusters that can occur in word-final and word-initial positions are often redundant with restrictions on the consonants that can cross within-word syllable boundaries, syllable-level representations carry more information. For instance, knowing *pk* cannot end and *km* cannot start a *syllable* tells us that *pkm* cannot occur crossing a syllable boundary within a word (e.g., neither *pupk.min*, with a syllable boundary after the *k*, nor *pup.kmin*, with a syllable boundary before the *k*, would be permissible; e.g., Ewen & van der Hulst, 2001), and it also tells us that neither *pupk* (with word final *pk*) nor *kmin* (with word-initial *km*) would be possible words. In contrast, knowing that *pk* cannot end and *km* cannot start *words* provides no information about whether the sequence *pkm* can occur at a syllable boundary that is not at word edge (i.e., crossing a syllable boundary within a word), and accounting for this fact would require an additional word-level restriction (e.g., *pkm* cannot occur within words). Syllable-rather than word-level representation would thus be more parsimonious.

Second, the syllable seems to be a unit available to language users; naturally occurring language games (e.g., Ubby Dubby in English, in which *ub* is added before each vowel; Patel & Patterson, 1982) and other linguistic phenomena (e.g., reduplication) apply at the level of the syllable (e.g., Blevins, 1995). Further indirect evidence for the syllable as a structural unit arises from experiments with multisyllabic words. For instance, when three-syllable nonwords were presented dichotically, participants erroneously reported hearing words that resulted from the movement of a whole syllable more often than words that resulted from the movement of only parts of syllables such as the vowel (e.g., Mattys & Melhorn, 2005).

Third, adult language users have been shown to be sensitive to syllable structure. In a speeded production task, they were faster to repeat a two-syllable word when its first syllable shared the structure of the one-syllable word that preceded it (e.g., participants were faster to repeat *til.-fer* when it followed *tem* than when it followed *temp*; Sevald, Dell, & Cole, 1995). Thus, several pieces of evidence suggest that the syllable is a unit readily used when learning about and processing speech sounds.

Evidence suggesting the need for other units of representation

However, there is also evidence which suggests that syllable-based representations may not be sufficient or even required for phonotactic learning, and which points to the utility of alternative units of representation. First, speakers may not use syllables when identifying words (Cutler, Mehler, Norris, & Segui, 1986), and when asked to divide words into syllables, speakers are not necessarily consistent with one another (e.g., Treiman & Zukowski, 1990). Moreover, speakers' syllable divisions do not always agree with the divisions suggested by phonotactic patterns; for example, although most would agree that *melon* contains 2 syllables, there is disagreement as to whether the syllabification is *me.lon*, *mel.on,* or *mel.lon* (e.g., Treiman & Danis, 1988). These issues raise questions about the usefulness of syllables as representational units (e.g., Treiman & Danis, 1988; Treiman & Zukowski, 1990).

Second, natural-language phonotactics cannot be fully characterized at the level of the syllable; the description of some naturally-occurring phonotactic constraints seems to require reference to morphemes and word boundaries, or to sequences that cross syllable boundaries. For example, Korean restricts consonant contact across syllable boundaries and native listeners are sensitive to these constraints, which cannot be reduced to restrictions on syllable codas and onsets (e.g., Kabak & Idsardi, 2007), implying a structural unit other than the syllable. If phonotactic constraints were solely represented at the level of the syllable, no information should be available regarding permissible consonant sequences across syllable boundaries, yet speakers show sensitivity to word-internal, cross-syllable information (e.g., Hay, Pierrehumbert, & Beckman, 2004; Mattys, Jusczyk, Luce, & Morgan, 1999; Richtsmeier, Gerken, & Ohala, 2009). For example, after being familiarized with two-syllable nonwords containing adjacent consonants that in English, were more (e.g., *k.t* in *bok.tem*) or less frequent (e.g., *p.k* in *bop.kem*) across the internal syllable boundary, children were more accurate at repeating words containing the frequent than the infrequent clusters (Richtsmeier et al., 2009).

Third, novel sound-sequence learning cannot always be easily explained using syllable-level representations alone. For instance, English-speaking adults can learn a consonant harmony pattern based on non-adjacent consonants, and generalize it to different word positions (e.g., based on whether a word started with either the sound *s* or *sh*, participants predicted the suffix to be either *su* or *shu*; Finley, 2012), suggesting that participants were able to encode information about patterns occurring in structures larger than the syllable.

Evidence suggesting the word as a possible unit of representation

If syllables are not the only (or even a necessary) structural unit, a likely alternative is the word. Several lines of evidence support words as a unit of representation available to the learner. First, English-speaking adults and English-learning infants are sensitive to frequencies of consonant sequences that occur across syllable boundaries within words. Adults are more likely to rate as well-formed, clusters that occur frequently within English words, than clusters that occur less frequently (Hay et al., 2004). Similarly, infants segmented units from a continuous speech stream more readily when the units were edged by clusters occurring rarely rather than frequently *within* English words (Mattys et al., 1999).

Second, under certain conditions, adults and infants treat word-initial and word-medial onsets differently, suggesting that all syllable onsets are not equivalent, and that these sounds are not represented only as *onsets*. For instance, in a language-game task, adults were shown pairs of words. The task was to take the capitalized letter(s) in word 2 (e.g., K in "bepniz Kupfam"), use them to replace the corresponding letter(s) in word 1 (e.g., B in "bepniz Kupfam"), and say the new version of word 1 aloud (e.g., *Kepniz*). Participants found it easier to do the replacement with a word-initial onset (e.g., K in "bepniz Kupfam", resulting in *Kepniz*) than a word-medial onset (e.g., F in "bepniz kupFam", resulting in *bepFiz*; Fowler, Treiman, & Gross, 1993). Moreover, in a tongue-twister task, adults were more likely to make speech errors that maintained the same word position than errors that maintained syllable but not word position (e.g., participants were more likely to produce ***p**ad* instead of *fad* when attempting to say ***p**arade fad* than when attempting to say *re**p**eat fad*; Shattuck-Hufnagel, 1992). This suggests that word-edge onset positions may not be equivalent to word-medial onset positions, and calls into question the primacy of syllables in phonotactic learning. Similarly, 9-month-old infants learned that classes of consonants (e.g., fricatives) could occur as an onset word initially but not word medially (e.g., ***s**a.pa* but not *pa.**s**a*), suggesting that they were able to represent the word-edge and word-medial onset positions independently despite the fact that both could have been represented as syllable onsets (Seidl & Buckley, 2005).

Third, adults learned experimental constraints on onset and coda consonants more easily when the restricted consonants were at word edges (marked by pauses) than when they were in word-medial positions (e.g., Endress & Mehler, 2010). For example, given the syllable-level constraints ('*f* as syllable onset', indicated by underlined ***f***; and '*p* as syllable coda', indicted by non-underlined ***p***), it was easier to learn the constraints in word-edge (e.g., ***f**al.ni**p***) than in word-medial (e.g., *la**p**.**f**in*) positions. The authors argued that because identification in both positions was near perfect, better learning of word-edge than word-medial phonotactics could not be attributed to greater processing difficulties for word-medial patterns. They concluded that their results were consistent with the idea that phonotactic knowledge is guided by a general sequence-learning mechanism in which position is represented relative to perceptually marked edges (i.e., silence at word edges), with no reference to word-internal syllable structure.

In summary, the syllable can be a unit for researchers to *describe* phonotactic patterns (e.g., Ewen & van der Hulst, 2001; Goldsmith, 2011). However, evidence is mixed with respect to how phonotactic knowledge is *represented* by language users. On one hand, there is evidence that the syllable is a unit that is readily used when learning about speech (e.g., Fowler et al., 1993; Mattys & Melhorn, 2005; Sevald et al., 1995; Treiman, Fowler, Gross, Berch, & Weatherston, 1995). On the other hand, there are suggestions that syllable-based units are not necessary (e.g., Endress & Mehler, 2010) or sufficient for phonotactic learning (e.g., Cutler et al., 1986; Finley, 2012; Fowler et al., 1993; Hay et al., 2004; Kabak & Idsardi, 2007; Mattys et al., 1999; Richtsmeier et al., 2009; Seidl & Buckley, 2005; Steriade, 1999; Treiman & Danis, 1988; Treiman & Zukowski, 1990). The availability of multiple levels of representation (e.g., syllable and word) might help explain why natural phonotactic constraints can be substantially, though not fully, described by reference to syllable structure.

Previous phonotactic learning experiments (e.g., Chambers, Onishi, & Fisher, 2003; Chambers, Onishi, & Fisher, 2010; Chambers, Onishi, & Fisher, 2011; Dell, Reed, Adams, & Meyer, 2000; Goldrick & Larson, 2008; Onishi, Chambers, & Fisher, 2002; Seidl, Cristià, Bernard, & Onishi, 2009; Warker, 2013; Warker & Dell, 2006) have described phonotactic patterns at the level of the syllable, but they did not directly test whether representations were at the syllable or word level (since most have used one-syllable, consonant-vowel-consonant or CVC items). The current experiments seek evidence that phonotactic knowledge *can* be represented at the level of the syllable (or syllable-sized unit), independent of the word, by examining whether syllable-level patterns generalize across word position and word structure, thus asking whether an onset is an onset and a coda is a coda regardless of word structure and position.

Both syllable-based and word-based representations would predict generalization of phonotactic constraints to novel words (see Fig. 1a) and novel word structures, as long as the word-edge relationship is maintained (e.g., a positional constraint on **C**, established word initially in **C**VCs would generalize to word-initial position in **C**VC.CVCs; see Fig. 1b). Yet, since previous studies of phonotactic learning did not vary word structure from training to test (e.g., participants were trained on CVCs and tested on CVCs), it is still unknown whether new phonotactic constraints learned with items of one word structure can be generalized to items of a novel word structure. Representing phonotactic constraints at the level of the syllable (but not at the level of the word) predicts that constraints learned in one word

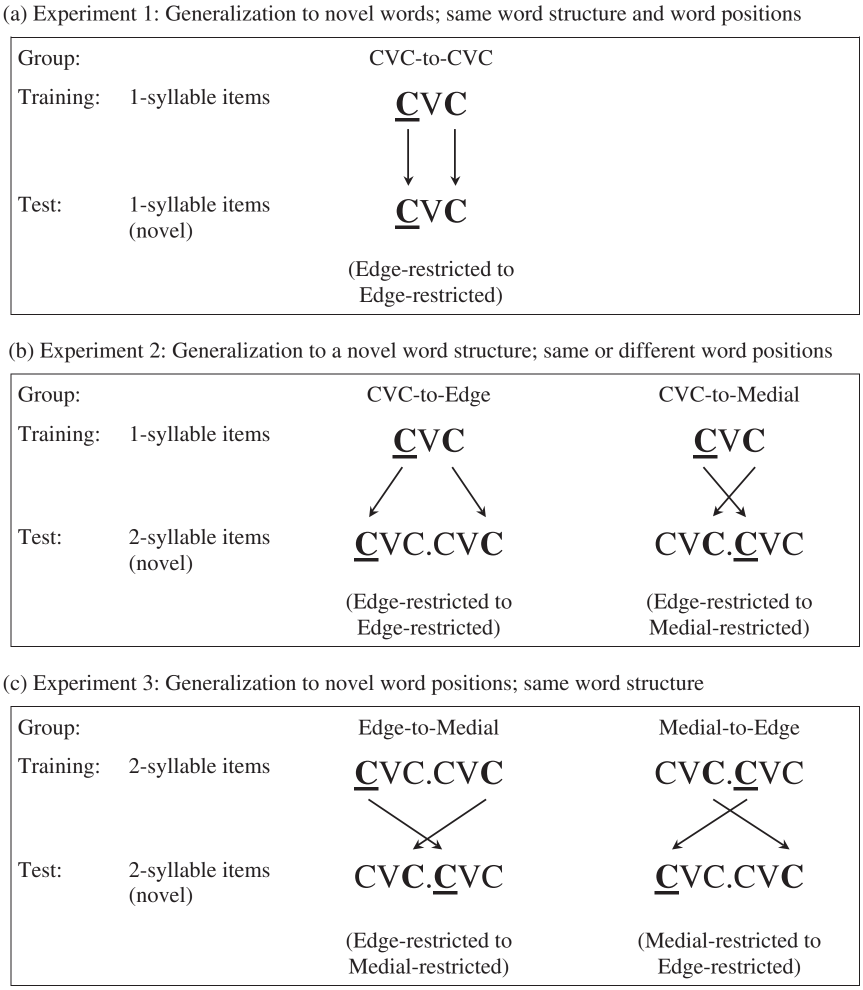

Fig. 1. Schematic representations of the word structures and consonant-restriction positions for training and test items in (a) Experiment 1, (b) Experiment 2, and (c) Experiment 3. **C** = syllable-onset restricted consonant; **C** = syllable-coda restricted consonant.

position (e.g., syllable onset at word edge, **C**VC.CVC) would generalize across different word positions as long as the syllable-level constraints are maintained (e.g., syllable onset word medially, CVC.**C**VC; see Fig. 1c). In contrast, representing phonotactic constraints at the level of the word but not at the level of the syllable predicts that constraints learned in one word position (e.g., **C**VC.CVC) would not generalize across different word positions (e.g., CVC.**C**VC).

The current experiments asked whether listeners spontaneously represent newly-learned phonotactic constraints at the level of the syllable by asking whether they generalize such constraints to new word structures and new word positions. Participants were trained on nonsense words in which particular consonants were restricted to syllable-onset or syllable-coda positions, and then tested on novel nonwords. Critically, training and test items were manipulated such that they either shared (or not) the same word structure (i.e., same or different number of syllables) and positioning of the constraints within the word (i.e., restricted consonants in the same or in a different position relative to the word edges).

The question of the current experiments is about how sounds and sound sequences are represented. Phonotactic generalization is used as a tool to better understand how speech sounds are represented, thus measures that assess changes in speech processing as a result of newly-experienced phonotactic patterns allow us to better understand these representations. As the current goal was to assess the influence of constraint violations occurring in different word positions, a continuous recognition memory task was used (e.g., Koo & Callahan, 2012; Mintz, 2002) since production accuracy measures (in which errors on earlier sounds may affect the production of later sounds; e.g., Dell et al., 2000; Goldrick & Larson, 2008; Kittredge & Dell, 2011; Warker, 2013; Warker & Dell, 2006) or repetition latency measures (in which latency is measured from the start of the word; e.g., Chambers et al., 2010; Onishi et al., 2002; Vitevitch & Luce, 2005) may not equally reflect violations at different positions in the word. Moreover, the recognition memory task has advantages over grammaticality judgment tasks (e.g., Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997), in that it is arguably a more implicit measure of phonotactic knowledge.

Participants thus heard a series of nonwords and were asked to indicate whether they had encountered each word earlier during the experiment. Initially, participants heard training and filler items. Part-way through the experiment, novel test items were introduced, mixed in with additional repetitions of the training and filler items. The measure of interest was the rate of false recognition responses to novel test items. If the experimental phonotactic constraints established by the training items were learned and generalized, novel test items that followed those constraints (*legal* items) should more often be falsely recognized as having been heard before than items that violated these constraints (*illegal* items), even though each test item had been presented only once.

Experiment 1 asked whether new phonotactic constraints on consonants in CVC items can be learned and generalized to novel CVC items (see Fig. 1a) given a structurally varied learning context containing filler items. Experiment 2 asked about the generality of phonotactic learning, specifically whether patterns could be extended from one word structure to another (see Fig. 1b). Participants were trained on one-syllable items (**C**V**C**, e.g., ***p**e**f***) that displayed the experimental constraints (e.g., *p* is onset and *f* is coda in items with a CVC word structure), then tested on items with a different word structure (two-syllable CVC.CVCs). Test items were composed only of novel CVC syllables and contained the restricted consonants (e.g., *p* and *f*) in syllable positions that were legal or illegal relative to the training. In the CVC-to-Edge group, test items always had the restricted consonants in word-edge positions and were either legal (e.g., ***p**ut.vi**f***) or illegal (e.g., ***f**ut.vi**p***) with respect to the syllable-position constraints. In the CVC-to-Medial group, test items always had the restricted consonants in word-medial positions and were either legal (e.g., *vi**f.p**ut*) or illegal (e.g., *vi**p.f**ut*) with respect to the syllable-position constraints. A tendency to falsely recognize novel test items in which the *p* is a syllable onset (rather than a syllable coda) in both Edge-restricted and Medial-restricted tests would demonstrate that learning of phonotactic patterns is not necessarily tied to word structure but that the constraints are likely represented at the level of the syllable. Experiment 3 further examined the necessity of syllable-level representations by asking whether patterns could be generalized across word positions within a single word structure (see Fig. 1c). In the Edge-to-Medial group, participants were trained on two-syllable items that displayed the experimental constraints in word-edge positions (**C**VC.CV**C**, e.g., ***p**ak.bu**f***) and were tested on two-syllable items containing the restricted consonants in new word positions (word medially) that followed (CV**C.C**VC, e.g., *vi**f.p**ut*) or violated (CV**C.C**VC, e.g., *vi**p.f**ut*) the syllable-position constraints. In the Medial-to-Edge group, participants were trained on two-syllable items that displayed the experimental constraints in word-medial positions (CV**C.C**VC, e.g., *bu**f.p**ak*) and were tested on two-syllable items containing the restricted consonants in new word positions (word edges) that followed (**C**VC.CV**C**, e.g., ***p**ut.vi**f***) or violated (**C**VC.CV**C**, e.g., ***f**ut.vi**p***) the syllable-position constraints.

Experiment 1

In Experiment 1, participants listened to CVC training items in which particular consonants were restricted to onset or coda position (e.g., *p* and *z* were onsets, *d* and *f* were codas) intermixed among filler items. Only the training items contained the restricted consonants and displayed the experimental constraints to be learned (e.g., ***p**a**f***), while filler items contained only unrestricted consonants (consonants that could occur in either onset or coda position). Filler items either shared the word structure of the training and test items (e.g., *tav*) or had a different structure (e.g., *biv.tuk*). First, participants received a Familiarization block in which they heard 2 repetitions of the training and filler items to establish the experimental constraints. Then, in each of the following 2 Test blocks, they heard novel test items intermixed with another repetition of the training and filler items. Test items shared the word structure of the training items and were either legal (e.g., ***p**av*) or illegal (e.g., ***f**av*). Thus, during the Test blocks, the training, filler and test items were intermixed allowing for testing while the experimental constraints were still being maintained (through the training items).

Method

Participants

Thirty-two college-aged adults, all native speakers of English (26 females), participated for course credit or a small monetary compensation. No participant reported a hearing impairment.

Design

The key manipulation involved restricting particular consonants to the syllable onset or coda position of CVC nonwords. Generalization of these experimental consonant-position constraints was tested using new items with the same structure (CVC). For each participant, 4 consonants were restricted: 2 were restricted to onset position, 2 were restricted to coda position. An additional 4 consonants were unrestricted and occurred freely in both onset and coda position. The assignment of particular consonants to restricted or to unrestricted status, and to onset or coda position within restricted status, was counterbalanced across participants (see Table 1).

Each participant received 24 training items,[1] 48 test items, and 36 filler items. The training items served to establish the experimental constraints. In the training items, restricted consonants appeared only in the assigned position: onset-restricted consonants appeared in onset position, and coda-restricted consonants appeared in coda position. The 24 training items comprised 8 items in which both the onset and the coda positions contained restricted consonants (**C**V**C**), 8 items in which only the onset position contained a restricted consonant while the coda position

[1] Due to a programming error, only 23 distinct training items (1 item was duplicated) were presented to 8 participants in Experiment 1 and to 8 in each group (CVC-to-Edge, CVC-to-Medial) in Experiment 2. Analyses excluding these participants show the same patterns, thus these participants are included in the analyses.

Table 1
The 4 experimental assignments of consonant pairs to roles.

	Onset restricted	Coda restricted	Unrestricted
1	/p, z/	/d, f/	/b, k, t, v/
2	/d, f/	/p, z/	/b, k, t, v/
3	/b, k/	/t, v/	/p, z, d, f/
4	/t, v/	/b, k/	/p, z, d, f/

contained an unrestricted consonant (**C̲**VC), and 8 items in which only the coda position contained a restricted consonant while the onset position contained an unrestricted consonant (CV**C**). The 3 types of training items were included to increase the variety of items providing evidence for the experimental constraints.

The 48 test items had the same word structure as the training items (one-syllable CVCs). Half were *legal*, containing either an onset-restricted consonant in onset position (12 **C̲**VCs) or a coda-restricted consonant in coda position (12 CV**C**s). Half were *illegal*, containing either a coda-restricted consonant in onset position (12 **C**VCs) or an onset-restricted consonant in coda position (12 CV**C̲**s). None of the syllables from the training items were repeated in the test items. The 36 filler items consisted of 12 one-syllable CVC items and 24 two-syllable CVC.CVC items. Filler items contained only unrestricted consonants; they were included to increase the diversity of the items that were heard more than once, and to introduce two-syllable items into the experiment for comparability with Experiments 2 and 3.

Each participant received 3 blocks of trials: 1 Familiarization block and 2 Test blocks. Participants were not made aware of the block division, and for each item (training, filler, or test) presented to them, they were asked whether the word had already been heard or not during the experiment. In the Familiarization block, all training and filler items (repeating items) were presented twice in a random order. This ensured that items were experienced as repeating early in the experiment, such that the correct answer to the recognition-memory question was sometimes 'Yes' (i.e., I have heard this word before) from the beginning of the experiment. Within each of the 2 Test blocks, the training and filler items were repeated once more, mixed in with novel test items each presented only once during the experiment. Fig. 2 shows the distribution of items across blocks as well as examples of the items presented.

Stimuli

Eight consonants (/b, d, f, k, p, t, v, z/) and 4 vowels (/ɪ/ as in *pit*, /ʌ/ as in *putt*, /ɛ/ as in *pet*, /æ/ as in *pat*) were used to create the stimuli. All consonants were legal onsets and codas in English, and were also chosen to ensure that the two medial consonants in two-syllable items would be perceived as separated by a syllable boundary (e.g., *biv.tuk* and not *bi.vtuk* or *bivt.uk*). Consonants were divided into pairs (/p, z/, /d, f/, /b, k/, /t, v/) for counterbalancing purposes; for a given participant one pair was restricted to onset position and another pair was restricted to coda position, while the remaining two pairs were unrestricted. Each participant received one of four assignments (see Table 1) of consonant pairs to roles in the experiment.

For example, participants who were assigned /p, z/ as onset, /d, f/ as coda, and /b, k, t, v/ as unrestricted consonants would be trained on items such as ***p̲ef***, ***p̲**at*, *bu**f*** and be tested with legal items such as ***p̲**ib* and illegal items such as ***f**ib* (see Fig. 2). Filler items would include items such as *tav* and *biv.tuk*.

Test items that were legal for participants who were assigned /p, z/ as onsets and /d, f/ as codas were illegal for participants who were assigned /d, f/ as onsets and /p, z/ as codas (and vice versa). The four assignments of consonant pairs to roles (see Table 1) ensured that, across participants, each consonant was restricted to each position and that each test item served equally often as a legal and as an illegal test item.

The nonsense words were recorded in a randomized order, intermixing items with different consonant assignments and word structures (one- or two-syllable). A female native English speaker from the Chicago area, unaware of the experimental questions and design, produced multiple tokens of each word. The speaker produced the two-syllable items with 2 strong syllables but greater stress on the first syllable (as in *NAP.kin*). For each item, a single token was selected; tokens were chosen to be clear, well-articulated recordings of the nonwords containing the desired consonants and vowels.

Procedure

Participants were tested individually. The experiment was run using E-prime software (Schneider, Eschmann, & Zuccolotto, 2002), and stimuli were presented at a comfortable listening level over headphones. Before the start of the experiment, participants were told that the experiment was about their memory for words, and that it would involve listening to nonsense words over headphones and answering questions using a response box. Detailed instructions were provided on the computer screen.

Participants were asked to 'listen to each word carefully and decide whether this word has already been presented, or whether this is the first time you have heard this word in the experiment'. They heard a series of nonsense words and for each, indicated whether they had (or had not) heard it earlier in the experiment ('Have you heard it before?' Yes/No) by pressing one of two buttons labeled 'Yes' and 'No' on the response box. The session began with two filler-item practice trials, then proceeded to the main experiment.

The Familiarization block consisted of 120 trials in which the training (all CVCs) and filler items (CVCs and CVC.CVCs) were each presented twice, in a random order. Each of the following 2 Test blocks consisted of 84 trials: the training (24) and filler (36) items were presented once, with novel test items (24 CVCs; half legal, half illegal) intermixed amongst them. Thus, after the practice trials, across all 3 blocks, there were a total of 288 trials; the correct response was 'Yes' for 182 trials (the second, third and fourth presentation of the 24 training and 36 filler items and the first presentation of the 2 fillers used as practice items), whereas the correct response was 'No' for the remaining 106 trials (the first presentation of the 24 train-

Familiarization Block		Test Block 1		Test Block 2	
24 training items (2x each)		24 (repeating) training items		24 (repeating) training items	
CVC (8)	***p**ef*	**C**VC (8)	***p**ef*	**C**VC (8)	***p**ef*
CVC (8)	***p**at*	**C**VC (8)	***p**at*	**C**VC (8)	***p**at*
CV**C** (8)	*bu**f***	CV**C** (8)	*bu**f***	CV**C** (8)	*bu**f***
36 filler items (2x each)		36 (repeating) filler items		36 (repeating) filler items	
CVC (12)	*tav*	CVC (12)	*tav*	CVC (12)	*tav*
CVC.CVC (24)	*biv.tuk*	CVC.CVC (24)	*biv.tuk*	CVC.CVC (24)	*biv.tuk*
		12 Legal test items		12 additional Legal test items	
		CVC (6)	***p**av*	**C**VC (6)	***p**ib*
		CV**C** (6)	*vi**f***	CV**C** (6)	*tu**f***
		12 Illegal test items		12 additional Illegal test items	
		CVC (6)	***f**av*	**C**VC (6)	***f**ib*
		CV**C** (6)	*vi**p***	CV**C** (6)	*tu**p***

Fig. 2. Design and example items for Experiment 1, assessing constraint learning (CVC-to-CVC). Example items are for a participant assigned to /p, z/ as onsets, /d, f/ as codas, and /b, k, t, v/ as unrestricted.

Table 2
For each subject, mean proportion of 'Yes' recognition responses by item type, and the Legality effect (Legal test minus Illegal test) were calculated for Blocks containing test items (Blocks 2 and 3). Table 2 presents mean (standard deviation) across subjects for each participant group, Experiments 1–3. Note that in the table, the Legality effect may not match Legal/Illegal difference due to rounding.

	Group	Training	Legal test	Illegal test	Legality effect
Experiment 1	CVC-to-CVC	.770 (.173)	.458 (.208)	.233 (.140)	.225
Experiment 2	CVC-to-Edge	.825 (.119)	.463 (.208)	.378 (.173)	.085
	CVC-to-Medial	.804 (.122)	.458 (.241)	.326 (.214)	.133
Experiment 3	Edge-to-Medial	.791 (.164)	.385 (.239)	.297 (.196)	.089
	Medial-to-Edge	.758 (.161)	.396 (.209)	.268 (.157)	.128

ing and 34 filler items not presented as practice items, and the sole presentation of the 48 test items). Across all trials, 192 presented one-syllable items and 96 presented two-syllable items. A participant with perfect memory should never recognize the test items as having been heard before, yet if participants learned the experimental constraints from the training items they might falsely recognize the legal test items more often than the illegal test items because only the legal items followed the phonotactic constraints established by the training items.

Results

Proportion of 'Yes' recognition responses as a function of item type, averaged across the 2 Test blocks are shown in Table 2. Perfect accuracy would be 'Yes' for all training items (i.e., 1.000) and 'No' to all test items (i.e., 0.000), whether legal or illegal, as each test item was presented only once. As Table 2 shows, participants were more likely to falsely recognize legal (.458) than illegal (.233) test items, reflecting sensitivity to the experimental phonotactic constraints displayed in the training items. In addition, although the overall rate of false recognition was high, participants still differentiated items that followed the experimental constraints and were repeated (training items) from those that were novel (legal test items), as demonstrated by higher recognition rates for training (.770) than for legal test (.458) items.

Because the data were categorical, responses to the test items were analyzed using linear mixed-effects models (with logistic link) predicting the log odds of a false recognition on each test trial (e.g., Jaeger, 2008). In this and the following experiments, models were fit using the *glmer* function of the lme4 package version 1.1–6 (Bates, Maechler, Bolker, & Walker, 2014) of the statistical software platform R (R Core Team, 2014). Linear mixed-effects models were fit using the Laplace approximation and the bobyqa optimizer. In Experiment 1, the "maximal model" justified by the experimental design (Barr, Levy, Scheepers, & Tily, 2013) included: a fixed-effect term for Legality (sum-coded such that: Legal = 0.5, Illegal = −0.5), random intercepts for Subjects and Items, random slopes by Subject and by Item for Legality, and correlations between random intercepts and random slopes. However, since this maximal model gave perfectly correlated random effects for both Subjects and Items, the reported model (see Table 3) included the same random intercepts and slopes, but without the correlations between random-effect terms[2] (as suggested in Barr et al., 2013).

Hypothesis testing for the effect of Legality on the likelihood of a false recognition was performed using a

[2] Critically, whenever a model without correlation is reported in this and the following experiments, the estimate terms (and standard error) were highly similar (within 0.05 for the fixed term estimate, and 0.02 for the standard errors) to the model including the correlations.

Table 3
Fixed and random effect estimates for the linear mixed-effects model for Experiment 1, assessing constraint learning (CVC-to-CVC). The model includes a fixed-effect term for Legality (sum-coded as: Legal = 0.5, Illegal = −0.5), random intercepts by Subject and Item, and random slopes by Subject and Item for Legality.

		Variance	Std. dev.
Random effects			
Items	(Intercept)	0.34	0.59
	Legality	0.00	0.00
Subjects	(Intercept)	0.70	0.84
	Legality	0.00	0.00

No. of observations: 1536 and No. of subjects: 32.

	Coefficient	Std. error	Wald *z*	Pr(>|z|)
Fixed effects				
(Intercept)	−0.84	0.18	−4.67	<.001*
Legality	1.22	0.12	9.83	<.001*

* *p < .05 (on normal distribution).*

likelihood ratio test comparing the maximal model (without Subject and Item correlations) to the model that was identical except that it did not include the fixed effect of Legality. The model's fit was significantly improved by the inclusion of the fixed effect of Legality [$\chi^2(1) = 47.12$, $p < .001$].

Discussion

Adult English speakers learned novel phonotactic restrictions and generalized them to novel items of the same word structure. This learning was shown by a higher rate of false recognition for legal than illegal test items (see Fig. 3 for plotted differences in false recognition for legal vs. illegal items for each participant).

These results confirm that a continuous recognition memory task can be used to assess phonotactic learning and generalization in the context of structurally diverse stimuli. They also verify that adults can learn and generalize phonotactic patterns even in an environment in which there are many distractors (filler items) and hence relatively few items displaying the experimental constraints. The next experiment then asked whether phonotactic patterns can be extended across word structures and positions.

Experiment 2

Experiment 2 asked whether adults would spontaneously generalize patterns they learned in one word structure (one-syllable items) to items of another structure (two-syllable items) when syllable-level constraints were maintained. Phonotactic patterns learned in one-syllable items should easily generalize to two-syllable items if word position is maintained, whether they are represented at the syllable or word level. For example, the *p*s in ***p**e**f*** and ***p**iv.ba**f*** have the same syllable position (onset) and word position (word initial). Critically, the patterns should also easily generalize to two-syllable items when the position in the word is different if they are represented at the syllable level, but not if they are represented at the word level. For example, the *p*s in ***p**e**f*** and *ba**f**.**p**iv* have the same syllable position (onset) but they have different word positions (word initial vs. word medial). Participants received the same training and filler items as in Experiment 1; training items contained the restricted consonants and reflected the new phonotactic constraints to be learned (e.g., *p* was an onset, *f* was a coda in CVCs like ***p**e**f***), while filler items contained only unrestricted consonants (CVCs and CVC.CVCs; e.g., *tav* and *biv.tuk*). As in Experiment 1, participants were tested on items that either followed or violated the experimental constraints. However, in contrast to Experiment 1, Experiment 2 varied word structure from training to test: the training items were one-syllable CVC items, but the test items were two-syllable CVC.CVC items.

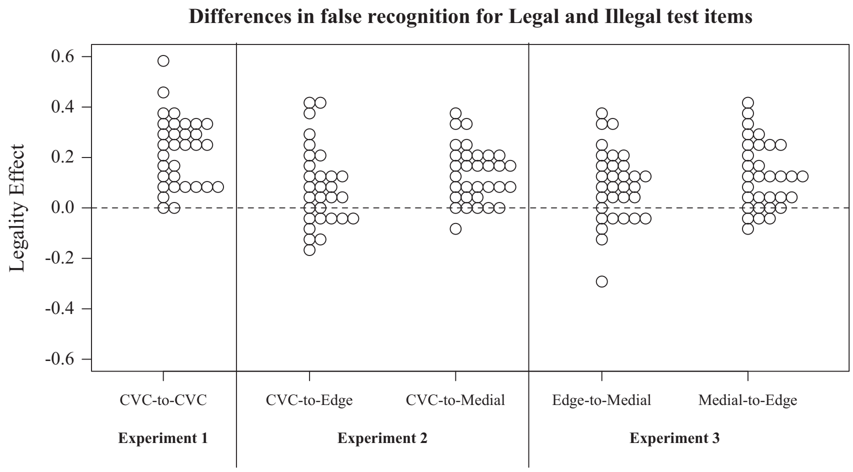

Fig. 3. Differences in false recognition for Legal and Illegal test items (Legality effect), for each participant group, Experiments 1 through 3. Each circle represents one participant's Legality effect.

Two groups of participants were tested. The test items for the CVC-to-Edge group had restricted consonants in the word-initial onset position and in the word-final coda position, but unrestricted consonants elsewhere (e.g., legal _**p**iv.ba**f**_ vs. illegal _**f**iv.ba**p**_). The test items for the CVC-to-Medial group had restricted consonants in the word-medial coda and word-medial onset position but unrestricted consonants elsewhere (e.g., legal _ba**f**.**p**iv_ vs. illegal _ba**p**.**f**iv_). If participants spontaneously represent the experimental constraints at the syllable level, they may extend them from the one-syllable training items to the two-syllable test items, showing higher false recognition for legal than illegal test items, regardless of the position of the restricted consonants (i.e., in both the CVC-to-Edge and CVC-to-Medial groups). In contrast, if they represent the constraints only at the word level, false recognition should be higher for legal than illegal test items only when the restricted consonants remain in the word-edge positions (i.e., only in the CVC-to-Edge group), and they should show similar recognition for legal and illegal test items when the restricted consonants are no longer in the same word positions as in the training items (i.e., CVC-to-Medial group).

Method

Participants

Sixty-two college-aged adults, all native speakers of English (44 females) participated for course credit or monetary compensation; 32 participants were assigned to the CVC-to-Edge group and 32 were assigned to the CVC-to-Medial group. No participant reported a hearing impairment. None of the participants from Experiment 1 participated in Experiment 2. Data from 2 participants in the CVC-to-Edge group were excluded due to programming error; thus for this group only, across participants, items occurred as legal and illegal test items with slightly different frequencies.

Design

As in Experiment 1, the key manipulation involved restricting particular consonants to either the onset or coda position of syllables. The training (CVCs) and filler items (CVCs and CVC.CVCs) were those of Experiment 1, but the test items differed, enabling the examination of spontaneous generalization of the consonant-position constraints to a novel word structure (from one-syllable CVC items to two-syllable CVC.CVC items). For test, there were two groups of participants. For the *CVC-to-Edge* group, test items contained restricted consonants at word edges and unrestricted consonants word medially (24 legal **C**VC.CV**C**, 24 illegal **C**VC.CV**C** test items). For the *CVC-to-Medial* group, test items contained restricted consonants word-medially, and unrestricted consonants at word edges (24 legal CV**C**.**C**VC, 24 illegal CV**C**.**C**VC test items; see Fig. 4). The Edge- and Medial-restricted test items were composed of the same syllables in reverse order (e.g., a participant in the CVC-to-Edge group would be tested on _**p**iv.ba**f**_ while a participant in the CVC-to-Medial group would be tested on _ba**f**.**p**iv_). None of the syllables in the training or filler items were repeated in the test items.

Stimuli

The training and filler items were the same as in Experiment 1. The two-syllable test items were created using the same 8 consonants and 4 vowels as in Experiment 1 and were recorded intermixed with those of Experiment 1. Across participants, each test item occurred as both a legal and an illegal test item.

Procedure

The procedure was identical to that of Experiment 1. As in Experiment 1, there were a total of 288 trials: the correct response was ‘Yes’ for 182 trials, whereas the correct response was ‘No’ for the remaining 106 trials. Across all trials, 144 presented one-syllable and 144 presented two-syllable items.

Results

As shown in Table 2, participants in both the CVC-to-Edge and the CVC-to-Medial groups were more likely to falsely recognize legal than illegal test items (CVC-to-Edge: .463 vs. .378, and CVC-to-Medial .458 vs. .326), suggesting that they learned the experimental constraints and spontaneously extended them to the new word structure, regardless of word position. Participants in each group also correctly recognized the (repeating) training items more often than they falsely recognized the (unique) legal test items (CVC-to-Edge: .825 vs. .463, and CVC-to-Medial: .804 vs. .458).

As in Experiment 1, responses to the test items were analyzed using linear mixed-effects models (with logistic link) predicting the log odds of a false recognition on each test trial. In Experiment 2, the maximal model included: fixed-effect terms for Legality (sum-coded such that: Legal = 0.5, Illegal = −0.5) and Group (sum-coded such that: CVC-to-Edge = 0.5, CVC-to-Medial = −0.5) and the Legality X Group interaction, random intercepts for Subjects and Items, random slopes by Subject and by Item for Legality, and correlations between random intercepts and random slopes.[3] However, this maximal model gave perfectly correlated random effects for Subjects (but not for Items), thus the reported model (Table 4) included the same random intercepts and slopes, but without the correlations between random-effect terms for Subjects.

A likelihood ratio test comparing the maximal model (without the Subject correlations) to an identical model excluding the fixed effect of Legality (and the Legality X Group interaction) confirmed that the model’s fit was significantly improved by the inclusion of the fixed effect of Legality [$\chi^2(2) = 35.54$, $p < .001$].

Separate likelihood ratio tests for each group (CVC-to-Edge, CVC-to-Medial) comparing the model with and without the fixed effect of Legality (without the Subject

[3] Due to different consonant assignments and positions of the restricted consonants, Group is a between-subjects factor (in Experiments 2 and 3), and is a between-items factor for most items (88% of the items in Experiment 2, 90% in Experiment 3), therefore, the models reported do not include random slopes by Subject and Item for Group.

(a) CVC-to-Edge group:

Familiarization Block	Test Block 1	Test Block 2
24 training items (2x each)	24 (repeating) training items	24 (repeating) training items
CVC (8) ***p**ef*	**C**VC (8) ***p**ef*	**C**VC (8) ***p**ef*
CVC (8) ***p**at*	**C**VC (8) ***p**at*	**C**VC (8) ***p**at*
CV**C** (8) *bu**f***	CV**C** (8) *bu**f***	CV**C** (8) *bu**f***
36 filler items (2x each)	36 (repeating) filler items	36 (repeating) filler items
CVC (12) *tav*	CVC (12) *tav*	CVC (12) *tav*
CVC.CVC (24) *biv.tuk*	CVC.CVC (24) *biv.tuk*	CVC.CVC (24) *biv.tuk*
	12 Legal test items	12 additional Legal test items
	CVC.CV**C** (12) ***p**ut.vi**f***	**C**VC.CV**C** (12) ***p**iv.ba**f***
	12 Illegal test items	12 additional Illegal test items
	CVC.CV**C** (12) ***f**ut.vi**p***	**C**VC.CV**C** (12) ***f**iv.ba**p***

(b) CVC-to-Medial group:

Familiarization Block	Test Block 1	Test Block 2
24 training items (2x each)	24 (repeating) training items	24 (repeating) training items
CVC (8) ***p**ef*	**C**VC (8) ***p**ef*	**C**VC (8) ***p**ef*
CVC (8) ***p**at*	**C**VC (8) ***p**at*	**C**VC (8) ***p**at*
CV**C** (8) *bu**f***	CV**C** (8) *bu**f***	CV**C** (8) *bu**f***
36 filler items (2x each)	36 (repeating) filler items	36 (repeating) filler items
CVC (12) *tav*	CVC (12) *tav*	CVC (12) *tav*
CVC.CVC (24) *biv.tuk*	CVC.CVC (24) *biv.tuk*	CVC.CVC *biv.tuk*
	12 Legal test items	12 additional Legal test items
	CV**C**.**C**VC (12) *vi**f**.**p**ut*	CV**C**.**C**VC *ba**f**.**p**iv*
	12 Illegal test items	12 additional Illegal test items
	CV**C**.**C**VC (12) *vi**p**.**f**ut*	CV**C**.**C**VC *ba**p**.**f**iv*

Fig. 4. Design and example items for Experiment 2, varying word structure from training to test (CVC-to-Edge, CVC-to-Medial). Example items are for a participant (a) in the CVC-to-Edge group or (b) in the CVC-to-Medial group, assigned to /p, z/ as onsets, /d, f/ as codas, and /b, k, t, v/ as unrestricted.

correlations in the CVC-to-Medial group) confirmed that for each group, the model's fit was significantly improved by the inclusion of the fixed effect of Legality [CVC-to-Edge: $\chi^2(1) = 6.94$, $p < .009$; CVC-to-Medial: $\chi^2(1) = 28.53$, $p < .001$].

Discussion

In Experiment 2, adult English speakers spontaneously extended patterns learned in one word structure to items of a different word structure using a syllable-sized unit. Restrictions on syllable onsets and codas were generalized regardless of their position in the word (at the edge or medially; see Fig. 3). Since the two-syllable items (filler, test) had never displayed the experimental constraints, differences in false recognition for legal and illegal test items reflect the extension of the constraints learned from the one-syllable training items. Participants generalized the constraints whether the position of the restriction relative to the word was the same from training to test (from word-edge position in one-syllable items to word-edge position in two-syllable items) or not (from word-edge position in one-syllable items to word-medial position in two-syllable items), suggesting that the syllable may be a privileged unit of generalization. The current results thus suggest that phonotactic constraints can be represented relative to syllable-sized units, where an onset is an onset, and a coda is a coda, regardless of word position.

Table 4
Fixed and random effect estimates for the linear mixed-effects model for Experiment 2, varying word structure from training to test (CVC-to-Edge, CVC-to-Medial). The model includes fixed-effect terms for Legality (sum-coded as: Legal = 0.5, Illegal = −0.5) and Group (sum-coded as: CVC-to-Edge = 0.5, CVC-to-Medial = −0.5) and the Legality *X* Group interaction, random intercepts for Subjects and Items, random slopes by Subject and Item for Legality, and correlations between random intercepts and random slopes for Items (but not for Subjects).

		Variance	Std. dev.	Correlation
Random effects				
Items	(Intercept)	0.26	0.51	
	Legality	0.15	0.39	−0.19
Subjects	(Intercept)	0.89	0.95	
	Legality	0.00	0.00	

No. of observations: 2976 and No. of subjects: 62.

	Coefficient	Std. error	Wald *z*	Pr(>|z|)
Fixed effects				
(Intercept)	−0.46	0.13	−3.43	<.001*
Legality	0.58	0.09	6.41	<.001*
Group	−0.21	0.26	−0.79	.430
Legality X Group	0.32	0.18	1.80	.072

* *p < .05 (on normal distribution).*

However, it is possible that the syllable-based generalization found in Experiment 2 was inadvertently facilitated by exposing participants to one-syllable CVC items (training and filler). For instance, the presence of CVC items might have led participants to treat the two-syllable items as a sequence of one-syllable items (e.g., $CVC_1 + CVC_2$) rather than treating them as unified two-syllable words. To minimize this possibility, Experiment 3 included only two-syllable training, filler, and test items.

Experiment 3

Experiment 3 sought further evidence that participants would spontaneously extend phonotactic constraints from one word position to a different word position, thus treating word-edge and word-medial onsets (and codas) as the same. The items were modified to reduce the likelihood that participants were cued to pay particular attention to CVC units as a result of being exposed to one-syllable CVC items. Participants were trained on the same experimental phonotactic constraints as in Experiments 1 and 2 (e.g., *p* and *z* were syllable onsets, *d* and *f* were syllable codas), but these constraints were now displayed in two-syllable, rather than one-syllable training items (e.g., ***p***_ak.buf_ or _buf._***p***_ak_). In addition, all filler items had two syllables (as opposed to being a mixture of CVCs and CVC.CVCs). As a result, participants heard only two-syllable items during the experiment. Participants in the *Edge-to-Medial* group were trained on Edge-restricted items (e.g., ***p***_ak.bu_***f***) and tested on Medial-restricted items (e.g., _vi_***f.p***_ut_ vs. _vi_***p.f***_ut_). Participants in the *Medial-to-Edge* group were trained on Medial-restricted items (e.g., _bu_***f.p***_ak_) and tested on Edge-restricted items (e.g., ***p***_ut.vi_***f*** vs. ***f***_ut.vi_***p***). If participants spontaneously represent the experimental constraints at the syllable level, they should extend them from one word position to another even within the same word structure, and thus be more likely to falsely recognize legal than illegal test items.

Method

Participants

Sixty-four college-aged adults, all native speakers of English (41 females) participated for course credit or monetary compensation; 32 participants were assigned to each group (Edge-to-Medial, Medial-to-Edge). No participant reported a hearing impairment. None of the participants from Experiments 1 or 2 participated in Experiment 3.

Design and stimuli

All two-syllable items from Experiment 2 were used again in Experiment 3 (filler, Edge-restricted, and Medial-restricted items). In addition, new two-syllable filler, Edge-restricted and Medial-restricted items were recorded in the same manner as before. As in Experiments 1 and 2, for each participant, no syllables were shared between the training, filler, and test items. Critically, restricted consonants never occurred in the same word position across training and test. Therefore, sensitivity to the legality of the test items required generalization to new syllables, items, and word positions. Across participants, Edge-restricted and Medial-restricted items occurred equally

(a) Edge-to-Medial group:

Familiarization Block	Test Block 1	Test Block 2
24 training items (2x each) **C**VC.CV**C** (24) ***p***_ak.bu_***f*** 36 filler items (2x each) CVC.CVC (36) *biv.tuk*	24 (repeating) training items **C**VC.CV**C** (24) ***p***_ak.bu_***f*** 36 (repeating) filler items CVC.CVC (36) *biv.tuk* 12 Legal test items CV**C.C**VC (12) _vi_***f.p***_ut_ 12 Illegal test items CV**C.C**VC (12) _vi_***p.f***_ut_	24 (repeating) training items **C**VC.CV**C** (24) ***p***_ak.bu_***f*** 36 (repeating) filler items CVC.CVC (36) *biv.tuk* 12 additional Legal test items CV**C.C**VC (12) _ba_***f.p***_iv_ 12 additional Illegal test items CV**C.C**VC (12) _ba_***p.f***_iv_

(b) Medial-to-Edge group:

Familiarization Block	Test Block 1	Test Block 2
24 training items (2x each) CV**C.C**VC (24) _bu_***f.p***_ak_ 36 filler items (2x each) CVC.CVC (36) *biv.tuk*	24 (repeating) training items CV**C.C**VC (24) _bu_***f.p***_ak_ 36 (repeating) filler items CVC.CVC (36) *biv.tuk* 12 Legal test items **C**VC.CV**C** (12) ***p***_ut.vi_***f*** 12 Illegal test items **C**VC.CV**C** (12) ***f***_ut.vi_***p***	24 (repeating) training items CV**C.C**VC (24) _bu_***f.p***_ak_ 36 (repeating) filler items CVC.CVC (36) *biv.tuk* 12 additional Legal test items **C**VC.CV**C** (12) ***p***_iv.ba_***f*** 12 addition Illegal test items **C**VC.CV**C** (12) ***f***_iv.ba_***p***

Fig. 5. Design and example items for Experiment 3, varying word position from training to test (Edge-to-Medial, Medial-to-Edge). Example items for a participant (a) in the Edge-to-Medial or (b) in the Medial-to-Edge group, assigned to /p, z/ as onsets, /d, f/ as codas, and /b, k, t, v/ as unrestricted.

often as training and test items, and equally often as legal and illegal test items. Participants were either trained on Edge-restricted and tested on Medial-restricted items (*Edge-to-Medial* group) or were trained on Medial-restricted and tested on Edge-restricted items (*Medial-to-Edge* group; see Fig. 5).

Procedure

The procedure was identical to that of Experiments 1 and 2 except that all 288 trials presented two-syllable items.

Results

As shown in Table 2, participants in both the Edge-to-Medial and the Medial-to-Edge groups were more likely to falsely recognize legal than illegal test items (Edge-to-Medial: .385 vs. .297, and Medial-to-Edge: .396 vs. .268). This pattern suggests that they implicitly learned the experimental phonotactic constraints from the training items, and extended them to the test items, thus spontaneously generalizing phonotactic constraints from word-edge onset and coda positions to word-medial onset and coda positions, or the reverse. As in Experiments 1 and 2, participants in each group also correctly recognized the (repeating) training items more often than they falsely recognized the (unique) legal test items (Edge-to-Medial: .791 vs. .385, and Medial-to-Edge: .758 vs. .396).

In Experiment 3, the maximal model included: fixed-effect terms for Legality (sum-coded such that: Legal = 0.5, Illegal = −0.5) and Group (sum-coded such that: Edge-to-Medial = 0.5, Medial-to-Edge = −0.5) and the Legality X Group interaction, random intercepts for Subjects and Items, random slopes by Subject and by Item for Legality, and correlations between random intercepts and random slopes. Since this maximal model gave perfectly correlated random effects for Subjects and Items, the reported model (see Table 5) included the same random intercepts and slopes, but without the correlations between random-effect terms.

A likelihood ratio test comparing the maximal model (without Subject and Item correlations) to an identical model excluding the fixed effect of Legality (and the Legality X Group interaction) confirmed that the model's fit was significantly improved by the inclusion of the fixed effect of Legality [$\chi^2(2) = 28.53$, $p < .001$].

Separate likelihood ratio tests for each group (Edge-to-Medial, Medial-to-Edge) comparing the model with and without the fixed effect of Legality (without correlations for Subjects and Items in both the Edge-to-Medial and Medial-to-Edge groups) confirmed that within each group, the model's fit was significantly improved by the inclusion of the fixed effect of Legality [Edge-to-Medial: $\chi^2(1) = 8.27$, $p < .005$; Medial-to-Edge: $\chi^2(1) = 19.12$, $p < .001$].

Table 5
Fixed and random effect estimates for the linear mixed-effects model for Experiment 3, varying word position from training to test (Edge-to-Medial, Medial-to-Edge). The model includes fixed-effect terms for Legality (sum-coded as: Legal = 0.5, Illegal = −0.5) and Group (sum-coded as: Edge-to-Medial = 0.5, Medial-to-Edge = −0.5) and the Legality *X* Group interaction, random intercepts for Subjects and Items, random slopes by Subject and Item for Legality (but not the correlations between the random-effect terms).

		Variance	Std. dev.
Random effects			
Items	(Intercept)	0.15	0.39
	Legality	0.00	0.00
Subjects	(Intercept)	0.80	0.89
	Legality	0.07	0.26
No. of observations: 3072 and No. of subjects: 64.			

	Coefficient	Std. error	Wald *z*	Pr(>|z|)
Fixed effects				
(Intercept)	−1.39	0.15	−9.16	<.001*
Legality	0.57	0.09	6.13	<.001*
Group	−0.22	0.30	−0.73	.465
Legality X Group	0.20	0.18	1.12	.262

* $p < .05$ (on normal distribution).

Discussion

In Experiment 3, adult English speakers again demonstrated spontaneous generalization of phonotactic constraints using a syllable-sized unit of representation (see Fig. 3). Phonotactic restrictions learned in word-edge positions were extended to word-medial positions, and vice versa. Since the restricted consonants never occurred in the same word position across training and test, differences in false recognition of legal and illegal test items necessarily reflect the extension of constraints learned in a different word position, and suggest that experimental constraints were represented at the level of the syllable. Moreover, participants generalized across word positions regardless of which position (word-edge, word-medial) was restricted in training, suggesting that restrictions in both positions were roughly equally learnable and extendable under the current circumstances.

General discussion

Naturally-occurring listening and speaking experience leads to the implicit learning of new phonotactic constraints. The unit over which this learning is represented has important implications for the many aspects of language learning and processing that are affected by phonotactic knowledge. The current experiments examined whether the syllable acts as a structural unit for the learning and generalization of new phonotactic constraints. The first experiment demonstrated a simple form of generalization: generalization from one-syllable items to novel one-syllable items. For instance, having learned that *p* is restricted to syllable-onset position from one-syllable items (e.g., ***p**ef*), participants generalized the restriction to novel items of the same word structure (e.g., ***p**av*; Experiment 1: CVC-to-CVC). This result was expected from previous studies but served to confirm that learning and generalization of phonotactic regularities can occur even when most items did not display the constraints, when items were structurally diverse, and that continuous recognition-memory can be used to assess this learning and generalization.

The second experiment provided clear evidence for the role of syllables as structural units within words. Constraints learned from one-syllable training items were spontaneously extended to novel items with a different word structure, whether the constraints were maintained relative to word-edge positions or not. For instance, having learned that *p* is restricted to word-initial onset position from one-syllable items (e.g., ***pef***), participants extended this restriction both to novel items in which the restricted consonant was in the same position relative to a word edge (e.g., *p* is an onset in word-initial position in ***p****ut.vi****f***; Experiment 2: CVC-to-Edge) and to novel items in which the restricted consonant was in a different position relative to a word edge (e.g., *p* is an onset in word-medial position in *vi****f.p****ut*; Experiment 2: CVC-to-Medial). Generalization to different word positions would be expected if the constraints were represented at the level of the syllable, but not if the constraints were represented only at the level of the word.

The third experiment provided further support for the spontaneous extension of newly-learned phonotactic constraints to novel word positions while maintaining word structure, and thus for the role of the syllable as a structural unit in phonotactic learning. For instance, having learned that *p* is restricted to word-edge onset position in two-syllable words (e.g., ***p****ak.bu****f***), participants extended this restriction to different word positions within the same word structure (e.g., *p* is in word-medial onset position in *vi****f.p****ut*; Experiment 3: Edge-to-Medial). Similarly, they spontaneously extended word-medial restrictions (e.g., *bu****f.p****ak*) to word-edge restricted items (e.g., ***p****ut.vi****f***; Experiment 3: Medial-to-Edge). Specifically, as the restricted consonants never occurred in the same word position across training and test, participants must have been generalizing the constraints across word positions, providing evidence for the syllable as a unit of representation.

The current results (extension to novel syllables with the same structure, extension to novel word structures, and extension to novel word positions) suggest phonotactic constraints can be represented at the level of the syllable, where a constraint on syllable-onset (or syllable-coda) position applies to any syllable onset (or coda) regardless of its position within a word. Experimental constraints exhibited by the training items may thus have been encoded as something like '*p* is syllable onset and *f* is syllable coda', thereby easily extending to both novel one-syllable items (e.g., ***p****av*, *vi****f***) and two-syllable items (e.g., ***p****ut.vi****f***, *vi****f.p****ut*) regardless of word position.

If phonotactic constraints were represented solely at the level of the word, where a constraint on a word-initial or word-final position applies to any word-initial or word-final position, extension to new syllables with the same structure, and extension to novel word structures (e.g., ***pef*** to ***p****ut.vi****f***) would be predicted, but extension to new word positions (e.g., edge in ***pef*** to medial in *vi****f.p****ut*, medial in *bu****f.p****ak* to edge in ***p****ut.vi****f***), would not. Learning that *p* is word initial and *f* is word final in ***pef*** would provide no direct information regarding items such as *vi****f.p****ut* in which both *p* and *f* are word medial. Thus, the current results suggest that adults can represent newly-learned phonotactic constraints relative to a syllable-sized unit.

The current results showed no apparent difference with respect to word-edge and word-medial constraints; adults seem able to learn from and generalize to both edge-restricted and medial-restricted items (i.e., in Experiments 2 and 3 neither Group alone nor the Legality by Group interaction reached significance). Thus, while Endress and Mehler (2010) found that phonotactic constraints were easier to learn at word edges than in word-medial positions, the current results show that both word-edge and word-medial phonotactic constraints can be learned and extended across word positions. One critical difference between the present experiments and those of Endress and Mehler (2010) is that the current experiments asked whether constraints learned in word-edge (or word-medial) positions are spontaneously extended to consonants in the same syllable positions even when they were in different word positions (rather than asking whether constraints are learned differentially in different word positions). Evidence for such spontaneous extension provides powerful support for the view that listeners can treat word-edge and word-medial onset (or coda) positions as similar.

In light of previous findings, the current results suggest that multiple levels of representation (e.g., word, syllable) may be available during phonotactic learning, and that the level of representation recruited may depend on the task and the stimuli. Thus, while word-level representations might allow participants to learn word-edge constraints independently of word-medial constraints in some contexts (e.g., Seidl & Buckley, 2005), syllable-level representations may support rapid and spontaneous generalization of constraints to novel word structures and positions (e.g., current experiments). The current results provide further evidence for representations that take syllables into account. For example, even if representations are based on positional allophones, the allophonic variants of individual sounds (e.g., *p*) must be organized such that *word-initial p* (e.g., in ***p****ak.buf*) and *word-medial-yet-syllable-initial p* (e.g., in *vif.****p****ut*) are represented by the same (or categorically related) allophones in order for generalization across word positions to occur. Thus, the current experiments show that syllable-sized units are necessary for the representation of some positional phonotactic constraints, and that patterns can be learned at that level. Further support for the availability of multiple levels of representation is also found in speech production, where syllable-level effects surface under certain conditions (e.g., word production; Cholin, Dell, & Levelt, 2011; Sevald et al., 1995) but not others (e.g., word identification; Cutler et al., 1986).

Although the current experiments support the role of the syllable in phonotactic learning, it must be recognized that the two-syllable items examined here had particularly clear syllable boundaries. As in the word *napkin* /næp.kIn/, the medial consonants in the two-syllable items left no ambiguity about the location of the syllable boundary, and the vowels of the less prominent (second) syllable were not strongly reduced such that the two-syllable words may have been treated as compound words. Thus, it remains to be seen whether the evidence for the role of syllable-sized units in phonotactic learning applies more generally in English, and in other languages, and whether it is found in other phonotactic learning measures such as production accuracy or repetition latency. Moreover, since orthographic knowledge has been shown to affect phonological processing (e.g., Castles, Holmes, Neath, & Kinoshita, 2003) and since syllabification based on orthography and production sometimes disagree (e.g., orthographic regularities suggest that *gentle* should be syllabified as *gent.le* even though it is actually pronounced as *gen.tle*; Taft, 1979), more research is needed regarding the role of orthography in the syllable-level representation of phonotactic knowledge.

To summarize, the current experiments demonstrate that phonotactic learning *can* occur at the level of the syllable; this is not to imply that learning cannot also occur at the level of the word, but merely that word-level representations (if they exist) are not sufficient. Nonetheless, given the materials and methods of these experiments, the current results provide additional support for the view that English speakers employ syllable-sized units in speech processing. At least in phonotactic learning, an onset is an onset, and a coda is a coda, regardless of word structure or position. The perceived equivalence of onsets and codas across word structures and positions reveals the abstract and flexible nature of phonological representations. Thus, our perception that a sequence such as *plok* is a plausible English word would seem to result, at least in part, from our cumulative experience with *pl* in syllable-onset position, in similar words (e.g., *plum*) and very different ones (e.g., *complain*). Such abstract phonological representations allow phonotactic knowledge to facilitate speech processing broadly, guiding word identification, word segmentation, and word learning in contexts beyond those in which the constraints were initially experienced.

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