Published in final edited form as:

J Mem Lang. 2017 October ; 96: 138–154. doi:10.1016/j.jml.2017.05.006.

Novel phonotactic learning: Tracking syllable-position and co-occurrence constraints

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Abstract

Are syllable-level and co-occurrence representations simultaneously available when one learns novel phonotactics? After training on word-medial consonant restrictions (e.g., word-medial onsets P/Z, codas D/F, and cross-syllable consonant clusters FP/DZ in items like baF.Pev, tiD.Zek), adults falsely recognized novel items containing restricted consonants with the same co-occurrences (e.g., FP) more often than those with different co-occurrences (e.g., FZ) when syllable-position information was kept constant (e.g., vuF.Pet vs. vuF.Zet; Experiment 1). Thus, adults tracked co-occurrence information. Additionally, even when co-occurrence information was different from training, participants more often falsely recognized novel items that contained restricted consonants in the same (e.g., onset-Z) rather than different syllable positions (e.g., coda-Z), whether the restricted consonants were in the same (word-medial, e.g., vuF.Zet vs. vuZ.Fet, Experiment 2) or different word positions (word-edge, e.g., Zut.veF vs. Fut.veZ, Experiment 3). Thus, adults also tracked syllable-level information. These findings show that adults spontaneously represent sound sequences at multiple levels.

Keywords

Adult language acquisition; Phonotactic learning; Statistical learning; Syllable position; Local co-occurrences; False recognition

For an English speaker, *dap* seems like a better potential word than *dah* (with a fully pronounced ‘h’ at the end); yet, *dah* is a possible word in Persian (meaning ‘ten’). What makes English speakers, but not Persian speakers, reject *dah* as a potential word is the fact that it violates how sounds can be arranged (phonotactics) in English, but not in Persian. Knowledge of phonotactic constraints affects speech processing: facilitating speech segmentation (e.g., Mattys & Jusczyk, 2001; Mattys, Jusczyk, Luce, & Morgan, 1999), speech repetition (Munson, 2001; Vitevitch & Luce, 2005), and novel word learning (e.g., Graf Estes, Edwards, & Saffran, 2011; MacKenzie, Curtin, & Graham, 2012; Storkel, 2001; Vitevitch, Armbrüster, & Chu, 2004). Sensitivity to phonotactic constraints is exhibited early

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(e.g., Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993; Jusczyk, Luce, & Charles-Luce, 1994; Zamuner & Kharlamov, 2016 for recent review) and remains flexible, allowing, in some cases, adult second-language learners to be nearly as sensitive to the phonotactics of their second language as to those of their first language, and nearly as sensitive as native speakers of that language (Weber & Cutler, 2006). Moreover, adults quickly learn novel phonotactic constraints such as P-starts and F-ends words from brief auditory (e.g., Bernard, 2015; Chambers, Onishi, & Fisher, 2010; Onishi, Chambers, & Fisher, 2002) or production experience (e.g., Dell, Reed, Adams, & Meyer, 2000; Goldrick, 2004; Goldrick & Larson, 2008; Kittredge & Dell, 2011; Warker & Dell, 2006, 2015; Warker, Dell, Whalen, & Gereg, 2008; Warker, Xu, Dell, & Fisher, 2009), enabling them to respond differentially to novel words like *paf* and *fap* that either follow or violate these constraints, as demonstrated by their rates of false recognition, repetition latencies, or production accuracies.

The fact that phonotactic knowledge leads to enhanced speech processing enables us to use phonotactic learning and generalization as a means to better understand how humans represent speech sounds and sound sequences. Evidence about how phonotactics are represented is mixed and somewhat ambiguous, in part because phonotactic learning has been studied from within different subdomains of speech processing, and thus has been described with variable terminology (for a similar discussion see Rapp, Buchwald, & Goldrick, 2014), and in part because relevant factors have often not been controlled. For example, some studies have shown a processing advantage for items with high, rather than low, phonotactic probability (e.g., Jusczyk et al., 1994; Vitevitch & Luce, 2005; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997), with phonotactic probability commonly operationalized as a combination of syllable position and a type of local co-occurrence information, making it impossible to know which information source participants used. In one study, English-learning infants preferred items like *riss* to items like *yowdge*, where *riss* contains both (1) sounds that occur frequently in their respective positions in English (i.e., in consonant-vowel-consonant words, R is frequently the onset or syllable start, I is frequently the vowel, and S is frequently the coda or syllable end) and (2) biphones that are frequent in English words (i.e., R followed by I, and I followed by S are combinations of sounds that often occur within English words), and *yowdge* contains both (1) sounds that occur rarely in their respective positions and (2) biphones that are rare (Jusczyk et al., 1994). However, since syllable-position and co-occurrence information were conflated in these studies, it remains unclear whether participants represented phonotactics at the level of the syllable, at the level of co-occurrences, or both. These studies are thus uninformative with regard to whether English speakers prefer *dap* over *dah*, because they have represented the fact that, in English, P is a better coda than H, or the fact that, in English, A and P form a better combination of sounds than A and H.

Since syllable-position and co-occurrences have often been conflated, one can ask whether people are sensitive to *syllable-position constraints* alone (when co-occurrence information is held constant; e.g., H can be an onset, but cannot be a coda in English). This idea is similar to what has been called *positional segment frequency* (e.g., Jusczyk et al., 1994; Vitevitch et al., 1997), *language-wide constraints* (for restrictions present in the native language), *experiment-wide constraints* (for restrictions present in an artificial language;

e.g., Dell et al., 2000; Warker & Dell, 2006, 2015), or *consonant-position constraints* (e.g., Chambers, Onishi, & Fisher, 2003; 2010; 2011; Onishi et al., 2002) in that representing syllable-position constraints involves tracking the position in which segments occur relative to a syllable-sized unit.

Similarly, one can ask whether people are sensitive to *local co-occurrence constraints* alone (when syllable-position information is held constant; e.g., A and P co-occur more often than A and H). The concept of local co-occurrence is akin, but not identical, to the concept of *biphones/diphones* (e.g., Gathercole, Frankish, Pickering, & Peaker, 1999; Majerus, Poncelet, Van der Linden, & Weekes, 2008; Munson, 2001; Richtsmeier, Gerken, Goffman, & Hogan, 2009a; Richtsmeier, Gerken, & Ohala, 2009b, 2011; Vitevitch et al., 1997; Weber & Cutler, 2006) in that it involves tracking sounds that are adjacent to one another. Unlike biphones/diphones, however, local co-occurrences could, in theory, be represented without linear information (i.e., AP and PA are, at some level, equivalent in that both are combinations of adjacent A and P) while biphone/diphone frequency calculations have tended to encode linear order (e.g., AP would have a different biphone frequency than PA). Thus, in some sense, biphones/diphones could be considered types of co-occurrences, that is, co-occurrences with order information. The concept of local co-occurrence is also related to the concept of *transitional probability* (e.g., Aslin, Saffran, & Newport, 1998; Pelucchi, Hay, & Saffran, 2009a; 2009b; Saffran, Aslin, & Newport, 1996) as it involves tracking the occurrence of adjacent units. However, in the case of local co-occurrences (as investigated here), the unit of interest is the phoneme, while in work on transitional probabilities, the unit of interest tends to be larger (i.e., the syllable).

Linguistic theories of phonological encoding are split with regard to the role of the syllable (see also Goldrick, 2004 for similar ideas); while some linguistic theories argue that phonotactic constraints are represented with reference to the syllable, which is decomposable into onset, nucleus, and coda constituents (e.g., Blevins, 1995), others argue that syllables are actually not sufficient and/or necessary for phonotactic encoding (e.g., Hirsch, 2014; Steriade, 1999). Nevertheless, previous psycholinguistic data hint at the ability to represent phonotactics at the level of the syllable. Adults appear to be sensitive to sound constraints at the level of the syllable in artificial-language learning experiments in which particular consonants were restricted to the beginning or the end of one-syllable consonant-vowel-consonant words (e.g., Chambers et al., 2003; Goldrick, 2004; Goldrick & Larson, 2008; Kittredge & Dell, 2011; Onishi et al., 2002; Warker & Dell, 2006, 2015; Warker et al., 2009). English speakers, for example, were more likely to accidentally produce *meNG* (where the critical sound, NG, is capitalized and represents a single consonant, /ŋ/) than *meH* (where the critical sound, H, is capitalized and represents a fully produced /h/) when attempting to say *mek*, showing sensitivity to the syllable-position constraints of English (e.g., in English, the sound NG (as in *siNG*) but not H (as in *Horse*) occurs at the end of syllables; called ‘language-wide constraints’ in Dell et al., 2000). Furthermore, after only brief training on one-syllable words that started with S and ended with F, participants were more likely to accidentally produce *keF* than *keS*, thus showing a sensitivity to experimentally established syllable-position constraints (e.g., the sound F, but not S, occurs at the end of syllables; called ‘experiment-wide constraints’ in Dell et al., 2000). Moreover,

participants' sensitivity to experimentally established constraints was comparable to their sensitivity to the native-language constraints (Dell et al., 2000). Thus, adults were able to learn novel phonotactics that could have been represented at the syllable level (e.g., F is coda). Results were similar even when local co-occurrence information differed between training and test. Specifically, after training on words like *saF* and *paF*, adults were faster to repeat (and infants preferred to listen to) words like *peF* than *Fep* even though local co-occurrence information was novel (F co-occurring with E rather than with A) in all test items (Chambers et al., 2010, 2011), suggesting that phonotactics may be represented at the syllable level and abstracted away from the co-occurrences in which they were learned.

However, because determining the role of the syllable in phonotactic learning was not the goal of their research, neither Dell et al. (2000) nor Chambers et al. (2010, 2011), manipulated syllable-position directly. Because they trained and tested participants on a single 1-syllable word structure (CVC), it was not necessary for participants to represent the constraints at the level of the syllable to successfully learn the regularities: representational levels other than position within the syllable (e.g., relative to linear ordering or relative to word edges/silences) could have accounted for adults' success in learning the regularities. In CVCs, all codas are also in the third linear position, in the final slot of the word, followed by a silence, etc. Thus, the constraints on F from *saF* and *paF* in training could have been represented at the syllable-position level ('F is a syllable coda'), enhancing processing for *peF* but not *Fep*. But the same regularity could also, however, have been represented (and extended to *peF* but not *Fep*) relative to the linear ordering ('F comes third'), relative to silence ('F is before a silence'), or relative to the word edge ('F ends words'). Thus, while the above-mentioned results suggest that phonotactic constraints can be represented at the level of the syllable, they are not definitive. Work using different syllable or different word structures is needed to directly investigate whether syllable-level representations are spontaneously accessed during learning of novel phonotactic patterns.

Although there are fewer studies of artificial-language learning using stimuli other than CVCs, the ones that are available tend to be consistent with the idea of syllable-level representations. For instance, Bernard (2015) found support for syllable-level learning while directly manipulating syllable position by varying word structure and word position between training and test words. For example, participants trained on items like *buF.Pak* (where the period indicates the syllable boundary and capital letters indicate restricted consonants) distinguished between test items such as *Pit.vuF* (with F and P in the same syllable positions as in the training items) and *Fit.vuP* (with F and P in different syllable positions). Bernard (2015) did not, however, manipulate co-occurrences: the unordered consonant-vowel and consonant-consonant co-occurrences were the same across training and test. Thus, while it is possible that adults represented syllable-position constraints beyond the particular co-occurring contexts in which the constraints were experienced (e.g., from *buF.Pak* in training to 'F is coda' regardless of the sounds that occurs adjacent to the F)—allowing them to process F-onset and F-coda items differently (e.g., *Pit.vuF* vs. *Fit.vuP* in test)—it is also possible that the presence of familiar co-occurrences (e.g., F with U) assisted their learning and their generalization to novel word positions (e.g., 'F is coda when it is adjacent to U'). It thus remains unclear whether syllable-position regularities can be represented in the absence of familiar co-occurrences. Using two-syllable words, Endress and Mehler (2010) also found

learning consistent with syllable-position representations. They found learning of regularities in word edges (e.g., from *Kal.riS* in training to *Kir.laS* but not *Sir.laK* in test) and, under some conditions, in word-medial positions (e.g., from *riS.Kal* in training to *laS.Kir* but not *laK.Sir* in test). Endress and Mehler (2010) did not, however, control for co-occurrence information; as a result the test items differed in both syllable-position information and consonant-vowel co-occurrences. Thus, while adults' differentiation of the test items might have reflected knowledge of syllable-position regularities, it remains unclear whether syllable-position regularities can be generalized when co-occurrence information is held constant. In summary, there is suggestive evidence that adults may track and thus represent syllable-level phonotactic constraints, but to date no research provides unambiguous evidence for syllable-position tracking when co-occurrence information is not available.

Independently, there is also suggestive evidence that children and adults might be sensitive to co-occurrence regularities (e.g., Chambers et al., 2011; Dell et al., 2000; Gathercole et al., 1999; Munson, 2001; Onishi et al., 2002; Richtsmeier et al., 2009a, 2009b, 2011; Warker & Dell, 2006; Warker et al., 2008). For instance, across different experiments, Richtsmeier and colleagues familiarized children with novel animals and their 'names'. The animals' 'names' were two-syllable nonwords containing particular consonant pairs word-medially; these consonant pairs were either high or low frequency word-medially in English, and either high or low frequency word-medially within the experiment). In test, the authors asked children to listen to and repeat items with the same consonant pairs (either the same nonwords, Richtsmeier et al., 2009a; or different nonwords, Richtsmeier et al., 2009b, 2011). Across experiments they found that English-speaking children were generally more accurate at producing words that contained consonant pairs (ordered co-occurrences) that were frequent rather than infrequent word-medially in English (e.g., KT in *boKTem* vs. PK in *boPKem*; Richtsmeier et al., 2009b), showing sensitivity to the co-occurrence frequencies of English. As the authors did not control for natural-language syllable-position information of the consonants within these consonant-consonant co-occurrences, it is however possible that participants were sensitive to syllable-position frequencies (e.g., K-coda might be more frequent than P-coda and/or T-onset more frequent than K-onset) rather than to the co-occurrence frequencies (e.g., KT is more frequent than PK).

Richtsmeier and colleagues (2009a, 2009b, 2011) also found inconsistent but suggestive evidence that children were more accurate at producing words containing co-occurrences that were manipulated to occur frequently, rather than infrequently, during the experiment. Thus, under specific circumstances, children could become more accurate at repeating words with co-occurrences like PK in *biPKem* than word with co-occurrences like FP in *maFPem*, although the frequencies in English for both PK and PF are low (Richtsmeier et al., 2011). In particular, the effect was apparent only for co-occurrences with low (rather than high) English frequencies, and seemed to require familiarization with a ratio of at least 3:1 between words instantiating the frequent and infrequent co-occurrences, and/or instantiations of these words by multiple talkers. The specificity of circumstances under which co-occurrence learning was detected when syllable-information was controlled suggests that the learning of consonant co-occurrences, while possible in the absence of syllable-position information, may be particularly difficult.

Additionally, suggestive evidence for the tracking of co-occurrence information can be found in studies assessing learning of second-order phonotactic constraints (e.g., F-coda with A but F-onset with I from items such as *sAF* and *Flp*; Chambers et al., 2011; Dell et al., 2000; Onishi et al., 2002; Warker & Dell, 2006; Warker et al., 2008). Learning in these studies required tracking of co-occurrences; however, co-occurrence information was never available independently of syllable-position information. Thus, participants may have tracked either the local co-occurrences (e.g., A and F) in conjunction with syllable-position (e.g., F is coda), or tracked ordered co-occurrences (e.g., A-before-F) to demonstrate learning (e.g., to differentiate *FAn* vs. *gAF*). Thus, while results from studies on learning of second-order phonotactic patterns are consistent with participants being able to track syllable-position and co-occurrence information jointly, direct evidence on whether co-occurrence can be encoded beyond syllable-position information is lacking. In summary, since most studies providing evidence for co-occurrence representations did not control for syllable-position information, and since the studies that controlled for syllable-position information did not find strong evidence for co-occurrence learning, it remains unclear whether co-occurrences can be learned when syllable-position information is not available to differentiate items in test.

One study, however, did attempt to independently assess sensitivity to syllable-position and co-occurrence frequencies (in children) for patterns found in their native language (Coady & Aslin, 2004). English-speaking children repeated novel nonwords made of English consonants and vowels. In one experiment, using two- and three-syllable words, the researchers compared words in which the onsets were either frequent or infrequent syllable-onsets in English, and found that children were more accurate at repeating words with higher syllable-onset frequency. In another experiment, using again two- and three-syllable words, they tested 2.5- and 3.5-year-olds and compared words for which the average biphone frequency (the frequency with which ordered pairs of adjacent sounds occurred) in English was either high vs. low. They found that 3.5-year-olds (but not 2.5-year-olds) were more accurate at repeating 3-syllable (but not 2-syllable) words with higher biphone frequency. These results are the most suggestive evidence for sensitivity to both syllable-position and (in some situations) to co-occurrence information. It must be noted, however, that because the stimuli exploited natural phonotactic regularities, it was not possible to (1) fully control co-occurrences when syllable-position learning was assessed, or (2) fully control syllable-position information when co-occurrence learning was assessed. The effect of syllable-position and co-occurrences thus potentially remained confounded. Considering previous work, it thus remains unclear whether either co-occurrence or syllable-position constraints can be learned independently of the other—in other words, whether co-occurrences can be tracked when syllable-position information is held constant, and whether syllable-positions can be tracked when co-occurrence information is held constant.

To summarize, we know that phonotactic knowledge affects language processing (e.g., Graf Estes et al., 2011; MacKenzie et al., 2012; Mattys & Jusczyk, 2001; Mattys et al., 1999; Munson, 2001; Storkel, 2001; Vitevitch et al., 2004; Vitevitch & Luce, 2005) and that phonotactic constraints are learned early (e.g., Jusczyk et al., 1993; Jusczyk et al., 1994) and rapidly (e.g., Dell et al., 2000). Some studies (mostly examining artificial-language learning) have suggested that people can track syllable-position constraints (e.g., Bernard, 2015;

Chambers et al., 2003; 2010; 2011; Dell et al., 2000; Goldrick, 2004; Goldrick & Larson, 2008; Kittredge & Dell, 2011; Onishi et al., 2002; Warker & Dell, 2006; Warker et al., 2008; Warker et al., 2009) while typically not controlling for segment co-occurrence information. Other studies (mostly examining knowledge of native-language phonotactics) have suggested that people can track co-occurrence constraints (e.g., Gathercole et al., 1999; Mattys et al., 1999; Munson, 2001; Richtsmeier et al., 2009a, 2009b, 2011) while typically not controlling for syllable position information. Since no study has manipulated these factors completely independently, it remains an open question as to whether the learning of sound constraints occurs at the level of the syllable, at the level of segment co-occurrence, or both.

To assess whether phonotactics can be represented at the level of the syllable and/or at the level of local co-occurrences alone, the current experiments build on recent work that suggests that adults can learn and represent sound constraints at the syllable-position level (Bernard, 2015). In the previous work, participants heard a series of words from an artificial language, and their task was to indicate, for each word, whether they had heard it earlier in the experiment (i.e., whether it was repeated) or not (i.e., whether it was novel). First, participants heard training items that instantiated particular syllable-position restrictions (e.g., P-onset and F-coda in items like *buF.Pak*, where the period indicates the syllable boundary and capital letters indicate restricted consonants). Partway through the experiment, intermixed with additional repetitions of the training items, novel test items were introduced unbeknownst to the participants. Participants' false recognition of the novel items was then compared for test items that maintained vs. violated the syllable-position restrictions instantiated by the training items. Participants falsely recognized novel test items more often when the items had restricted consonants in the same, rather than in different, syllable positions relative to the training items. Specifically, false recognition rates were higher for items with the same, rather than different, syllable-position restrictions whether test items had the same number of syllables (e.g., from *PaF* in training to *Pit.vuF* but not *Fit.vuP* in test), and whether the restricted consonants were in the same positions in the word (e.g., from *buF.Pak* in training to *Pit.vuF* but not *Fit.vuP* in test). Since participants falsely recognized novel items more often when the items had consonants in the same, rather than different, syllable positions regardless of the similarity in word structure or word position, the results suggested spontaneous generalization of syllable-position constraints. However, since the training items included all combinations of the restricted onsets and codas (and all combinations of restricted consonants and vowels), it remains unclear whether participants also tracked co-occurrence information and whether they would be able to generalize the syllable-position constraints to items with novel co-occurrences (e.g., if they learned an F-coda constraint from items like *buF.Pak*, would they generalize it to *biF.Zek* even though F was never heard co-occurring with Z?).

The current experiments tested whether syllable-position constraints on consonants are tracked in an environment in which co-occurrence constraints, in addition to consonant-position constraints, are present. Thus, in addition to consonants occurring in restricted syllable positions (as in Bernard, 2015)—thereby allowing for assessment of syllable-position tracking, consonants also occurred in restricted co-occurrences (by permitting only a subset of the possible medial consonant co-occurrences)—thereby allowing for assessment of co-

occurrence tracking. For example, for one participant, coda-P co-occurred only with onset-F, while coda-D co-occurred only with onset-Z. Although adults represented phonotactics at the syllable level in an environment that exhibited only syllable-position restrictions (Bernard, 2015), they may not spontaneously do so when co-occurrence restrictions are also available. Specifically, syllable-level regularities may not be as readily available when co-occurrence regularities are also available in the same word position, drawing attention away from syllable-level patterns.

Three experiments asked whether, from the same input, participants would track phonotactic regularities (1) at the co-occurrence level (Experiment 1), and (2) at the syllable-position level (Experiments 2 and 3). To better understand how phonotactic constraints are represented, participants in each experiment were trained with the same artificial languages (in which consonants followed both syllable-position and co-occurrence restrictions), and were tested on how they treated novel test items that had either the same or different restrictions at one level or the other (while the other level was held constant across the different types of test items).

Experiment 1

Experiment 1 asked whether adults can track co-occurrence restrictions and generalize them to novel items when syllable-position information is held constant—more specifically, whether adults would differentiate between test items in which the consonant co-occurrences are the same vs. different from those in the training items, when the restricted consonants in all test items maintain the syllable-position information of the training items. Artificial languages, in which words were composed of two consonant-vowel-consonant syllables, were created such that both syllable-position and co-occurrence information could be manipulated independently in word-medial position (i.e., cvC.Cvc, where the period indicates the syllable boundary and capital letters indicate restricted consonants). Thus, the key manipulations involved restricting certain consonants (the restricted consonants) to occur in specific syllable positions in word-medial position (as in Bernard, 2015), as well as restricting the combinations of these consonants to co-occur word medially.

Thus, from the Training items (e.g., *ba**FP**ev* and *ti**DZ**ek*), participants were given the opportunity to track (1) syllable-position restrictions (e.g., P and Z as syllable onsets, shown in **bold**, and D and F as syllable codas, not bold), (2) co-occurrence restrictions that cross syllable boundaries (e.g., F and P co-occurring in an FP cluster, shown underlined, and D and Z co-occurring in a DZ cluster, not underlined), or both. Participants were tested with two types of test items: Same-cluster (e.g., *vu**FP**et*, *te**DZ**ev*) and Different-cluster (e.g., *vu**FZ**et*, *te**D**Pev*) which differed in whether the word-medial co-occurrences were the same (e.g., FP/DZ clusters) or different (e.g., FZ/DP clusters) from the training items. Note that both types of test items were equivalent with respect to syllable-level information: both had restricted consonants in the same syllable positions as in the training items (e.g., P and Z as onsets with D and F as codas). Thus, if participants track co-occurrence constraints across syllable boundaries from the training items, they should differentiate between the two types of test items. If, instead, they only represent the constraints at the syllable level (i.e., as

syllable-position constraints), they may not distinguish between the two types of test items, since for both types, the syllable-position information was the same as in the training items.

Method

Participants—16 college-aged adults (10 females), all native speakers of English, participated for course extra-credit or small remuneration. No participant reported any hearing impairment.

Design—For each participant, four consonants (P/Z/D/F) were restricted to specific syllable positions word-medially, and four other consonants (B/K/T/V) were unrestricted and could occur in both onset and coda positions, both word-medially and at word edges. There were four consonant-to-role assignments created by crossing syllable-position restrictions with co-occurrence restrictions, as shown in Table 1 (along with example items). Thus, a consonant-to-role assignment had items displaying one of two syllable-position restrictions (1: *oPZ/cDF*, onset Ps and Zs with coda Ds and Fs; or 2: *oDF/cPZ*, onset Ds and Fs with coda Ps and Zs) and one of two co-occurrence restrictions (1: *FP/DZ*, F and P as well as D and Z co-occurring; or 2: *FZ/DP*, F and Z as well as D and P co-occurring).

Critically, for each participant, consonants that were restricted to onset and coda positions only occurred word medially, and in their restricted clusters. The four consonant-to-role assignments ensured that, across participants, each restricted consonant was restricted equally often to onset and coda position and that each onset was restricted equally often to co-occur with each coda. Since each consonant was assigned equally often as an onset and as a coda, and to co-occur with each other coda and onset, any native-language bias that would facilitate learning for participants in one consonant-to-role assignment (e.g., P-onset) would hinder participants with the opposite assignment (e.g., P-coda), thus controlling for native-language biases.

Each consonant-to-role assignment was instantiated by 4 conditions, for a total of 16 conditions to which participants could be assigned, which ensured that across all participants, each test item served as a Same and a Different test item equally often (see Appendix A for details about design and Appendix B for a list of all stimuli used). Each condition had 48 *Training* items¹ that instantiated the syllable-position and co-occurrence restrictions (e.g., *baFPe_v*, *tiDZe_k*), as well as 24 *Filler* items which contained only unrestricted consonants (e.g., *bat.ke_v*, *vub.te_k*). All 72 training and filler items were repeated twice in a random order in the Familiarization phase.

Each condition also had 48 test items, 24 of each type (Same, Different). *Same-cluster* test items had the same co-occurrence restrictions (clusters) as in the training items (e.g., *vuFPe_t*, *teDZe_v*), while *Different-cluster* test items had different co-occurrence restrictions from the training items (e.g., *vuFZe_t*, *teDPe_v*). Different-cluster test items were created by

¹Although all conditions, in this and the following experiments, were designed to have 48 restricted items as Training items, and 24 of each Same- and Different-test items, potentially vulgar words (e.g., words containing syllables with both F-onset and K-coda) were replaced by unused filler items. These replacement items were included when running the experiment (to maintain the total number of trials in each condition) but were not included in the analyses as they neither instantiated nor violated the restrictions established by the training items (see Appendix B for additional details).

crossing the clusters from the training items (FP and DZ became FZ and DP); thus, while Same and Different test items differed on whether the restricted consonants were in the same or different co-occurrences (relative to the training items), the syllable-position information in both was equivalent (e.g., even in the new FZ cluster, F was still a coda and Z was still an onset, as they had been in the training items). See Figure 1 for a schematic depiction of the design with example items. In the Test phase, half of the Same and half of the Different test items were intermixed with a third repetition of the Training and Filler items. The remaining test items were intermixed with a fourth repetition of the Training and Filler items.

Stimuli—Eight consonants (/b, d, f, k, p, t, v, z/) and 5 vowels (/ɪ/ as in *pɪt*, /ʌ/ as in *putt*, /e/ as in *pɛt*, /æ/ as in *pæt*, /ə/ as in *blanket*) were used to create the words of the artificial languages. Consonants were chosen to be legal onsets and codas in English and to be perceived as separated by a syllable boundary in consonant-consonant word-medial position. The first syllable always contained a lax vowel (/ɪ, ʌ, e, æ/) while the second syllable always contained a schwa (/ə/). Each two-syllable word was pronounced with a strong/weak stress pattern (as in *DOC.tor*, where capitalization represents stress). Words were recorded in a randomized order, intermixing filler and restricted items with different consonant-to-role assignments. A female native English speaker from the Chicago area, unaware of the experimental questions and design, produced multiple tokens of each word. Words were transcribed by two naive listeners, unaware of the experimental questions and design. For each word, a single token that had been transcribed as containing the intended consonants and vowels by at least 2 listeners, and that had the best-sounding strong-weak stress pattern, was selected (in cases where the two listeners did not agree, a third naive listener transcribed the word). In cases where no token was found, words were rerecorded and the process was repeated. In the few cases where, after several iterations of the process, no token was agreed upon, some disagreement on vowels (but not consonants) was tolerated.

Procedure—The experiment was run using E-prime software (Schneider, Eschmann, & Zuccolotto, 2002). Participants were tested individually with stimuli presented at a comfortable listening level over headphones. 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 words and, for each, indicated whether they had (or had not) heard it earlier in the experiment (“Have you heard it before?”) by pressing one of two buttons labeled ‘Yes’ and ‘No’ on a response box or keyboard. The session began with two filler-item practice trials then proceeded to the main experiment.

In the Familiarization phase, participants heard two repetitions of each Training and Filler item presented in a random order. Thus, for half the familiarization trials, from the start of the experiment, the correct response was NO (i.e., the first presentation of each Training and Filler item), and for the other half, the correct response was YES (i.e., the second presentation of each Training and Filler item).

In the Test phase (which, from the point of view of participants, was continuous with the Familiarization phase), participants heard two additional repetitions of Training and Filler

items intermixed with the novel Same-cluster and Different-cluster test items. Thus, in the Test phase, the correct response was YES for each Training and Filler item and NO for each Same and Different test item. However, if participants tracked the co-occurrence restrictions from the training items, they might falsely recognize Same-cluster test items more often than Different-cluster test items (even though both have the same syllable-position information as in the training items), because only the Same-cluster items have restricted consonants co-occurring in the same clusters as in the (repeating) training items.

Results

Mean proportions of Yes-recognition responses across participants as a function of Item Type (Training, Filler, Same Test, Different Test) for the Test phase are shown in Table 2. Perfect accuracy would be a Yes-recognition rate of 1.000 for repeating items (i.e., Training and Filler items) since they had already been presented at least twice before (in the Familiarization phase), and of 0.000 for novel test items (i.e., Same and Different test items) since they were presented only once during the entire experiment.

Participants differentiated repeating from novel items, as demonstrated by higher Yes-recognition rates for Training and Filler (.831) than for Same and Different test items (.654). Participants also differentiated items that had the restricted consonants in the same, rather than in different, co-occurrence combinations (see Table 2), as demonstrated by higher rates of false recognition for Same (.700) than Different (.608) test items, suggesting sensitivity to the experimental co-occurrence restrictions instantiated by the training items. Plotted differences in false recognition rates between Same and Different test items for individual participants are shown in Figure 2.

Because the data were categorical and binary, responses to the test items were analyzed using linear mixed-effects models (with logistic link), predicting the log-odds of a false recognition response 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 1.1–7 (Bates, Mächler, Bolker, & Walker, 2014) of the statistical software platform R (R Core Team, 2015) and RStudio (RStudio Team, 2015). Linear mixed-effects models were fit using the Laplace approximation and the `bobyqa` optimizer. Predictor variables were rescaled using the `rescale` function of the `arm` package (Gelman & Su, 2015).

To assess differentiation of the test items that contained the same vs. different co-occurrence restrictions, the model for Experiment 1 (see Table 3) included rescaled fixed-effect terms for Test-type (Same, Different), Training Syllable restrictions (1: oPZ/cDF, 2: oDF/cPZ) and Training Cluster restrictions (1: FP/DZ, 2: FZ/DP), random intercepts for Subjects and Items, and random slopes by Subject for Test-type but not the correlations between random-effect terms².

²For this and the following Experiments, because the model with correlations between random-effect terms gave perfectly correlated random effects, the reported models included the random intercepts and slopes, but not the correlations between intercepts and slopes (as suggested in Barr, Levy, Scheepers, & Tily, 2013). Critically, in all cases, the estimate terms (and standard errors) were highly similar (within 0.07 for the fixed-effect estimates, and 0.04 for the standard errors) for the models including and excluding the correlations.

Hypothesis testing for the effect of Test-type on the likelihood of a false recognition was performed using a 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 Test-type. The model's fit was significantly improved by the inclusion of the fixed effect of Test-type [$\chi^2(4) = 15.46, p < .004$]³, suggesting that participants tracked the co-occurrence restrictions from the training items, allowing them to differentiate between the Same and Different test items.

Discussion

Adult English speakers learned novel co-occurrence restrictions that crossed a word-medial syllable boundary, and learned them in an environment in which the regularities could have been represented as syllable-position restrictions, as local co-occurrence restrictions, or both. As shown by the different rates of false recognition for the Same-cluster and Different-cluster test items, participants generalized these co-occurrence restrictions to new items that had equivalent syllable-position information, allowing them to differentiate test items that had clusters that were the same vs. different relative to the training items. Thus, phonotactic constraints can be represented in terms of segment co-occurrences even when learned in an environment in which constraints could be represented in at least two ways (at the syllable and/or co-occurrence levels) and even when syllable-position information is held constant.

Experiment 2

Experiment 2 asked whether adults can track syllable-position restrictions and generalize them even when co-occurrence information is not maintained—more specifically, whether adults would differentiate between test items in which the restricted consonants are in the same vs. different syllable positions relative to the training items, when the restricted consonants in all test items violate the co-occurrence restrictions of the training items. Again, participants heard two-syllable items (cvC.Cvc) in which medial coda-restricted and onset-restricted consonants were further restricted to co-occur.

From the Training items (e.g., *baFPev*, *tiDZek*), which were the same as those in Experiment 1, participants were given the opportunity to track (1) syllable-position restrictions (e.g., P and Z as onsets with D and F as codas), (2) co-occurrence restrictions (e.g., FP as well as DZ clusters), or both. Participants were tested with two new types of test items: Same-syllable-position (e.g., *vuFZet*, *teDPev*) and Different-syllable-position (e.g., *vuZ.Fet*, *teP.Dev*) which differed in whether the restricted consonants were in the same (e.g., onset-PZ/coda-DF) or different (e.g., onset-DF/coda-PZ) syllable position relative to the training items. Note that both types of test items were equivalent with respect to co-occurrence information (neither maintained the co-occurrences from the training items). Thus, if, from the training items, participants track syllable-position restrictions (even in an environment in which adults are known to track co-occurrence restrictions), and track them

³The maximal model also suggested a significant interaction of Test-type and Training syllable restriction, which seemed to be driven by the fact that participants trained with one syllable-position restriction (1: oPZ/cDF) had a smaller Same/Different difference than participants trained on the other (2: oDF/cPZ). Both groups of participants showed the effect in the same direction; thus, although some co-occurrence restrictions may be easier to learn, the presence of the interaction does not take away from the main conclusion that adults can track local co-occurrences when syllable-position information is held constant.

independently of co-occurrence information, they should differentiate between the two types of test items. If, instead, the training environment led participants to track only the co-occurrence restrictions (or to fail to generalize syllable-level information in the context of novel co-occurrences), participants may not distinguish between the two types of test-items since neither type has the same co-occurrences as the training items.

Method

Participants—16 college-aged adults (9 females), all native speakers of English, participated for course extra-credit or small remuneration. No participant reported any hearing impairment.

Design—As in Experiment 1, each participant was assigned to one of 16 conditions which instantiated one of four consonant-to-role assignments. Across participants, each restricted consonant was restricted to onset and coda position equally often, and each test item served as a Same and a Different test item equally often (see Appendices A and B for details about design and items).

Each condition had the same 48 *Training* items and 24 *Filler* items as in Experiment 1, which were repeated twice in a random order in the Familiarization phase. Each condition also had 48 test items, 24 of each of two types (Same, Different). *Same-syllable-position* test items had restricted consonants in the same syllable positions as in the training items (e.g., *vuEZet*, *teD.Pev*) while *Different-syllable-position* test items had restricted consonants in different syllable positions than in the training items (e.g., *vuZ.Fet*, *teP.Dev*). Thus, while Same and Different test items differed on whether the restricted consonants were in the same or different syllable positions, all test items had the restricted consonants in different co-occurrence combinations relative to the training items (see Figure 1 for schematic depiction of design with examples). As in Experiment 1, in the Test phase, half of the Same and half of the Different test items were intermixed with a third repetition of the Training and Filler items. The remaining test items were intermixed with a fourth repetition of the Training and Filler items.

Stimuli—Training and Filler items were the same as in Experiment 1. Individual test items were the same as in Experiment 1, but their assignment to the 16 conditions differed.

Procedure—The procedure was the same as in Experiment 1.

Results

As in Experiment 1, participants differentiated repeating from novel items, as demonstrated by higher Yes-recognition rates for Training and Filler (.825) than for Same and Different test items (.471). Participants also differentiated items that had the restricted consonants in the same, rather than different, syllable positions (see Table 2), as demonstrated by higher rates of false recognition for Same (.542) than Different (.393) test items⁴, suggesting sensitivity to the experimental syllable-position restrictions instantiated by the training

⁴Rate of false recognition for test items varied across experiments, possibly due to global similarity between the training and test items. For example, whereas test items in Experiment 1 were highly similar to the training items (same word positions, same syllable

items. Plotted differences in false recognition rates between Same and Different test items for individual participants are shown in Figure 2. Responses were analyzed as in Experiment 1.

To assess differentiation of the test items that contained the same vs. different syllable-position restrictions, the model for Experiment 2 (see Table 4) included rescaled fixed-effect terms for Test-type (Same, Different), Training Syllable restrictions (1: oPZ/cDF, 2: oDF/cPZ), and Training Cluster restrictions (1: FP/DZ, 2: FZ/DP), random intercepts for Subjects and Items, and random slopes by Subject for Test-type, but did not include the correlations between random-effect terms.

Hypothesis testing for the effect of Test-type on the likelihood of a false recognition response was performed using a 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 Test-type. The model's fit was significantly improved by the inclusion of the fixed effect of Test-type [$\chi^2(4) = 15.99$, $p < .004$], suggesting that participants tracked the syllable-position restrictions from the training items, allowing them to differentiate between the Same and Different test items.

Discussion

Adult English speakers tracked syllable-position restrictions from a training environment in which both syllable-position restrictions and co-occurrence restrictions were available, and from which adults spontaneously track co-occurrence restrictions (Experiment 1). As shown by the different rates of false recognition for the Same-syllable-position and Different-syllable-position test items, participants generalized these syllable-position restrictions to items that had different co-occurrences than in the training items, allowing them to differentiate novel test items that had restricted consonants in the same rather than different syllable positions relative to the training items. Thus, even when the co-occurrences from the learning environment were not available in the test items, participants falsely recognized novel words with familiar syllable-position information, suggesting that phonotactics are represented at the syllable level and beyond the co-occurrences in which they were learned.

It is also possible, however, that participants in Experiment 2 encoded the word (or serial) position in which the restricted consonants occurred in the training items (e.g., F is in the third position in *baF.Pev*) rather than encoding the syllable positions in which the restricted consonants occurred (e.g., F is syllable onset). Thus, it may be that participants in Experiment 2 falsely recognized Same over Different test items because only the former had restricted consonants occurring in the same word (serial) position as in the training items (e.g., F also occurs in the third word/serial position in Same-test item *vuF.Zet*, but not in Different-test item *vuZ.Fet*). Even though in previous work (e.g., Bernard, 2015) adults have

positions, and same OR different clusters), test items in Experiment 2 were less similar to the training items (same word positions, same OR different syllable positions, and different clusters), perhaps shifting the false-recognition rates to be lower in Experiment 2 than those in Experiment 1. The test items in Experiment 3 were the least similar to training items (different word positions, same OR different syllable positions, and different clusters). The idea of a global shift in false recognition based on overall similarity of items used throughout the experiment is supported by the fact that the same test items (Same-syllable/Different-cluster in the word-medial position) had lower false recognition rates in Experiment 2 than in Experiment 1.

been shown to generalize phonotactic patterns across to word position, several factors in the current experiments could impede such generalization. First, because a second level of restriction was introduced in the training items (i.e., co-occurrence restrictions were present word-medially in addition to the syllable-position restrictions from Bernard, 2015), participants might be biased to attend to the consonants in these medial (third and fourth serial) positions; as a result, participants may have represented the constraints as “word-medial” or tied to the third and fourth word positions. Second, because only a subset of all possible restricted-consonant combinations were presented (e.g., for a particular participant, all training items had either FP or DZ word-medially, rather than all 4 potential combinations: FP, FZ, DP, or DZ), the variability within the training set was reduced; as a result, the consonant combinations presented word-medially may have seemed invariant, which could have hindered abstract generalization (e.g., Gómez, 2002). Third, because items were produced to suggest unified disyllabic words (and minimize compound-like processing) by having the speaker produce strong/weak stress pattern as well as fully reduce the vowel in the second syllable (which was produced as a schwa, as in /bæfpæk, kɪdzəb/, rather than having lax vowels in both syllables), the first and second syllables were acoustically more different than in Bernard, 2015; these acoustic differences between syllable 1 and 2 might make it more difficult to generalize patterns from one word position (e.g., syllable 1 onset) to another (e.g. syllable 2 onset).

If the results of Experiment 2 reflected the encoding of syllable-level constraints (beyond the co-occurrences and word/serial positions in which they were learned), participants should readily generalize the syllable-position constraints to novel word positions (i.e., from one syllable onset to another syllable onset). In contrast, if the results of Experiment 2 reflected the encoding of word-position (or serial-order) constraints, participants should not generalize the constraints to novel word (or serial) positions. Experiment 3 examined this prediction by asking whether participants trained with the same word-medial syllable-position and co-occurrence restrictions as in Experiment 2 would generalize these restrictions to the word edges.

Experiment 3

Experiment 3 asked whether adults can generalize syllable-position restrictions even when, in addition to co-occurrence information not being maintained, the restricted consonants are in different word positions. More specifically, do adults differentiate between test items in which the restricted consonants are in the same vs. different syllable positions (relative to the training items) when the restricted consonants in all test items are in novel (word edge) positions and violate the co-occurrence (relative to the training items)? As in Experiments 1 and 2, participants heard two-syllable training items (cvC.Cvc) in which medial coda-restricted and onset-restricted consonants were further restricted to co-occur. In contrast to Experiments 1 and 2, all test items contained the restricted consonants at word edges (and contained only unrestricted consonants word-medially).

From the Training items (e.g., *baFPev*, *tiDZek*), which were the same as in Experiments 1 and 2, participants were given the opportunity to track (1) syllable-position restrictions (e.g., P and Z as onsets with D and F as codas), (2) co-occurrence restrictions (e.g., FP clusters as

well as DZ clusters), or both. Participants were tested with two new types of test items: Same-syllable-position (e.g., *Zut.veF*, *Pev.teD*) and Different-syllable-position (e.g., *Fut.veZ*, *Dev.teP*) which differed in whether the syllable positions of the restricted consonants were the same (e.g., onset-PZ/coda-DF) or different (e.g., onset-DF/coda-PZ) from the training items. Note that both types of test items were equivalent with respect to both co-occurrence information and position within the word: neither maintained the co-occurrences nor the position within the word from the training items.

For example, a participant trained with items such as *baFPeV* and *tiDZeK*, would get filler items such as *bat.keV* and *vub.teK*, and would be tested with Same-syllable-position test items such as *Zut.veF* and *Pev.teD* and with Different-syllable-position test items such as *Fut.veZ* and *Dev.teP*. Thus, from the Training items, participants were again given the opportunity to track (1) syllable-position restrictions, (2) co-occurrence restrictions, or both. Moreover, the novel word positions of the restricted consonants in the test items were highly disruptive of co-occurrence information; consonants which were only experienced word-medially, as part of consonant-consonant clusters, were now at word edges. Experiment 3 thus represents a stronger test of the role of the syllable in the representation of the phonotactic constraints. If participants spontaneously abstract the syllable-position restrictions beyond the context in which they were presented in the training items (that is, if their representations are relative to the syllable and independent of word position and of co-occurrences) from an environment in which both syllable-position and co-occurrence restrictions were available (and can be tracked), they should differentiate between the Same and Different test items. If, instead, the training environment led participants to track consonant-position constraints relative to word (serial) position, participants may not distinguish between the two types of test items, since neither type has the restricted consonants in the same word (or serial) positions as the training items.

Method

Participants—16 college-aged adults (10 females), all native speakers of English, participated for course extra-credit or small remuneration. No participant reported any hearing impairment.

Design—As in Experiments 1 and 2, each participant was assigned to one of 16 conditions which instantiated one of four consonant-to-role assignments. Across participants, each restricted consonant was restricted to onset and coda position equally often, and each test item served as a Same and a Different test item equally often (see Appendices A and B for details about design and items).

Each condition had the same 48 *Training* items and 24 *Filler* items as in Experiments 1 and 2, which were repeated twice in a random order in the Familiarization phase. Each condition also had 48 test items, 24 of each of two types (Same, Different). *Same-syllable-position* test items had restricted consonants in the same syllable positions as in the training items (e.g., *Zut.veF*, *Pev.teD*), while *Different-syllable-position* test items had restricted consonants in different syllable positions relative to the training items (e.g., *Fut.veZ*, *Dev.teP*). Thus, while Same and Different test items differed on whether the restricted consonants were in the same

or different syllable positions, all test items had the restricted consonants in new word positions and in different co-occurrence combinations relative to the training items (see Figure 1 for schematic depiction of design with examples). As in Experiments 1 and 2, in the Test phase, half of the Same and half of the Different test items were intermixed with a third repetition of the Training and Filler items. The remaining test items were intermixed with a fourth repetition of the Training and Filler items.

Stimuli—Training and Filler items were the same as in Experiments 1 and 2. Test items were in recorded intermixed with those of Experiments 1 and 2.

Procedure—The procedure was the same as in Experiments 1 and 2.

Results

As in Experiments 1 and 2, participants differentiated repeating from novel items, as demonstrated by higher Yes-recognition rates for Training and Filler (.854) than for Same and Different test items (.418). Participants also differentiated items that had the restricted consonants in the Same (.471) rather than Different (.364) syllable positions (see Table 2), demonstrating sensitivity to the experimental syllable-position restrictions instantiated by the training items. Plotted differences in false recognition rates between Same and Different test items for individual participants are shown in Figure 2. Responses were analyzed as in Experiments 1 and 2.

To assess differentiation of test items that contained the same vs. different syllable-position restrictions in novel word positions, the model for Experiment 3 (see Table 5) included rescaled fixed-effect terms for Test-type (Same, Different), Training Syllable restrictions (1: oPZ/cDF, 2: oDF/cPZ), and Training Cluster restrictions (1: FP/DZ, 2: FZ/DP), random intercepts for Subjects and Items, and random slopes by Subject for Test-type, but did not include the correlations between random-effect terms.

Hypothesis testing for the effect of Test-type on the likelihood of a false recognition response was performed using a 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 Test-type. The model's fit was significantly improved by the inclusion of the fixed effect of Test-type [$\chi^2(4) = 10.65, p < .031$], suggesting that participants tracked the syllable-position restrictions in word-medial position from the training items, allowing them to differentiate between the Same and Different test items with restricted consonants at word edges.

Discussion

Even when restrictions could be represented as syllable-position restrictions, co-occurrence restrictions, or both, adult English speakers tracked the syllable-position restrictions independently of both co-occurrences and word (or serial) position information. As shown by the different rates of false recognition for Same-syllable-position and Different-syllable-position test items, participants generalized the syllable-position restrictions to new items that had the restricted consonants in novel word positions (as well as different consonant-

consonant co-occurrences), allowing them to differentiate test items that had restricted consonants in the same vs. different syllable-position relative to the training items. The results of Experiment 3 thus further support the hypothesis that phonotactic constraints can be represented abstractly at the level of the syllable.

General Discussion

Previous work has provided suggestive evidence that adults might be sensitive to syllable-position information (e.g., P in *dap* is a better coda than H in *dah*) as well as to local co-occurrence information (e.g., AP in *dap* is a better combination of sounds than AH in *dah*), supporting the idea that sounds and sound regularities could be represented at both levels. However, because previous research did not manipulate each type of information (co-occurrence and syllable-position) while controlling for the other, it remained unclear whether adults could represent both co-occurrence and syllable-position information. The current experiments manipulated syllable-position and co-occurrence information independently to assess whether phonotactic constraints could, from the same input, be represented at the level of the syllable, at the level of local co-occurrence, or both.

The current experiments, using artificial-language learning, show that adults can indeed track both co-occurrence and syllable-level restrictions from regularities that could have been represented as syllable-position restrictions, local co-occurrence restrictions, or both. In Experiment 1, adults demonstrated tracking of co-occurrence restrictions across syllable boundaries, as indicated by higher rates of false recognition for items with the same (e.g., *vuFPet*) rather than different co-occurrences (e.g., *vuFZet*) relative to the training items (e.g., *baFPev*) when syllable-position information was held constant across all test items (and was the same as in the training items). With the same training items, in Experiment 2, adults demonstrated tracking of syllable-position restrictions, as indicated by higher rates of false recognition for items with restricted consonants in the same (e.g., *vuFZet*) rather than in different syllable positions (e.g., *vuZ.Fet*) relative to the training items (e.g., *baFPev*) when co-occurrence information was held constant across all test items (and was different from the training items). Experiment 3 supported and added to the conclusion from Experiment 2, confirming that syllable-position information was represented abstractly by demonstrating generalization to new word positions (maximally disrupting co-occurrence information). Adults had higher rates of false recognition for items with restricted consonants in the same (e.g., *Zut.veF*) rather than in different syllable positions (e.g., *Fut.veZ*) relative to the training items (e.g., *baFPev*) even when the restricted consonants were in novel (word edge) positions and co-occurrence was held constant for all test items (and was different from training items).

The results of Experiment 1, demonstrated adults' sensitivity to co-occurrences learned through exposure to artificial languages in which syllable-position information, as well as many aspects of the learning environment (e.g., type and token frequency of segments in different syllable positions and their co-occurrences, mixed vs. blocked exposure, etc.), were controlled. These results are consistent with, yet go beyond, previous studies that found sensitivity to co-occurrence information (e.g., Coady & Aslin, 2004; Gathercole et al., 1999; Mattys et al., 1999; Munson, 2001; Richtsmeier et al., 2009a, 2009b, 2011) by

demonstrating that co-occurrences can be represented even when syllable-level information is fully controlled. In a parallel manner, the findings of Experiments 2 and 3, demonstrated adults' sensitivity to syllable-position constraints learned through exposure to artificial languages in which co-occurrence information was controlled. These results add to previous studies that found results consistent with syllable-level representations (e.g., Bernard, 2015; Chambers et al., 2003, 2010, 2011; Coady & Aslin, 2004; Dell et al., 2000; Goldrick, 2004; Goldrick & Larson, 2008; Kittredge & Dell, 2011; Onishi et al., 2002; Warker & Dell, 2006; Warker et al., 2008; Warker et al., 2009) while additionally establishing that syllable-level abstraction can be found even when co-occurrence information is controlled.

The current results suggest that syllable-position tracking, while possibly occurring concurrently with co-occurrence tracking, appears to be independent of the co-occurrences in which syllable-position restrictions were experienced: in test, adults successfully differentiated between items that all had novel co-occurrences. Specifically, in both Experiments 2 and 3, participants had higher false recognition rate for items with consonants in the same syllable positions (and different clusters) than for items with consonants in different syllable positions (and different clusters) relative to the training items. Thus, the syllable-level information is represented independently from word (serial) position and beyond the co-occurrence contexts in which it was learned. The current results also confirm that phonotactic constraints can be represented at the level of co-occurrences. In Experiment 1, participants had higher false recognition rate for items with the same co-occurrences (and same syllable-position information) than for items with different co-occurrences (and same syllable-position information). Since syllable-level information was equivalent in both types of test items, differentiation of the test items suggests that co-occurrences (even crossing syllable boundaries) are represented above and beyond syllable-level information.

What underlying mechanisms or architectures would be consistent with the current pattern of data (that is, syllable-level representations whether co-occurrence information is maintained or not; and co-occurrence level representations when syllable-level information is maintained)? Architectures that encode syllable-position but not word-position information would likely predict generalization of syllable-position restrictions across word positions (Experiment 3). For example, a model whose output consists of individual syllables coded as an onset, a nucleus, and a coda (Warker & Dell, 2006) and which processes multi-syllabic words by sequential input of syllables (Dell, 1986) ought to generalize from one word position to another (e.g., from syllable 2 onsets to syllable 1 onsets), since each onset (or coda) activates the same nodes regardless of its word position. These same models would *not*, however, seem to support learning of co-occurrences crossing syllable boundaries (Experiment 1) since there would be no link between the final consonant of syllable 1 and the initial consonant of syllable 2 in a two-syllable word. In contrast, architectures that encode linear information (e.g., TRACE II, McClelland, & Elman, 1986; PARSYN, as implemented by Luce, Goldinger, Auer, & Vitevitch, 2000), by treating adjacent sounds as overlapping in their features or by encoding patterns of adjacency between sounds, ought to predict learning of co-occurrences (even when these co-occurrences cross syllable boundaries as in Experiment 1), since adjacency would be encoded similarly regardless of syllable membership. These models would *not*, however, predict generalization of syllable-position restrictions across word positions (Experiments 3)

since nodes for a particular sound in one word position (e.g., word-initial onset) are not linked to nodes for the same sound in other word positions (e.g., word-medial onset). Thus, to account for the current results, processing architectures must incorporate both a way to link corresponding sounds across different positions within the word, ideally based on the phoneme's position within the syllable, as well as a way to link the individual syllables of multi-syllabic words.

In architectures that encode both kinds of information (position relative to the syllable as in Warker & Dell, 2006 and linear information regardless of syllable position as in Luce et al., 2000), it is still an open question as to how these two types of representations (syllable-position and co-occurrences) interact. Experiment 1 only tested tracking of co-occurrences in items that maintained syllable-position information relative to the training items (in order to provide maximal chances of finding co-occurrence learning, given that prior evidence was rather inconsistent). Thus, it is unknown whether participants are sensitive to co-occurrence restrictions when the syllable-level information is not maintained. If participants *are* sensitive to co-occurrence information even when syllable-level information is violated, the outcome would, considering the current results, suggest independent representation of co-occurrence and syllable-level information (each level affects processing regardless of whether the other level is maintained or violated). If, however, participants are *not* sensitive to co-occurrence regularities when syllable position is violated, the outcome would, considering the current results, be consistent with a hierarchical representation. In other words, if participants are sensitive to syllable-level information whether co-occurrences are maintained or violated, but are sensitive to co-occurrence information *only* when syllable-level information is maintained, the results would suggest that syllable-level information is represented first or that syllable-level information serves as the primary representation on which co-occurrence representations are built.

One potential difficulty in comparing test items with the same vs. different co-occurrences relative to the training items while violating syllable-position restrictions (at least with the current experimental design) is that changes in syllable-position word-medially would be confounded with changes in the linear order of the co-occurring consonants. Specifically, to violate the syllable-position restrictions (e.g., F-coda, P-onset) word-medially, the linear order of the co-occurring consonants needs to be changed (e.g., from FP in *baFPev* to PF in *vuPFet*). Co-occurrences could, in theory, be encoded as unordered sets of segments where FP and PF are equivalent in that both are combinations of adjacent F and P. If co-occurrences are represented without linear information, violating the syllable-position restrictions word-medially may not necessarily disrupt co-occurrence information, and thus it would be possible to test whether co-occurrences are or are not represented independently of syllable-position information. If, however, co-occurrences are represented with linear information (i.e., segments occurring in a particular linear order, e.g., F-before-P in *baFPev*, as assumed when biphones/diphones are studied), then violating the syllable-position restrictions word-medially would also violate the ordered co-occurrence information (e.g., *vuPFet* violates both the syllable-position restriction of P-onset and the linear information of the co-occurrence F-before-P). If adults failed, with the current design, to generalize co-

occurrence patterns when syllable-position information was violated, it would be impossible to determine which factor (syllable-position or linear order) was responsible.

Since work on transitional probabilities suggests that adults and infants are sensitive to the linear order in which syllables co-occur (e.g., they are sensitive to the fact that BI always precedes DA in *golabubidakupadotbidaku* but that BI is not always preceded by BU; Aslin et al., 1998; Pelucchi et al., 2009a, 2009b; Perruchet & Desauty, 2008; Saffran et al., 1996; Saffran & Wilson, 2003), it is possible that co-occurrences (be it co-occurrences of syllables or phonemes) are always tracked in terms of their linear order. However, given that adults are able to track multiple levels of information (e.g., syllable-position and co-occurrence restrictions in the current experiments), and since work on transitional probabilities suggests that even infants track both forward (Pelucchi et al., 2009b) and backward (Pelucchi et al., 2009a) transitional probabilities, it is possible that co-occurrences are tracked both with linear information (e.g., F is before P in FP, but after P in PF) and independent of linear order (e.g., F and P are adjacent in both FP and PF). To better understand how co-occurrences are represented, one could hold consonant combinations constant while varying their linear order and test how people treat novel items that maintain or violate the linear order.

It should be noted that, in the current experiments, there exists a logical possibility that participants determined what information to represent from the training items only after hearing some of the test items, and thus that they did not represent both levels (co-occurrence, syllable-level) information simultaneously. Though unlikely, this alternative could be investigated by testing each participant with items crossing both same/different syllable-position and same/different co-occurrence information, rather than using a between-participants design as in the current experiments.

Future work can also ask about the developmental trajectory of the ability to track both syllable-position and co-occurrence information. Since there is suggestive evidence that children are sensitive to syllable-position and possibly co-occurrence information in their native language (e.g., Coady & Aslin, 2004), and since infants are able to track both positional information (e.g., preferring words that start with F after being familiarized with F-onset restrictions; Chambers et al., 2003, 2011; Seidl, Cristià, Bernard, & Onishi, 2009) and co-occurrences between larger units (e.g., segmenting words out of a continuous stream based on transitional probabilities between syllables; e.g., Aslin et al., 1998; Saffran et al., 1996; Saffran, Johnson, Aslin, & Newport, 1999; Saffran & Wilson, 2003), it may also be possible for children and young infants to track both syllable-position and local co-occurrence information simultaneously.

Although some questions remain open, the current findings suggest that adults can track both syllable-level and co-occurrence level information simultaneously from the same input. Participants in all 3 experiments received the same training items, and from these items, they extracted the necessary information to distinguish items that matched or mismatched the training items in co-occurrence information (Experiment 1) and syllable-position information (Experiments 2 and 3). The results are also consistent with previous work in several domains showing that multiple levels of representation are available to both adults

and infants, for instance in sound-pattern learning (e.g., Lee & Goldrick, 2008), speech segmentation (Mattys, White, & Melhorn, 2005), object categorization (Behl-Chadha, 1996), and for predicting object function (e.g., Gweon & Schulz, 2011; Gweon, Tenenbaum, & Schulz, 2010). The current results thus add to the existing literature on our capacity to attend to and to represent multiple levels of information simultaneously.

Moreover, since adults seem to track both syllable-position and co-occurrence information, it would be useful to have a tool that allows us to control for one when manipulating the other in an experiment. Phonotactic probability (as operationalized using methods similar to those used by phonotactic calculators; e.g., Vitevitch & Luce, 2004) has shown reliable predictive power, successfully predicting listening preference (e.g., Jusczyk et al., 1994), goodness ratings (e.g., Vitevitch et al., 1997), word recognition (e.g., Gathercole et al., 1999; Storkel & Rogers, 2000), repetition speed (e.g., Munson, 2001; Vitevitch et al., 1997; Vitevitch & Luce, 1998; Vitevitch & Luce, 2005), and repetition accuracy (e.g., Edwards, Beckman, & Munson, 2004; Munson, 2001). In addition, phonotactic calculators (e.g., Storkel & Hoover, 2010; Vaden, Halpin, & Hickok, 2009; Vitevitch & Luce, 2004) are regularly used to create stimuli balanced on phonotactic probability (e.g., Berent, 2008; Cole, 2009; Lee & Goldrick, 2008; Vouloumanos & Werker, 2009). Unfortunately, the phonotactic calculators currently available do not encode syllable-position information. Instead, the frequency of any given segment is calculated relative to its position from the start of the word.

For instance, the Phonotactic Probability Calculator (available at <http://www.people.ku.edu/~mvitevitch/PhonoProbHome.html>; Vitevitch & Luce, 2004), with an item like *bafpev* as input, returns the probability of each segment in its relative linear position (e.g., B in 1st, F in 3rd, and P in 4th position), as well as the probability of each (ordered) local co-occurrence in its specific position within the word (e.g., BA as first biphone, AF as second biphone; see Appendix C), but does not inform us about the probability of each segment or segment co-occurrence relative to its syllable position (e.g., the frequency of F as syllable coda in any word position, or the frequency of F-coda followed by P-onset within a word). Given that adults seem to spontaneously and independently track syllable-position and co-occurrence information, it would be useful to incorporate syllable-position information into existing phonotactic calculators so that researchers can ensure that while one source of information (e.g., co-occurrence frequency) is manipulated, the other (e.g., syllable-position frequency) remains constant and thus cannot be responsible for the results.

In sum, the current results demonstrate that adults can track both syllable-position and co-occurrence constraints when the other level of information is fully controlled. These findings provide additional support for the view that, for individual consonants, listeners track both the syllable positions in which they occur as well as the consonants adjacent to them. Even though the current experiments used an artificial language learning paradigm, and thus do not inform us directly about how we represent the words we learn in our natural languages, the results suggest that we can simultaneously represent regularities in speech sounds both at the syllable and co-occurrence levels. Broadly, the results suggest that we (as English speakers) accept nonwords like *dap* as potential words, but reject nonwords like *dah*, both because we are sensitive to which sounds are acceptable in which syllable positions *and*

because we are sensitive to which sounds can co-occur in our language. The availability of multiple levels of representation is likely useful to both language learners and expert users, allowing them to take advantage of multiple sources of information to enable flexible and efficient processing of speech.

Acknowledgments

Thanks to K. Onishi for discussion and feedback, including support from her NSERC Discovery grant. Thanks to C. Fisher, including support from her research grant NIH-HD044458. The author was supported by NSERC (Natural Sciences and Engineering Research Council of Canada), FQRSC (Fonds de recherche sur la société et la culture), as well as stipends from the CRBLM (Centre for Brain, Language and Music; funded by the Government of Quebec via the Fonds de Recherche Nature et Technologies and Société et Culture). Additional thanks to S. Baharian, K. Chambers, Y. Chudasama, G. Dell, L. Hetrovicz, L. James, A. Martin, C. Palmer, and M. Sonderegger.

Appendix A

		MEDIANALLY-RESTRICTED ITEMS (cvC.Cvc)				EDGE-RESTRICTED ITEMS (Cvc.cvC)			
		Consonant-to-role assignment				Consonant-to-role assignment			
Cons-to-role #:		1	2	3	4	1	2	3	4
Syll-pos:		(1) oPZ/cDF	(1) oPZ/cDF	(2) oDF/cPZ	(2) oDF/cPZ	(1) oPZ/cDF	(1) oPZ/cDF	(2) oDF/cPZ	(2) oDF/cPZ
Co-occ:		(1) FP/DZ	(2) FZ/DP	(1) FP/DZ	(2) FZ/DP	(1) FP/DZ	(2) FZ/DP	(1) FP/DZ	(2) FZ/DP
Frames:		<u>FP</u> / <u>DZ</u>	<u>FZ</u> / <u>DP</u>	<u>PF</u> / <u>ZD</u>	<u>ZF</u> / <u>PD</u>	<u>F</u> <u>F</u> / <u>Z</u> <u>D</u>	<u>Z</u> <u>F</u> / <u>P</u> <u>D</u>	<u>F</u> <u>P</u> / <u>D</u> <u>Z</u>	<u>F</u> <u>Z</u> / <u>D</u> <u>P</u>
Sublist:		1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Experiment 1: Same vs Different co-occurrence (cluster) constraints									
Condition									
1		T	T	S					
2		T	T	S					
3		S		T	T				
4		S		T	T	D			
5			D		T	T	S		
6			D		T	T	S		
7			D		T	T	S		
8		D			S		T	T	
9					S		T	T	
10					T	T	S		
11					T	T	S		
12					S		T	T	
13					S		T	T	
14						D		T	T
15						D		T	T
16						D		T	T
Experiment 2: Same vs Different syllable-position constraints									
Condition									
1		T	T			S			
2		T	T			S			
3			T	T		S			
4			T	T		S			
5			S		T	T			
6			S		T	T			
7		S			T	T			
8		S			T	T			
9					T	T			
10					T	T			
11					T	T			
12					T	T			
13					T	T			
14					T	T			
15					T	T			
16					T	T			
Experiment 3: Same vs Different syllable-position constraints (new word position)									
Condition									
1		T	T						
2		T	T						
3			T	T					
4			T	T					
5				T	T				
6				T	T				
7				T	T				
8				T	T				
9				T	T				
10				T	T				
11				T	T				
12				T	T				
13				T	T				
14				T	T				
15				T	T				
16				T	T				

Appendix A.

Design for Experiments 1–3. Each participant in each experiment received 1 Condition (row). Each row contains Training items (T in white) with a specific consonant-to-role assignment as well as two types of test items: Same (S in pale gray) and Different (D in dark gray). The boxes on the left side represent items with restricted consonants in word medial position and boxes on the right side represent items with restricted consonants at word edges. There were 4 types of consonant-to-role assignments created by crossing Syllable-

position (1: oPZ/cDF, 2: oDF/cPZ) and Co-occurrence (1: FZ/PZ, 2: FZ/DP) restrictions. Frame shows the locations (medial, edge), syllable positions (onset, coda), and co-occurrences in a slightly more visual manner. There were 4 Sublists of items that instantiated each consonant-to-role assignment (See Appendix B for the particular stimuli composing each Sublist). Each participant received 2 Sublists as Training items and 2 Sublists as test items (1 Same, 1 Different).

For example, a participant in Experiment 3 assigned to Condition 1 would receive 2 Sublists of Training items with medially-restricted consonants that have Syllable-position restriction (1) and Co-occurrence restriction (1). For Test items, the participant would receive the restricted consonants at word edges. Relative to training items, Same test items would have the same syllable-position restrictions (1) but different co-occurrence restrictions (2) while Different test times would have different syllable-position restrictions (2) as well as different co-occurrence restrictions (2).

Appendix B

(A) MEDIALY-RESTRICTED ITEMS (evC,Cvc)

Cons-to-role #1					2					3					4				
Syll-pos	(1) oPZ/cDF				(1) oPZ/cDF				(2) oDF/cPZ				(2) oDF/cPZ						
Co-occ	(1) FP/DZ				(2) FZ/DP				(1) FP/DZ				(2) FZ/DP						
Frames	<u>FE</u> / <u>DE</u>				<u>FE</u> / <u>DE</u>				<u>FE</u> / <u>DE</u>				<u>FE</u> / <u>DE</u>						
Subst1	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4			
Items	bæfɒk	bɛfɒk	bɪfɒk	bʌfɒk	bɛfɒk	bæfɒk	bʌfɒk	bɪfɒk	*kɪbɒv	bɪpɒk	*tɪbɒv	bʌpɒk	*kɛvɒk	bɛzɒk	*vɪbɒk	bæzɒk			
	bɛfɒv	kæfɒb	bʌfɒv	kɪfɒb	bæfɒv	kɛfɒb	bɪfɒv	kʌfɒb	bɪpɒv	kæpɒb	bʌpɒv	kɛpɒb	bɛzɒv	kʌfɒb	bæzɒv	kɪzɒb			
	kæfɒv	kɛfɒk	kɪfɒv	kʌfɒk	kæfɒv	kɛfɒk	kɪfɒv	kʌfɒk	kæpɒv	kɪpɒk	kɛpɒv	kʌpɒk	kʌzɒv	kɛzɒk	kɪzɒv	kæzɒk			
	tɛfɒk	tæfɒb	tʌfɒk	tɪfɒb	tæfɒk	tɛfɒb	tɪfɒk	tʌfɒb	*vɛkɒk	tæpɒb	*vækɒk	tɛpɒb	*bɪkɒv	tʌzɒb	*kɪvɒb	tzɒk			
	tæfɒv	vɛfɒb	tɪfɒv	vʌfɒb	tɛfɒv	væfɒb	tʌfɒv	vɪfɒb	tæpɒv	vɪpɒk	tɛpɒv	vʌpɒk	tʌzɒv	vɛzɒk	tzɒv	væzɒb			
	vɛfɒk	væfɒv	vɪfɒk	vʌfɒv	væfɒk	vɛfɒv	vɪfɒk	vʌfɒv	*bʌkvɒ	væpɒk	*bɪkvɒ	vɛpɒk	*tɛkvɒk	vʌzɒk	*tʌkvɒk	vɪzɒk			
	bɪdzɒk	bʌdzɒk	bɛdzɒk	bɛdzɒk	bʌdpɒk	bɪdpɒk	bɛdpɒk	bɛdpɒk	bɛzɒk	bʌzɒk	bæzɒk	bɪzɒk	bɪpɒk	bæpɒk	bʌpɒk	bɛpɒk			
	kʌdzɒb	bɪdzɒv	kɛdzɒb	bædzɒv	kɪdpɒb	bʌdpɒv	kædpɒb	bɛdpɒv	kʌzɒb	bɛzɒv	kɪzɒb	bæzɒv	kæpɒk	bɪpɒv	kɛpɒk	bʌpɒv			
	kɪdzɒk	kʌdzɒv	kædzɒk	kɛdzɒv	kʌdpɒk	kɪdpɒv	kɛdpɒk	kædpɒv	kɛzɒk	kʌzɒv	kæzɒk	kɪzɒv	kɪpɒk	kæpɒv	kʌpɒk	kɛpɒk			
	ʌdzɒb	tɪdzɒk	tɛdzɒb	tædzɒk	tɪdpɒb	ʌdpɒk	tædpɒb	tɛdpɒk	tʌzɒb	tɛzɒk	tzɒb	tæzɒk	tɛpɒk	tzpɒk	tɛpɒk	ʌdpɒk			
	vɪdzɒb	tʌdzɒv	vædzɒb	tɛdzɒv	vʌdpɒb	tɪdpɒv	vɛdpɒb	tædpɒv	vɛzɒk	tʌzɒv	væzɒk	tzɒv	vɪpɒk	tæpɒv	vʌpɒk	tɛpɒv			
	vʌdzɒk	vɪdzɒk	vɛdzɒk	vædzɒk	vɪdpɒk	vʌdpɒk	vædpɒk	vɛdpɒk	vʌzɒk	vɛzɒk	vɪzɒk	væzɒk	væpɒk	vɪpɒk	vɛpɒk	vʌpɒk			
	bɛfɒk	bæfɒk	bʌfɒk	bɪfɒk	bæfɒk	bɛfɒk	bʌfɒk	bɪfɒk	*kɪbɒv	bɛfɒk	*kɛbɒv	bɛfɒk	*bɪkɒv	bʌzɒk	*kɛbɒv	bɪzɒk			
	bæfɒv	kɛfɒb	bɪfɒv	kʌfɒb	bɛfɒv	kæfɒb	bʌfɒv	kɪfɒb	bæpɒv	kɪpɒb	bɛpɒv	kʌpɒb	bʌzɒv	kɛzɒk	bɪzɒv	kæzɒk			
	kɛfɒv	kæfɒk	kʌfɒv	kɪfɒk	kæfɒv	kɛfɒk	kɪfɒv	kʌfɒk	kɪpɒv	kæpɒk	kʌpɒv	kɛpɒk	kɛzɒv	kʌzɒk	kæzɒv	kɪzɒk			
	tæfɒk	tɛfɒb	tɪfɒk	tʌfɒb	tɛfɒk	tæfɒb	tʌfɒk	tɪfɒb	*vɪkɒk	tɪpɒk	*bɛkvɒ	tʌpɒk	*kævɒk	tɛzɒk	*kɛvɒk	tæzɒk			
	tɛfɒv	væpɒb	tʌfɒv	vɪpɒb	tæfɒv	vɛzɒb	tʌfɒv	vʌzɒb	tɪpɒv	væpɒb	tʌpɒv	vɛpɒb	tɛzɒv	vʌzɒb	tæzɒv	vɪzɒb			
	væfɒk	vɛfɒk	vɪfɒk	vʌfɒk	vɛfɒk	væfɒk	vʌfɒk	vɪfɒk	*kɪvɒk	vɪpɒk	*bʌkvɒ	vʌpɒk	*kævɒk	vɛzɒk	*vækvɒk	væzɒk			
	bʌdzɒk	bɪdzɒk	bɛdzɒk	bædzɒk	bɪdpɒk	bʌdpɒk	bɛdpɒk	bɛdpɒk	bʌzɒk	bɛzɒk	bɪzɒk	bæzɒk	bæpɒk	bɪpɒk	bɛpɒk	bʌpɒk			
	kʌdzɒb	bʌdzɒv	kædzɒb	bɛdzɒv	kʌdpɒb	bɪdpɒv	kɛdpɒb	bædpɒv	kɛzɒb	bʌzɒv	kæzɒb	bɪzɒv	kɪpɒk	bæpɒv	kʌpɒk	bɛpɒk			
	kʌdzɒk	kɪdzɒv	kɛdzɒk	kædzɒv	kɪdpɒk	kʌdpɒv	kædpɒk	kɛdpɒv	kʌzɒk	kɛzɒk	kɪzɒk	kæzɒk	kæpɒk	kɪpɒk	kɛpɒk	kʌpɒk			
	tɪdzɒb	tʌdzɒk	tædzɒb	tɛdzɒk	tʌdpɒb	tɪdpɒk	tɛdpɒb	tædpɒk	tɛzɒb	tʌzɒk	tæzɒb	tzɒk	tɪpɒk	tæpɒk	tʌpɒk	tɛpɒk			
	vʌdzɒb	tɪdzɒv	vɛdzɒb	tædzɒv	vɪdpɒb	tʌdpɒv	vædpɒb	tɛdpɒv	vʌzɒb	tɛzɒk	vɪzɒk	tæzɒk	væpɒk	tɪpɒk	vɛpɒk	tʌpɒk			
	vɪdzɒk	vʌdzɒk	vɛdzɒk	vædzɒk	vʌdpɒk	vɪdpɒk	vædpɒk	vɛdpɒk	vʌzɒk	vʌzɒk	væzɒk	vɪzɒk	vɪpɒk	væpɒk	vʌpɒk	vɛpɒk			

(B) EDGE-RESTRICTED ITEMS (Cvc.evC)

Cons-to-rol #1 Syll-Pos Co-occ Frames Substlist					2 (1) oPZ/cDF (2) FZ/DP F ̥ F ̥ DP ̥					3 (2) oDF/cPZ (1) FP/DP F ̥ DP ̥ F ̥					4 (2) oDF/cPZ (2) FZ/DP F ̥ DP ̥ F ̥				
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4			
Items	pitbak̥	pæbtæk̥	pæbkæk̥	pæbtæk̥	zæbkæk̥	zæbtæk̥	zæbkæk̥	zæbtæk̥	fæbkæp	fæbtæp	fæbkæp	fæbtæp	fæbkæz	fæbtæz	fæbkæz	fæbtæz			
	pæbvæk̥	ptkbfæk̥	pæbvæk̥	pæbkbfæk̥	zæbvæk̥	zækbæk̥	zæbvæk̥	zækbæk̥	fæbvæp	*vætkæb	fæbvæp	*vætkæb	fæbvæz	*kæbvæz	fæbvæz	*tækvæb			
	ptkbfæk̥	pæktæk̥	pæktæk̥	pæktæk̥	zækvæk̥	zæktæk̥	zækvæk̥	zæktæk̥	*bætkæv	*bævtæk	*tæbkæv	*kæbtæv	*tævkæb	*btkæv	*vætkæb	*vætkæb			
	pætkæk̥	pttbfæk̥	ptækæk̥	pættbfæk̥	zætkæk̥	zættbfæk̥	zætkæk̥	zættbfæk̥	fætkæp	fættbæp	fætkæp	fættbæp	fætkæz	fættbæz	fætkæz	fættbæz			
	pttvæk̥	pævttæk̥	pætvæk̥	pævttæk̥	zætvæk̥	zævttæk̥	zætvæk̥	zævttæk̥	fætvæp	fævttæp	fætvæp	fævttæp	fætvæz	fævttæz	fætvæz	fævttæz			
	pævkæk̥	ptvtæk̥	pævkæk̥	pævtæk̥	zævkæk̥	zævtæk̥	zævkæk̥	zævtæk̥	fævkæp	fævtæp	fævkæp	fævtæp	fævkæz	fævtæz	fævkæz	fævtæz			
	zæbtæd	zæbkæd	zæbtæd	zæbkæd	pttbtæd	pæektæd	pættbtæd	pæektæd	dæbtæz	dæbkæz	dæbtæz	dæbkæz	dæbtæz	dæbkæz	dæbtæz	dæbkæz			
	zæktæd	zæbvæd	zæktæd	zæbvæd	pæktæd	pttbtæd	pæktæd	pættbtæd	dæktæz	dæbvæz	dæktæz	dæbvæz	*tævkæb	dævttæp	dæktæp	dævttæp			
	zæktæd	zækvæd	zæktæd	zækvæd	ptktæd	pækvæd	pæktæd	pækvæd	*vætkæb	dækvæz	dæktæz	dækvæz	dæktæp	*vætkæb	dæktæp	dækvæp			
	zættæd	zætkæd	zættæd	zætkæd	pættbæd	ptkæd	pættbæd	ptkæd	dættbæz	dætkæz	dættbæz	dætkæz	dættbæp	dætkæp	dættbæp	dætkæp			
	zævttæd	zætvæd	zævttæd	zætvæd	pttvbæd	pætvæd	pætvbæd	pætvæd	dætvbæz	dætvæz	dætvbæz	dætvæz	dætvbæp	dætvæp	dætvbæp	dætvæp			
	zævtæd	zævkæd	zævtæd	zævkæd	pævtæd	pttvæd	pævtæd	pætvæd	dævtæz	dævkæz	dævtæz	dævkæz	dævtæp	dævkæp	dævtæp	dævkæp			
	pæbkæk̥	pttbtæk̥	pæktæk̥	pættbfæk̥	zæbkæk̥	zæbtæk̥	zæbkæk̥	zæbtæk̥	fæbkæp	fæbtæp	fæbkæp	fæbtæp	fæbkæz	fæbtæz	fæbkæz	fæbtæz			
	pttbfæk̥	pæktbfæk̥	pætvbfæk̥	pæktbfæk̥	zætvbfæk̥	zækbæk̥	zætvbfæk̥	zækbæk̥	fætvbæp	*bævkæt	fætvbæp	*bætkæv	fætvbæz	*tkæbvæz	fætvbæz	*bævtæk			
	pækvæk̥	ptktæk̥	pækvæk̥	pæktæk̥	zækvæk̥	zæktæk̥	zækvæk̥	zæktæk̥	*vætkæb	*kævbæt	*vætkæb	*vætkæb	*tækvæb	*vttæk	*tækvæb	*bævtæk			
	pttbfæk̥	pættbfæk̥	pætkæk̥	pættbfæk̥	zætkæk̥	zættbfæk̥	zætkæk̥	zættbfæk̥	fætkæp	fættbæp	fætkæp	fættbæp	fætkæz	fættbæz	fætkæz	fættbæz			
	pttvæk̥	pttvæk̥	pttvæk̥	pttvæk̥	zætvæk̥	zævttæk̥	zætvæk̥	zævttæk̥	fætvæp	fævttæp	fætvæp	fævttæp	fætvæz	fævttæz	fætvæz	fævttæz			
	pttvæk̥	pævttæk̥	pævkæk̥	pævttæk̥	zævkæk̥	zævtæk̥	zævkæk̥	zævtæk̥	fævkæp	fævtæp	fævkæp	fævtæp	fævkæz	fævtæz	fævkæz	fævtæz			
	zættæd	zæbkæd	zættæd	zæbkæd	pættbæd	pttbtæd	pættbæd	pættbtæd	dættbæz	dætkæz	dættbæz	dætkæz	dættbæp	dætkæp	dættbæp	dætkæp			
	zæktæd	zækvæd	zæktæd	zækvæd	pæktæd	pttbtæd	pæktæd	pttbtæd	dæktæz	*kævttæb	dæktæz	dækvæz	*vætkæb	dækvæp	dæktæp	dækvæp			
	zættæd	zætkæd	zættæd	zætkæd	pttbtæd	pættbæd	pttbtæd	pættbæd	dættbæz	dætkæz	dættbæz	dætkæz	dættbæp	dætkæp	dættbæp	dætkæp			
	zævttæd	zætvæd	zævttæd	zætvæd	pætvbæd	pttvæd	pætvbæd	pætvæd	dætvbæz	dætvæz	dætvbæz	dætvæz	dætvbæp	dætvæp	dætvbæp	dætvæp			

Appendix B.

Stimuli for Experiments 1–3. Each participant received 2 Sublists as Training items and 2 Sublists (1 Same, 1 Different) as Test items (See Appendix A for the Sublist assignments for each condition). Each column of 24 items represents a Sublist. For each word position (medially-restricted, edge-restricted), 4 Sublists instantiate each consonant-to-role assignment created by crossing Syllable position (1: oPZ/cDF, 2: oDF/cPZ) and Co-

occurrence (1: FZ/PZ, 2: FZ/DP) restrictions. Items preceded by * are filler items replacing potentially vulgar words and thus do not contain the restricted consonants and were not included in the analyses.

Appendix C

Position:	1	2	3	4	5	6	Sum
Phoneme	b	@	f	p	x	v	
Position-specific probability	.0512	.0794	.0197	.0362	.0816	.0088	.2769
Biphone	b@	@f	fp	fx	xv		Sum
Position-specific probability	.0059	.0013	.0000	.0042	.0011		.0125

Appendix C.

Example output using the Phonotactic Probability Calculator (<http://www.people.ku.edu/~mvitevitch/PhonoProbHome.html>; Vitevitch & Luce, 2004) with one of the training items (*bafpev*) as input. The vowel /æ/ as in “cat” is entered as “@” and the schwa, /ə/, as in “blanket” is entered as “x”

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Highlights

Adults trained on phonotactic constraints on consonant positions and co-occurrences

Participants in 3 experiments learned from the same training items

They tracked co-occurrences when syllable position was held constant (E1)

They tracked syllable position when co-occurrences were held constant (E2, E3)

Sound patterns are represented at multiple levels (syllable position, co-occurrences)

Figure 1.

Schematic depiction of design with representative items from training and test for one participant in each experiment. Experiment 1 manipulated co-occurrence information while keeping syllable-level information constant (i.e., compared the two types of test items in the rounded rectangle labeled Experiment 1). Experiments 2 and 3 manipulated syllable information while keeping co-occurrence information constant (i.e., compared the two types of test items in the ovals labeled Experiment 2 or Experiment 3 respectively). Test items in Experiment 2 maintained restricted consonants word medially (as in Training items) while test items in Experiment 3 had the restricted consonants in a novel word position (word edge) relative to the Training items.

Consonant constraints from the training items are indicated using both coloured/patterned shapes and typography. Co-occurrence constraints are represented by shared colour *and* underlining (FP: purple/darker & underlined, DZ: yellow/paler & not underlined). Syllable-position constraints are represented by the orientation of the double wedge and bolding (2 points toward center of syllable) and the bolding (onset: 2 points toward right & bolded, coda: 2 points toward left & not bolded).

Figure 2.

Differences in false recognition rates for Same vs. Different test items (Experiment 1: Same-cluster minus Different-cluster; Experiments 2 and 3: Same-syllable-position minus Different-syllable-position). The horizontal bars represent the mean differences across participants between false recognition rates for the two types of test items within each experiment. Each circle represents the mean difference (Same minus Different) for an individual participant, with darker shading indicating overlapping circles.

Table 1

The 4 experimental consonant-to-role assignments crossing two syllable-position restrictions (1: oPZ/cDF, 2: oDF/cPZ) and two co-occurrence restrictions (1: FP/DZ, 2: FZ/DP).

#	Syllable-position restrictions	Co-occurrence restrictions		Example items
	Code	Onsets	Codas	Clusters
1	1: oPZ/cDF	/p, z/	/d, f/	1: FP/DZ /f, p, d, z/ <i>baF.Pev, tiD.Zek</i>
2	1: oPZ/cDF	/p, z/	/d, f/	2: FZ/DP /f, z, d, p/ <i>baF.Zev, tiD.Pek</i>
3	2: oDF/cPZ	/d, f/	/p, z/	1: FP/DZ /p, f, z, d/ <i>baP.Fev, tiZ.Dek</i>
4	2: oDF/cPZ	/d, f/	/p, z/	2: FZ/DP /z, f, p, d/ <i>baZ.Fev, tiP.Dek</i>

Table 2

During the Test phase, for each participant, mean proportions of Yes-recognition responses by item type were calculated. Table 2 presents mean (standard deviation) Yes-recognition rates across participants for each item type, as well as the difference between the responses to Same and Different test items, for Experiments 1 through 3. Training items had restricted consonants in word-medial positions. Test items had restricted consonants in medial positions in Experiments 1 and 2, and in edge positions in Experiment 3.

Item Type	Filler	Training	Test	Same-Diff			
Restrictions:							
Syllable-position	Co-occurrence			Same		Different	
				Same	Different	Same	Different
Experiment 1	.810 (.138)	.842 (.120)	.700 (.164)	.608 (.148)	NA	.092	
Experiment 2	.807 (.136)	.834 (.109)	NA	.542 (.190)	.393 (.223)	.149	
Experiment 3	.818 (.120)	.873 (.092)	NA	.471 (.194)	.364 (.186)	.107	

Table 3

Fixed and random effect estimates for the linear mixed-effects model for Experiment 1, assessing differentiation of the test items that contained the same vs. different co-occurrence restrictions relative to the training items. The model included rescaled fixed-effect terms for Test-type (Same, Different), Training Syllable restrictions (1, 2) and Training Cluster restrictions (1, 2), random intercepts for Subjects and Items, and random slopes by Subject for Test-type.

Random effects			
		Variance	Std. Dev.
Items	(Intercept)	0.00	0.00
Subjects	(Intercept)	0.32	0.56
	Test-type	0.00	0.00

Fixed effects				
	Coefficient	Std. Error	Wald z	Pr(> z)
(Intercept)	0.71	0.16	4.33	< .001 *
Test-type	0.46	0.17	2.74	< .007 *
Train-syll-restrict	0.28	0.33	0.85	.394
Train-clus-restrict	0.17	0.33	0.52	.606
Test-type X Train-syll-restrict	0.81	0.34	2.41	< .016 *
Test-type X Train-clus-restrict	-0.32	0.33	-0.96	.339
Train-syll-restrict X Train-clus-restrict	-0.53	0.66	-0.80	.423
Test-type X Train-syll-restrict X Train-clus-restrict	-1.21	0.67	-1.80	.072

Number of observations: 708; Number of items: 354; Number of subjects: 16

*
 $p < 0.05$ (on normal distribution)

Table 4

Fixed and random effect estimates for the linear mixed-effects model for Experiment 2, assessing differentiation of the test items that contained the same vs. different syllable-position restrictions relative to the training items. The model included rescaled fixed-effect terms for Test-type (Same, Different), Training Syllable restrictions (1, 2) and Training Cluster restrictions (1, 2), random intercepts for Subjects and Items, and random slopes by Subject for Test-type.

Random effects			
		Variance	Std. Dev.
Items	(Intercept)	0.12	0.35
Subjects	(Intercept)	0.57	0.75
	Test-type	0.00	0.00

Fixed effects				
	Coefficient	Std. Error	Wald z	Pr(> z)
(Intercept)	−0.13	0.21	−0.64	.525
Test-type	0.71	0.17	4.22	< .001*
Train-syll-restrict	0.37	0.41	0.91	.365
Train-clus-restrict	0.10	0.41	0.23	.815
Test-type X Train-syll-restrict	−0.19	0.34	−0.57	.572
Test-type X Train-clus-restrict	0.46	0.33	1.40	.161
Train-syll-restrict X Train-clus-restrict	−0.79	0.82	−0.97	.334
Test-type X Train-syll-restrict X Train-clus-restrict	0.33	0.68	0.49	.626

Number of observations: 720; Number of items: 360; Number of subjects: 16

* $p < 0.05$ (on normal distribution)

Table 5

Fixed and random effect estimates for the linear mixed-effects model for Experiment 3, assessing differentiation of the test items that contained the same vs. different syllable-position restrictions, in novel word positions, relative to the training items. The model included rescaled fixed-effect terms for Test-type (Same, Different), Training Syllable restrictions (1, 2) and Training Cluster restrictions (1, 2), random intercepts for Subjects and Items, and random slopes by Subject for Test-type.

Random effects			
		Variance	Std. Dev.
Items	(Intercept)	0.18	0.43
Subjects	(Intercept)	0.51	0.71
	Test-type	0.00	0.00

Fixed effects				
	Coefficient	Std. Error	Wald z	Pr(> z)
(Intercept)	−0.39	0.20	−1.96	< .050 *
Test-type	0.51	0.17	3.03	< .003 *
Train-syll-restrict	0.53	0.40	1.33	.183
Train-clus-restrict	0.22	0.40	0.54	.587
Test-type X Train-syll-restrict	−0.19	0.35	−0.56	.880
Test-type X Train-clus-restrict	−0.05	0.33	−0.15	.575
Train-syll-restrict X Train-clus-restrict	−0.47	0.79	−0.59	.555
Test-type X Train-syll-restrict X Train-clus-restrict	−0.76	0.69	−1.09	.276

Number of observations: 720; Number of items: 360; Number of subjects: 16

* $p < 0.05$ (on normal distribution)