The Quarterly Journal of Experimental Psychology

ISSN: 1747-0218 (Print) 1747-0226 (Online) Journal homepage: http://www.tandfonline.com/loi/pqje20

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To cite this article: Katherine S. White, Kyle E. Chambers, Zachary Miller & Vibhuti Jethava (2017) Listeners learn phonotactic patterns conditioned on suprasegmental cues, The Quarterly Journal of Experimental Psychology, 70:12, 2560-2576, DOI: 10.1080/17470218.2016.1247896

To link to this article: https://doi.org/10.1080/17470218.2016.1247896

Accepted author version posted online: 13 Oct 2016.
Published online: 02 Nov 2016.

THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2017
VOL. 70, NO. 12, 2560–2576
http://dx.doi.org/10.1080/17470218.2016.1247896

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Listeners learn phonotactic patterns conditioned on suprasegmental cues

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ABSTRACT

Language learners are sensitive to phonotactic patterns from an early age, and can acquire both simple and 2nd-order positional restrictions contingent on segment identity (e.g., /f/ is an onset with /æ/but a coda with /ɪ/). The present study explored the learning of phonototactic patterns conditioned on a suprasegmental cue: lexical stress. Adults first heard non-words in which trochaic and iambic items had different consonant restrictions. In Experiment 1, participants trained with phonotactic patterns involving natural classes of consonants later falsely recognized novel items that were consistent with the training patterns (legal items), demonstrating that they had learned the stress-conditioned phonotactic patterns. However, this was only true for iambic items. In Experiment 2, participants completed a forced-choice test between novel legal and novel illegal items and were again successful only for the iambic items. Experiment 3 demonstrated learning for trochaic items when they were presented alone. Finally, in Experiment 4, in which the training phase was lengthened, participants successfully learned both sets of phonotactic patterns. These experiments provide evidence that learners consider more global phonological properties in the computation of phonotactic patterns, and that learners can acquire multiple sets of patterns simultaneously, even contradictory ones.

ARTICLE HISTORY
Received 21 November 2015
Accepted 26 September 2016
First Published Online 2 November 2016

KEYWORDS
Lexical stress; Phonological features; Phonotactic learning; Statistical learning; Suprasegmental

Languages differ in where speech sounds are located and how speech sounds are combined (Hill, 1958). For example, an English-learning child must learn not only that /ŋ/ is an English speech sound and that /ɖ/ is not, but also that, although /ŋ/ occurs at the end of words like *sing* and *tongue,* it does not begin English words. Infants have already started to learn these phonotactic regularities by the age of 9 months (Friederici & Wessels, 1993; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993; Jusczyk, Luce, & Charles-Luce, 1994; for a review of early phonotactic knowledge and learning, see Zamuner & Kharlamov, 2016). Phonotactic knowledge affects many aspects of language processing and learning: Infants, children, and adults show sensitivity to native-language phonotactics during word processing, word production, word segmentation, and word learning (e.g., Mattys, Jusczyk, Luce, & Morgan, 1999; Munson, 2001; Munson, Swenson, & Manthei, 2005; Storkel, 2001; Vitevitch & Luce, 1998, 1999; Zamuner, 2006; Zamuner, Gerken, & Hammond, 2004). Phonotactic learning is supported by mechanisms that track distributional information available in the linguistic environment (Aslin, Saffran, & Newport, 1998; Gomez, 2002; Lany & Saffran, 2010; Maye, Werker, & Gerken, 2002; Mintz, 2002). For example, when listeners are exposed to new phonotactic patterns in the laboratory, they quickly acquire these patterns. Infants demonstrate this ability as early as 9 months of age (Chambers, Onishi, & Fisher, 2003, 2011; Saffran & Thiessen, 2003; Seidl & Buckley, 2005), and adults retain the ability to rapidly acquire novel phonotactic patterns well after their native phonotactics are established (Dell, Reed, Adams, & Meyer, 2000; Goldrick, 2004; Onishi, Chambers, & Fisher, 2002; Taylor & Houghton, 2005; Warker, 2013; Warker & Dell, 2006).

Natural languages contain a variety of types of phonotactic patterns that are learned by native listeners.

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However, artificial language paradigms, in which people are presented with new phonotactic patterns in the lab, are critical for understanding the nature of the phonotactic learning system. Presenting participants with novel, carefully controlled, patterns can reveal the characteristics of the representations involved, the types of information that enter into phonotactic computations, and whether learning is biased, such that some patterns are easier to learn than others. In such paradigms, infants and adults learn not only new simple (or first-order) phonotactic patterns involving restrictions of segments or features to particular word or syllabic positions (Bernard, 2015; Chambers et al., 2003; Chambers, Onishi, & Fisher, 2010; Chambers et al., 2011; Dell et al., 2000; Endress & Mehler, 2010; Goldrick, 2004; Onishi et al., 2002; Saffran & Thiessen, 2003; Seidl & Buckley, 2005), but also second-order patterns, such as consonant restrictions that are conditioned on adjacent vowel identity or vowel quality—for example, that /f/ is an onset with /æ/ but a coda with /ɪ/ (Chambers et al., 2011; Onishi et al., 2002; Seidl & Buckley, 2005; Seidl, Cristià, Bernard, & Onishi, 2009; Warker, 2013; Warker & Dell, 2006). These studies vary based on whether participants are exposed to novel phonotactic regularities via auditory experience (e.g., Chambers et al., 2011) or production practice (e.g., Warker, 2013; Warker & Dell, 2006; Warker, Dell, Whalen, & Gereg, 2008), but they all indicate that the learning of second-order patterns is more difficult or slower than the learning of first-order patterns. In fact, when exposure occurs via production, participants may not show learning of second-order patterns unless testing sessions are distributed over multiple days (Warker & Dell, 2006; Warker et al., 2008), possibly because a period of consolidation is necessary in order for these patterns to be established (Gaskell et al., 2014; Warker, 2013). In addition, perception studies have suggested that, although participants can learn patterns both when the restricted segments form a natural class (or the patterns are phonetically grounded) and when the patterns are more arbitrary, learning is more difficult in the latter case (Endress & Mehler, 2010; Saffran & Thiessen, 2003). Finally, the patterns that can be learned change as infants acquire language-specific knowledge. For example, although second-order patterns conditioned on vowel nasality can be learned by 4-month-old infants learning French or English, only French-learning infants can learn the patterns at 7 months old (presumably because nasality is phonemic in French, but allophonic in English; Seidl et al., 2009).

Although there is now ample evidence that infants and adults can learn second-order phonotactic patterns in artificial language experiments, an important limitation has been observed. In particular, participants can learn second-order patterns when the conditioning context involves linguistic segments, but not when the patterns are conditioned on extra-linguistic aspects of the signal. In particular, failures have been observed for both talker voice, an indexical feature, and speech rate, which affects surface form but is on many accounts not thought to be part of phonological representations. In a perception task, adults in Onishi et al. (2002) were exposed to second-order regularities contingent on speaker voice (e.g., /f/ is an onset if the syllable is spoken by Speaker A; /f/ is a coda if spoken by Speaker B) or vowel identity (e.g., /f/ is an onset if the syllable contains /æ/, but a coda if it contains /ɪ/). Although participants learned the regularities conditioned on vowels, they did not learn the voice-based regularities. Using a production paradigm, Warker et al. (2008) tested the learning of second-order patterns contingent on speech rate (e.g., /f/ is an onset, and /s/ is a coda for fast speech rates, but /s/ is an onset, and /f/ is a coda for slow rates). Consistent with Onishi et al. (2002), there was no learning in this condition. Because both voice and rate are highly salient aspects of the speech signal, these failures have been interpreted as reflecting a fundamental constraint on the implicit phonotactic learning system (Onishi et al., 2002; Warker et al., 2008)—that it is modular, tracking only information internal to the abstract phonological system. As pointed out by Warker and colleagues, this type of modularity would make phonotactic learning different from some other aspects of speech and lexical learning. For example, the fact that word recognition is affected by whether a word has been previously heard in the same acoustic form (voice, pitch, rate) has been used as support for exemplar models in which such detail is included in word representations (Creel, Aslin, & Tanenhaus, 2008; Goldinger, 1998), and there is growing evidence that listeners learn talker-specific phonetic categories (Allen & Miller, 2004).

However, the scope of the constraints on phonotactic learning remains unclear, as previous studies of second-order learning have only compared local (segmental) linguistic conditioning contexts to more global, extra-linguistic contexts. Critically, no previous study has asked whether learning can be conditioned on *global*, but *linguistic* properties. Indeed, in a discussion of their failure to find rate-based learning, Warker et al. (2008) wrote that the phonotactic learning system does not appear to be able to track "non-linguistic properties that are globally present for large chunks of the speech stream, such as speaker identity or speech rate" (p. 1294), conflating linguistic status and size of the conditioning context. This gap leaves open the alternative possibility that the constraint is not based on linguistic status, but that, instead, learning is restricted to local conditioning contexts. If true, then the phonotactic learning system would not have access to phonological information extending over longer contexts. The present study seeks stronger evidence that it is indeed the linguistic status of the conditioning context that is relevant, by exploring implicit learning of second-order patterns conditioned by a suprasegmental, but linguistic, cue: lexical stress. Whether participants are able to learn such patterns will have important implications for models of phonotactic learning (e.g., Warker et al., 2008).

We chose to use stress as a conditioning context because it is highly salient to both adult and young listeners (for a summary, see Cutler, Dahan, & van Donselaar, 1997). For example, adult English listeners are likely to perceive word boundaries before stressed syllables, in keeping with the predominance of trochaic (strong–weak) words in the language (Cutler & Norris, 1988). And infants quickly demonstrate knowledge of the word stress patterns of their language: Between six and nine months of age, English-learning infants develop a preference for trochaic words over iambic (weak–strong) words (Jusczyk, Cutler, & Redanz, 1993; Turk, Jusczyk, & Gerken, 1995), while French-learning infants develop a preference for the iambic pattern that is more typical of French, at least in phrase-final position (Polka & Sundara, 2012).

We created an artificial language, in which half of the items were trochaic (strong–weak), and half were iambic (weak–strong). The trochaic and iambic items displayed incompatible phonotactic patterns. Thus, when the entire familiarization language was considered as a whole, without regard for stress type, the items displayed no consistent phonotactic patterns. However, the two distinct sets of patterns should be learnable if participants are able to categorize items by stress type[1] and track segment distributions within a stress type. If participants are able to learn such suprasegmentally conditioned patterns, it is not clear that the course of learning will be the same as for other second-order regularities. According to Warker and colleagues (Warker & Dell, 2006; Warker et al., 2008), learning second-order patterns is more difficult than learning first-order patterns because the learning system attempts to assign input segments to syllable slots and, in the case of second-order patterns, receives conflicting information: The same input (e.g., an /f/) leads to different outputs (onset vs. coda), depending on the conditioning context (e.g., the adjacent vowel). The same type of conflict would also arise in the case of the stress-conditioned second-order regularities explored here. However, it is possible that it takes longer to resolve the conflict in this case, because a system designed to learn about segmental regularities may be biased to track segmental information (even if other phonological information is eventually considered).

Given that the learning of second-order patterns is generally more difficult than the learning of first-order patterns, we presented (between groups of participants) phonotactic patterns that involved either an arbitrary group of consonants or consonants that formed a natural class. Although phonotactic regularities that involve arbitrarily grouped consonants can be learned (Chambers et al., 2003, 2011), grouping the consonants into natural classes seems to make the task easier for both infants (Saffran & Thiessen, 2003) and adults (Endress & Mehler, 2010) and may be more ecologically valid, since many naturally occurring linguistic regularities involve phonetically similar segments. We reasoned that, if stress-based patterns are difficult to learn, participants exposed to groupings of phonetically similar consonants would be more likely to succeed.

Experiment 1

Method

Participants

Sixty-four undergraduate students, all native English speakers, participated for psychology course credit. Thirty-two were assigned to each condition (natural and arbitrary). Within each condition, there were two counterbalancing groups (with 16 participants in each). All participants indicated that they spoke English at least 85% of the time in their daily communication. None of the participants reported any hearing or language deficits.

Training stimuli

Training stimuli were created by arranging consonants and vowels into 64 items (non-words in English) of the form C_1vcvC_3 (where C = consonant, V = vowel). The word-initial (C_1) and word-final (C_3) consonants came from the set /p, b, t, d, s, z, f, v/. The medial consonant was either /m/ or /l/, and the vowels were /ɑ/, /o/, or /i/ (there was no repetition of vowels within an item). During training, participants heard 32 trochaic items and 32 iambic items. The items in each of these sets were generated from 16 consonant frames (e.g., p _ _ _ b) by filling each frame with two different medial vcv combinations. Critically, the trochaic and iambic items displayed different phonotactic patterns. Participants were assigned to either the natural or the arbitrary condition (see Table 1), differing in how the consonants, /p, b, t, d, s, z, f, v/, were assigned to C_1 and C_3.

Natural training stimuli

In the natural condition, the set of consonants assigned to C_1 matched in voicing, as did consonants assigned to C_3; thus, voicing differed across the two word positions. In counterbalancing Group 1 of the natural condition, the trochaic training items had voiceless consonants (/p, t, s, f/) in the C_1 position and voiced consonants (/b, d, z, v/) in the C_3 position (e.g., /ˈtomɑd/). The iambic training items had voiced consonants in the C_1 position and voiceless consonants in the C_3 position (e.g., /doˈmɑt/). In counterbalancing Group 2, the assignment of consonant sets to position was reversed for the two stress types (see Table 1).

Arbitrary training stimuli

In the arbitrary condition, the consonants assigned to C_1 did not share any single value of voicing, place of articulation, or manner of articulation. The same was true for the consonants assigned to C_3. In other words, the assignment of consonants to position was completely arbitrary. In counterbalancing Group 1 of the arbitrary condition, trochaic training items had consonants from the first arbitrary set /p, d, s, v/ in C_1 position and consonants from the second arbitrary set /b, t, z, f/ in C_3 position (e.g., /ˈpomɑt/). Iambic training items had consonants from the second arbitrary set in C_1 position and consonants from the first arbitrary set in C_3 position (e.g., /tɑˈmop/). In counterbalancing Group 2, the assignment of consonant sets to position was reversed for the two stress types.

Table 1. Summary of the training frames.

Condition	Word type	Group 1	Group 2
Natural	Trochaic	{p,s,t,f}_ _ _{b,z,d,v}	{b,z,d,v}_ _ _{p,s,t,f}
	Iambic	{b,z,d,v}_ _ _{p,s,t,f}	{p,s,t,f}_ _ _{b,z,d,v}
Arbitrary	Trochaic	{p,d,s,v}_ _ _{b,t,z,f}	{b,t,z,f}_ _ _{p,d,s,v}
	Iambic	{b,t,z,f}_ _ _{p,d,s,v}	{p,d,s,v}_ _ _{b,t,z,f}

Test stimuli

There were two testing blocks, each with 128 items. Of these, 64 were novel (untrained) test items: 32 (16 trochaic and 16 iambic) were consistent with the stress-contingent phonotactic patterns presented in the training items (i.e., *legal*), and 32 (16 trochaic and 16 iambic) were inconsistent with the patterns in the training items (i.e., *illegal*) since they were drawn from the familiarization and legal stimuli of the opposing counterbalancing group. Medial vcv combinations for the test stimuli were assigned such that, for a particular consonant frame, neither the legal nor the illegal test stimuli contained the same medial combinations as the training stimuli with the same frame. In addition, the 64 training items were also presented in each test block (for a total of 128 items in each test block). Repetitions of training items were included in the test blocks to reinforce the training patterns. Because learners are sensitive to the strength of probabilistic phonotactic patterns (Goldrick & Larson, 2008) and learn continuously throughout the session, including equal numbers of consistent and inconsistent stimuli (i.e., only novel legal and illegal items) during the test phase would lead to faster unlearning of training patterns. Therefore, we chose to include training items in the test to ensure that the training patterns remained probabilistically dominant. This approach has been adopted in previous studies of phonotactic learning (e.g., Bernard, 2015; Chambers et al., 2010). A summary of the training and test blocks is given in Table 2.

Stimuli recording

The stimuli were recorded by a female native speaker of English in a sound-proofed room. Multiple tokens of each stimulus were recorded, and the experimenters selected the token that best exemplified the intended stress pattern and target segments. Selected stimuli were normalized in Praat to reduce amplitude differences (Boersma & Weenink, 2012).

It is important to note that the instantiation of word stress was completely suprasegmental in our stimuli (i.e., marked only by relative syllable pitch, duration, and amplitude). Pitch, duration, and amplitude are all important cues to stress in English (Lieberman, 1960, and many others). Although English listeners

Table 2. Summary of the training and test blocks for Experiment 1.

	Group 1		Group 2	
Condition	Familiarization block	Each testing block ($N = 2$)	Familiarization block	Each testing block ($N = 2$)
Natural	64 training words CVcv**c** (32) **c**vCVC (32)	64 repeated training CVcv**c** (32) **c**vCVC (32) 32 legal CVcv**c** (16) **c**vCVC (16) 32 illegal **C**Vcvc (16) cvCV**C** (16)	64 training words **C**Vcvc (32) cvCV**C** (32)	64 repeated training **C**Vcvc (32) cvCV**C** (32) 32 legal **C**Vcvc (16) cvCV**C** (16) 32 illegal CVcv**c** (16) **c**vCVC (16)
Arbitrary	64 training words C_xVcvc_y (32) c_yvCVC_x (32)	64 repeated training C_xVcvc_y (32) c_yvCVC_x (32) 32 legal C_xVcvc_y (16) c_yvCVC_x (16) 32 illegal C_yVcvc_x (16) c_xvCVC_y (16)	64 training words C_yVcvc_x (32) c_xvCVC_y (32)	64 repeated training C_yVcvc_x (32) c_xvCVC_y (32) 32 legal C_yVcvc_x (16) c_xvCVC_y (16) 32 illegal C_xVcvc_y (16) c_yvCVC_x(16)

Note: Experiment 3 had the same stimuli and structure, but contained only half of the items (the trochaic items). Experiment 2 had the same familiarization items, but test trials involved pairs of only legal and illegal items. C = voiceless consonant; **C** = voiced consonant; C_x = consonant from arbitrary set /p, d, s, v/; C_y = consonant from arbitrary set /b, t, z, f/; CVcvc = strong–weak; cvCVC = weak–strong.

rely heavily on vowel quality to determine stress (Cutler, 2009), we chose not to include vowel reduction in our stimuli. We did this to eliminate the possibility that participants would learn the consonant restrictions based on segmental cues (i.e., full vs. reduced vowels). The absence of vowel reduction meant that participants needed to attend to the relative suprasegmental information across syllables. If anything, this decision works against our hypothesis, making the tracking of stress potentially more difficult for our English listeners.

To assess whether the stimuli had the intended stress patterns, we obtained perceptual judgments from 34 naïve monolingual English speakers who did not participate in the main experiment (each participant judged stimuli for both the natural and the arbitrary conditions). Participants predominantly judged trochaic items as having stress on the first syllable (86% and 82% for the natural and arbitrary stimuli, respectively) and iambic items as having stress on the second syllable (72% and 73% for the natural and arbitrary stimuli, respectively). Although some of our naïve listeners may have had difficulty explicitly assigning stress, our stimuli clearly exemplified the desired patterns, as 25% of the participants gave the intended stress pattern for >90% of both the trochaic and iambic items, and all items were correctly endorsed by the majority of participants. To corroborate these judgments, we also conducted acoustic analyses (see Table 3). The first syllables of trochaic items were significantly higher in peak pitch and intensity than second syllables; the reverse was true for iambic items. The difference in peak pitch and intensity for first and second syllables was highly significant in the intended direction for both trochaic and iambic items. Duration measurements showed that, for trochaic items, the second syllable was slightly longer than the first, but that this difference was much larger for iambic items. These syllable durations are difficult to compare directly across word types because of the nature of the medial consonants in our stimuli, /m/ and /l/. These consonants were perceptually judged to be ambisyllabic in the trochaic stimuli, but part of the second syllable in the iambic stimuli. Regardless, the acoustic measures were consistent in showing that the first syllable was stronger in trochaic items, and the second syllabic was stronger in iambic items.

Procedure

Stimuli were presented and responses recorded using PsyScope X (Cohen, MacWhinney, Flatt, & Provost, 1993). Participants were tested individually and listened to stimuli through Bose Quietcomfort 15

Table 3. Mean peak pitch, peak intensity, and duration values for first and second syllables.

	Pitch (Hz)		Intensity (dB)		Duration (ms)	
Word type	First syllable	Second syllable	First syllable	Second syllable	First syllable	Second syllable
Trochaic	285 (247–324)	213 (182–272)	67.7 (57–75)	61.4 (56–65)	389 (260–550)	457 (350–607)
Iambic	199 (166–234)	264 (232–301)	62.7 (57–68)	66.1 (61–71)	301 (156–459)	624 (467–807)

Note: Range in parentheses. Pitch, intensity, and duration differences between the syllables were highly significant for both trochaic and iambic words (all *ps* < .0001). The relatively long duration of the stimuli overall reflected the fact that there was no vowel reduction and that stimuli were bisyllabic, were articulated carefully, and had fully released offsets (to ensure that information about consonant identity was completely unambiguous in both onset and coda positions).

noise-cancelling headphones at a comfortable listening level of 60 to 65 decibels. They were asked to respond as quickly as possible without sacrificing accuracy. The experimenter remained in the room during the study to ensure that participants were attentive throughout.

During the familiarization block, participants were instructed to listen and indicate with a key press whether or not they liked each item. This task was included to encourage participants to pay attention to the familiarization stimuli. At the beginning of the first testing block, participants were given on-screen instructions stating that they would hear more items and that, for each item, they should indicate by key press whether or not they had heard it before. Note that participants were never instructed to pay attention to the stress or phonotactic patterns, and that during both familiarization and test, items with different patterns were randomly interspersed. However, if participants did not track word stress, the phonotactic patterns across the two stress types would cancel each other out.

To summarize, participants heard one familiarization block containing 64 training items, and two testing blocks, each containing 128 total items: 32 novel legal and 32 novel illegal items (as well as a repetition of the 64 training items). There was no break between testing blocks; participants simply continued making judgments about whether or not they had heard each item before. Within each block, stimuli were heard in random order.

Results

We examined the proportion of "yes" responses for each word type (training, legal, illegal). All "yes" responses would yield a score of 1, and all "no" responses would yield a score of 0. As seen in Table 4, participants in both the natural and arbitrary conditions responded "yes" more frequently for the training items than for the legal or illegal items. However, the critical test of learning the phonotactic patterns (as opposed to remembering specific training items) involves performance on the legal versus illegal test items. All of these items should be identified as new. However, if participants have learned the phonotactic patterns, they should be more likely to falsely recognize legal items than illegal items, even though they have never heard either previously. Thus, only legal and illegal test items were included in the analyses.

For each experiment, proportions derived from the categorical dependent variable were regressed, using mixed effects logistic regression[2] (Bates, Maechler, Bolker, & Walker, 2014; Jaeger, 2008; R Core Team, 2015), onto the full factorial design that included all fixed effects and interactions. Fixed effects were centred to reduce collinearity with interaction terms, and unless reported otherwise, collinearity remained low (<0.2). Models contained the maximal random effects structure justified by the design of the experiment that would converge (Barr, 2013; Jaeger, 2011).

In Experiment 1, the proportions of false recognition were regressed onto the fixed effects of condition (natural, arbitrary), stress pattern (trochaic, iambic), word type (legal, illegal), test block (first, second), and their interactions. For random effects, intercepts for subjects and items were included, as well as by-subject and by-item random slopes for the effects of stress pattern and word type. There was a main effect of word type ($\beta = 0.18$, $SE = 0.05$, $p < .001$), with participants falsely recognizing more legal than illegal test items (a "legality advantage"; see Figure 1). Interestingly, there was a significant two-way interaction between word type and stress pattern ($\beta = 0.27$, $SE = 0.10$, $p < .01$); the observed legality advantage was carried by the iambic and not the trochaic test items.[3] We also found that condition interacted with word type ($\beta = 0.28$, $SE = 0.10$, $p < .01$). The legality advantage was clearly apparent in the natural, but not the arbitrary, condition. Finally, participants were more likely to falsely recognize test items in the first rather than the second test block ($\beta = 0.11$, $SE = 0.05$, $p < .05$), especially in the natural condition ($\beta = 0.29$, $SE = 0.09$, $p < .05$), as

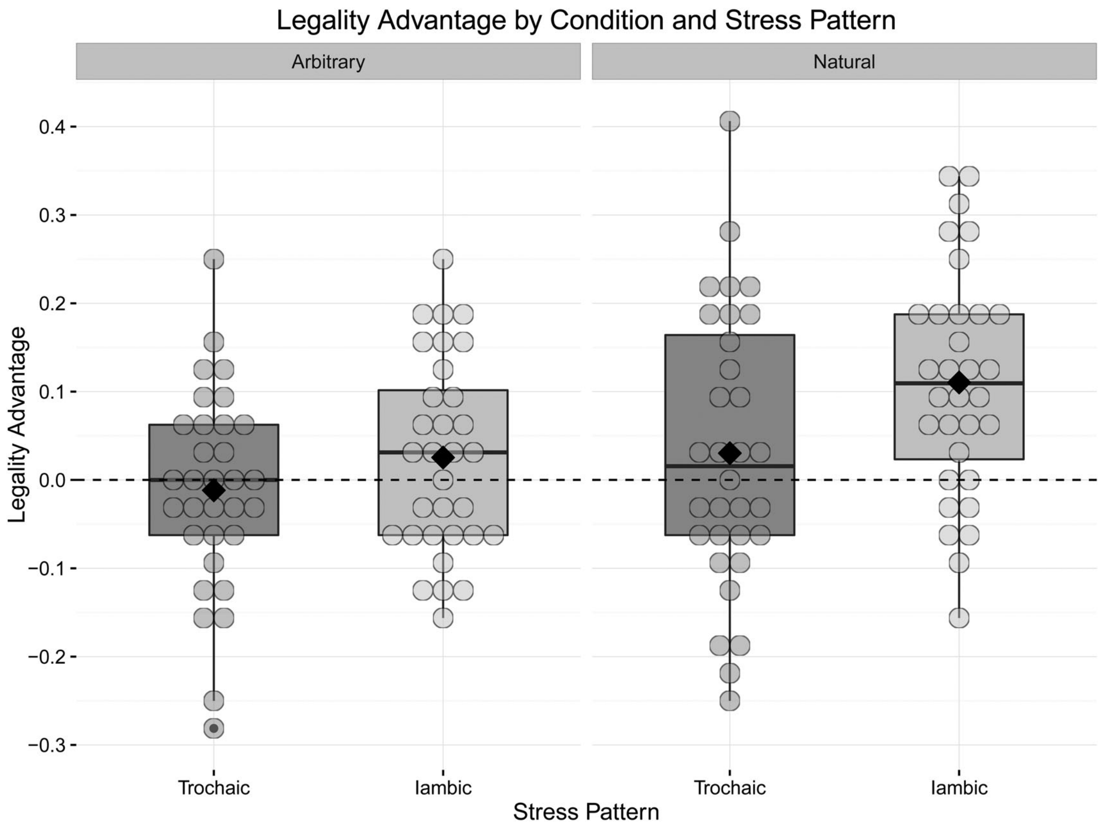

Figure 1. Proportion of "yes" responses for the legal items minus the proportion of "yes" responses for the illegal items for each participant (filled circles) and group means (solid black diamonds) by condition and stress pattern in Experiment 1.

demonstrated by the two-way interaction between block and condition. In studies with multiple testing blocks, learning is always more robustly demonstrated in the first block of testing, because the presence of illegal items during that block dilutes the regularities by the second block.

As was the case in the main analysis, when each condition was modelled separately, with counterbalancing group added as a fixed effect, the natural condition showed a significant effect of word type ($\beta = 0.33$, $SE =$ 0.07, $p < .0001$). Although participants showed an overall legality advantage, there was again a significant two-way interaction between word type and stress pattern ($\beta = 0.37$, $SE = 0.13$, $p < .01$), since the observed legality advantage was carried by the iambic test items. In fact, modelling each stress pattern separately within the natural condition showed a significant effect of word type ($\beta = 0.51$, $SE = 0.11$, $p < .0001$) within iambic test items but not trochaic test items ($\beta = 0.14$, $SE =$ 0.12, $p = .26$). Finally, participants in the natural condition were more likely to falsely recognize test items in the first than in the second test block ($\beta = 0.26$, $SE = 0.07$, $p < .001$). In contrast, none of the fixed effects or interactions significantly predicted outcomes for participants in the arbitrary condition.

To interpret these effects, recall that if participants have learned the phonotactic patterns present in familiarization, they should be more likely to falsely recognize legal items than illegal items. Overall, the pattern of results indicates that participants in the natural, but not the arbitrary, condition were successful in learning the familiarization patterns. This means that participants tracked consonant position contingent on stress pattern, despite the fact that the familiarization items were presented in random, intermixed order, and there was no instruction to attend to stress. However, their performance was not equivalent for the two types of stress patterns—participants were more successful with iambic test items (i.e., they were better able to differentiate legal and illegal items). Because this asymmetry was unexpected, we sought to determine whether it would be robust across

Table 4. Mean proportion of "yes" responses for each word type in Experiments 1, 3, and 4.

Experiment	Condition	Training	Legal	Illegal	Legality advantage
Experiment 1	Natural (overall)	.633 (.16)	.577 (.18)	.508 (.16)	.068 (.09)
	Trochaic	.623 (.16)	.551 (.2)	.516 (.18)	.035 (.15)
	Iambic	.644 (.17)	.603 (.19)	.501 (.18)	.102 (.12)
	Arbitrary (overall)	.668 (.15)	.578 (.17)	.571 (.16)	.007 (.06)
	Trochaic	.657 (.16)	.549 (.21)	.561 (.2)	−.012 (.11)
	Iambic	.68 (.16)	.606 (.17)	.581 (.16)	.025 (.11)
Experiment 3	Natural				
	Trochaic only	.8 (.10)	.678 (.11)	.197 (.149)	.480 (.15)
	Arbitrary				
	Trochaic only	.711 (.12)	.580 (.17)	.25 (.23)	.330 (.23)
Experiment 4	Natural (overall)	.627 (.2)	.542 (.18)	.453 (.16)	.09 (.09)
	Trochaic	.603 (.21)	.511 (.2)	.444 (.18)	.066 (.12)
	Iambic	.652 (.2)	.574 (.2)	.461 (.17)	.113 (.17)

Note: Legality advantage represents the legal score minus the illegal score. Standard deviations in parentheses.

different types of recognition tasks. Experiment 2 contained the same training phase as Experiment 1, but a different type of test in which participants made a forced choice between legal and illegal items (see Endress & Mehler, 2010, for use of a forced-choice test in phonotactic learning).

Experiment 2

Method

Participants

Forty-eight undergraduate students, all native English speakers, participated for psychology course credit. Twenty-four were assigned to each condition (natural and arbitrary). Within each condition, there were two counterbalancing groups (with 12 participants in each). All participants indicated that they spoke English at least 85% of the time in their daily communication. None of the participants reported any hearing or language deficits.

Training stimuli

Training stimuli were identical to those in Experiment 1.

Test stimuli

The legal and illegal stimuli from Experiment 1 were used.

Procedure

The familiarization phase was identical to that of Experiment 1. In test, two items (one legal and one illegal) were presented in each trial, separated by 500 ms. Legal and illegal stimuli were paired (pseudo-randomly), with the constraint that only trochaic or iambic items occurred within a trial. The order of trials was random (including whether the trial was trochaic or iambic). Participants indicated (by key press) whether the first or second item of the pair sounded more like the training items. Again, the primary motivation for using a forced-choice task was to seek converging evidence for the unexpected asymmetry with a different task. In addition, previous research has demonstrated that some sensitivities are more apparent when forced-choice, as opposed to single item, responses are employed (e.g., Daland et al., 2011).

Results

Each test trial involved a forced choice between a legal and illegal stimulus of the same stress type. If participants have learned different phonotactic patterns for the two types of words, they should choose the legal items at rates significantly above 50%. The percentages of legal choices by condition and word type are shown in Figure 2.

The proportions of choosing legal test items were regressed onto the fixed effects of condition (natural, arbitrary), stress pattern (trochaic, iambic), and their interaction. For random effects, intercepts for subjects and items were included, as well as by-subject and by-item random slopes for the effect of stress pattern.

Participants were more likely to choose the legal item when the test pair included iambic rather than trochaic words ($\beta = 0.22$, $SE = 0.11$, $p < .05$) in both the natural (iambic: $M = 58.5\%$; trochaic: $M = 50\%$) and the arbitrary (iambic: $M = 54\%$; trochaic: $M = 52\%$) conditions. When compared to chance (50%), we found that performance on iambic items exceeded chance in both conditions [natural: $t(23) = 3.3$, $p < .005$;

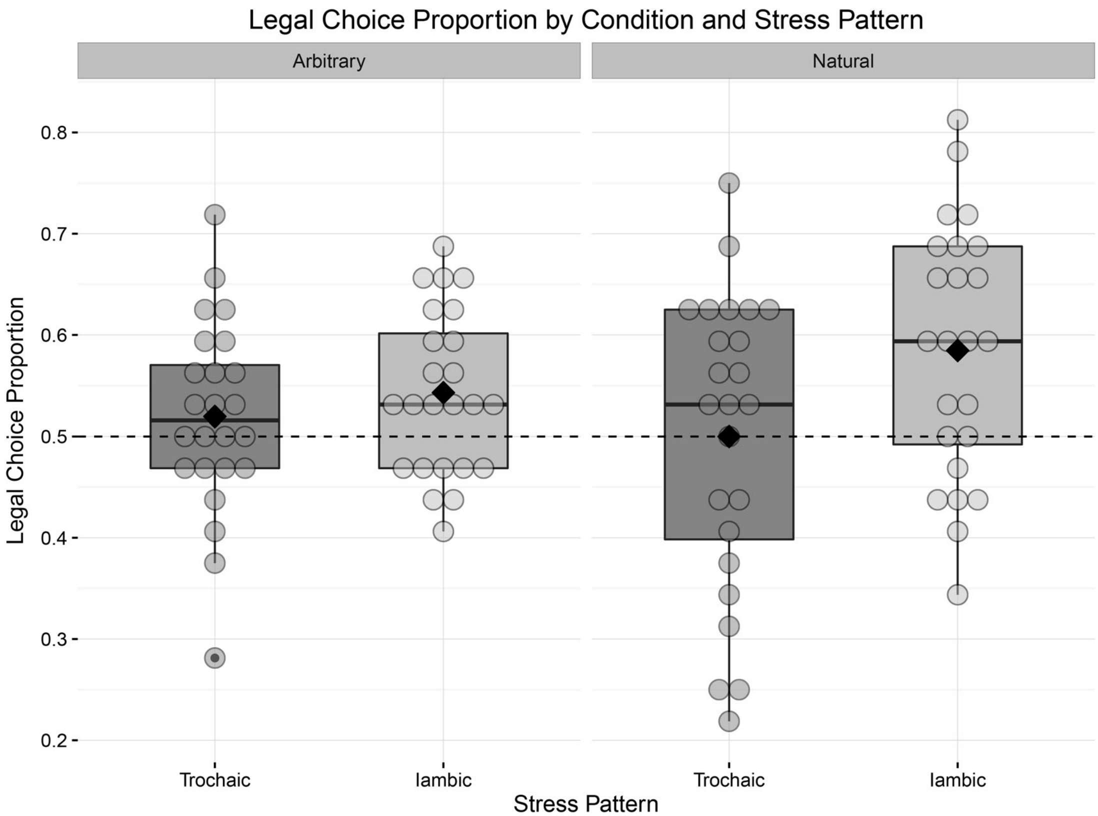

Figure 2. Proportion of legal items chosen for each participant (filled circles) and group means (solid black diamonds) by condition and stress pattern in Experiment 2.

arbitrary: $t(23) = 2.62$, $p < .05$], but that performance on trochaic items did not [$t(23) = 0$, *ns*; $t(23) = 1.01$, *ns*].

The analyses above reveal that, again, phonotactic patterns were easier to learn for iambic items, replicating the trochaic–iambic learning asymmetry observed in Experiment 1. In order to determine whether participants were able to learn novel phonotactic patterns involving trochaic items in a simpler situation, we conducted Experiment 3. Experiment 3 followed the same procedure as that of Experiment 1. However, only the trochaic stimuli were included. Therefore, in contrast to Experiments 1 and 2, learners were exposed to first-order regularities and did not need to track stress.

Experiment 3

Method

Participants

Thirty-two undergraduate students, all native English speakers, participated for psychology course credit. Sixteen were assigned to each condition (natural and arbitrary). Within each condition, there were two counterbalancing groups (with eight participants in each). All participants indicated that they spoke English at least 85% of the time in their daily communication. None of the participants reported any hearing or language deficits.

Training stimuli

The trochaic training stimuli from Experiments 1 and 2 were used. To equate the length of the training phase, each item was repeated twice during training.

Test stimuli

The trochaic legal and illegal stimuli from Experiment 1 were used. As only trochaic test stimuli were used, the test phase contained half the number of stimuli as Experiment 1.

Procedure

The procedure was identical to that of Experiment 1.

Results

As in Experiment 1, we examined the proportion of "yes" responses for each word type. These proportions are given in Table 4. To assess whether participants learned the trained patterns, the proportions of false recognition were regressed onto the fixed effects of condition (natural, arbitrary), word type (legal, illegal), test block (first, second), and their interactions. Since all stimulus items were trochaic, stress pattern was not included. For random effects, intercepts for subjects and items were included, as well as a by-item random slope for the effect of word type. Participants falsely recognized more legal than illegal items, as shown by a significant effect of word type ($\beta = 2.00$, $SE = 0.13$, $p < .0001$). This legality advantage was greater in the natural than in the arbitrary condition ($\beta = 0.78$, $SE = 0.23$, $p < .001$). In addition, a significant three-way interaction emerged ($\beta = -1.31$, $SE = 0.42$, $p < .005$), since the larger legality advantage in the natural than in the arbitrary condition was carried by participants' performance in the first block of testing (see Figure 3).

When each condition was modelled separately, with counterbalancing group as a fixed effect, the natural condition showed a significant effect of word type ($\beta = 2.33$, $SE = 0.16$, $p < .0001$). Participants in this condition showed a robust legality advantage. There was also a significant two-way interaction between word type and block ($\beta = -1.29$, $SE = 0.31$, $p < .0001$), since the observed legality advantage was larger in the first test block. In the arbitrary condition, only a significant effect of word type ($\beta = 1.63$, $SE = 0.15$, $p < .0001$) was observed, with participants falsely recognizing legal test items more frequently than illegal test items. Therefore, participants were able to learn both natural and arbitrary patterns involving trochaic items when these were the only items in the training set.

Experiment 4

Experiments 1–3 demonstrate that adults can rapidly learn new phonotactic patterns contingent on word stress. However, they provide no evidence that two sets of contradictory patterns can be learned simultaneously (unlike second-order patterns contingent on vowel identity). In Experiment 4, we replicated the training and test procedure of Experiment 1, but lengthened the training phase to determine whether the failure to learn patterns on trochaic items was due to an absolute constraint on learning (such that it is only possible to learn one pattern at a time) or instead due to relative difficulty in learning novel patterns on iambic and trochaic words. Because the previous experiments found robust learning only when phonetically related segments were involved, we tested only the natural condition in Experiment 4.

Method

Participants

Thirty-two undergraduate students, all native English speakers, participated for psychology course credit. All were assigned to the natural condition, with 16 per counterbalancing group. All participants indicated that they spoke English at least 85% of the time in their daily communication. None of the participants reported any hearing or language deficits.

Training stimuli

The training stimuli from the natural condition of Experiment 1 were used. However, each stimulus was repeated three times during training.

Test stimuli

The test stimuli were identical to those of the natural condition of Experiment 1.

Procedure

The procedure was identical to that of Experiment 1, with the exception that the added repetitions of the training stimuli increased the length of the experimental session.

Results

As in Experiment 1, we examined the proportion of "yes" responses for each word type. These proportions are given in Table 4. In the current experiment, the proportions of false recognition were regressed onto the fixed effects of stress pattern (trochaic, iambic), word type (legal, illegal), test block (first, second), and their interactions. For random effects, intercepts for subjects and items were included, as well as by-subject and by-item random slopes for the effects of stress pattern and word type. There was a main effect of word type ($\beta = 0.41$, $SE = 0.08$, $p < .0001$), with participants falsely recognizing more legal than illegal test items, again showing a legality advantage. Participants falsely recognized iambic test items more frequently than trochaic test items ($\beta = 0.18$, $SE = 0.09$, $p < .05$). Unlike Experiment 1, in this experiment, there was no significant two-way interaction between word type and

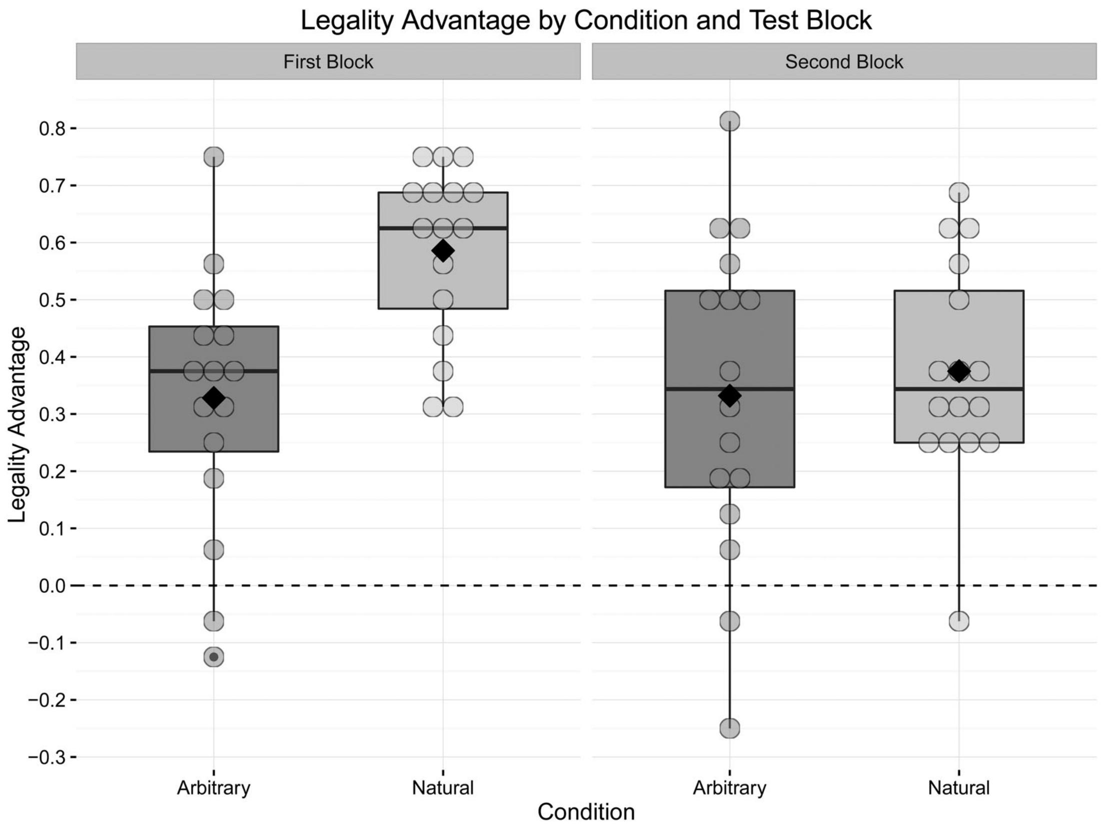

Figure 3. Proportion of "yes" responses for the legal items minus the proportion of "yes" responses for the illegal items for each participant (filled circles) and group means (solid black diamonds) by condition in the first test block (left) and second test block (right) for Experiment 3.

stress pattern ($\beta = 0.21$, $SE = 0.13$, $p = .11$). With increased familiarization, the observed legality advantage was present for both the iambic and trochaic test items. This was confirmed by a significant effect of word type for both iambic ($\beta = 0.52$, $SE = 0.14$, $p < .0005$) and trochaic ($\beta = 0.31$, $SE = 0.10$, $p < .005$) items when each stress pattern was modelled separately. Finally, participants were overall more likely to show a legality advantage in the first test block ($\beta = -0.51$, $SE = 0.13$, $p < .001$), especially for iambic test items, as seen in Figure 4 and supported by a significant three-way interaction between stress type, word type, and test block ($\beta = -0.53$, $SE = 0.27$, $p < .05$).

Therefore, when the amount of training is increased, learning both sets of patterns simultaneously is possible.

General discussion

Previous work has found that, although second-order phonotactic patterns contingent on segment (e.g., vowel) identity are learnable in laboratory experiments, those based on extra-linguistic cues, such as talker voice or speech rate, are not. These findings have been used as support for the modularity of the phonotactic learning system (Warker et al., 2008). However, the modularity claim has not been directly tested because of the types of conditioning contexts used in previous studies. In four experiments, we explored whether the constraint on learning is a result of linguistic status (as would be predicted on the modularity account) or is instead due to the grain of the information (segmental vs. global) monitored by the learning system. To test this, we presented participants with second-order patterns conditioned on a suprasegmental, but linguistically relevant, property—word stress. In Experiment 1, participants who were familiarized with patterns involving natural groupings of consonants falsely recognized more legal test items than illegal test items, showing that they had internalized the familiarization patterns. However, further inspection revealed

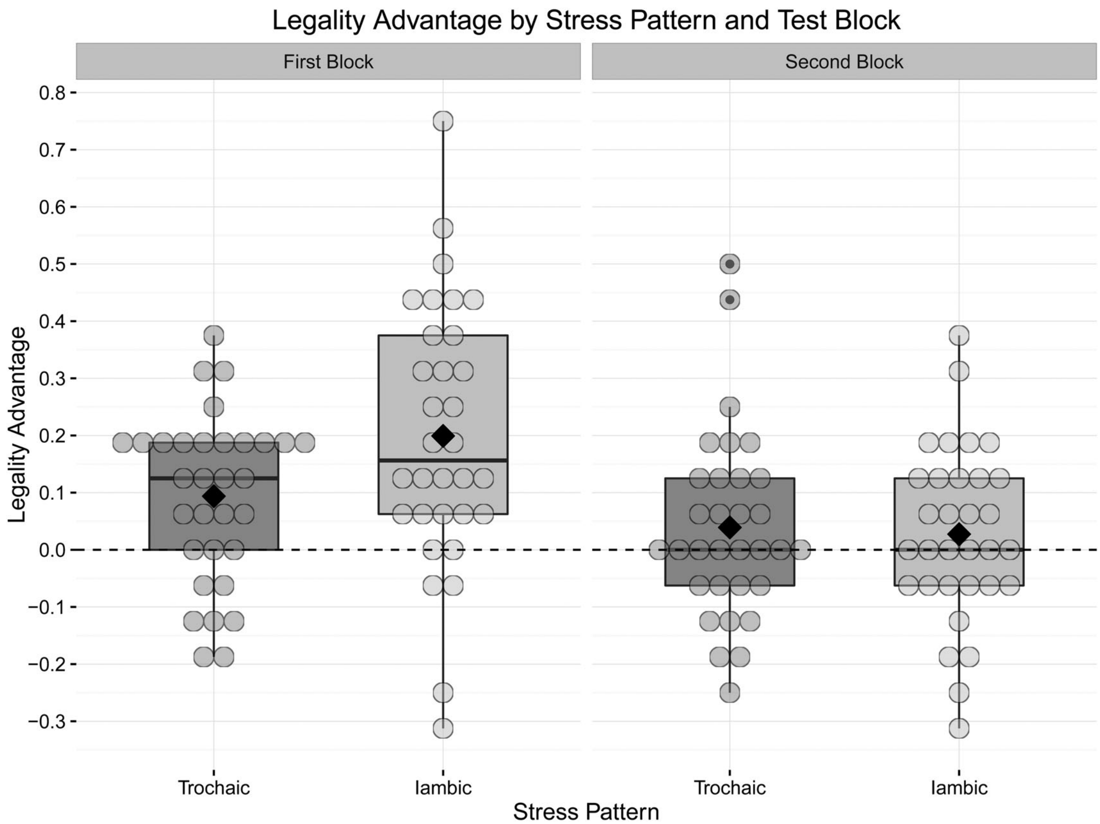

Figure 4. Proportion of "yes" responses for the legal items minus the proportion of "yes" responses for the illegal items for each participant (filled circles) and group means (solid black diamonds) by stress type in the first test block (left) and the second test block (right) for Experiment 4.

that this was only statistically significant for iambic stimuli. Experiment 2 replicated these findings with a forced-choice test. Experiment 3 demonstrated that participants were successful in learning phonotactic patterns for trochaic items when there were no iambic items presented. Finally, Experiment 4 demonstrated that participants were able to learn both sets of patterns when the training phase was lengthened.

The learning of at least one set of patterns in all four experiments demonstrates that suprasegmental information is indeed tracked during phonotactic learning, adding to the body of research showing that both adults and infants can use secondary cues for phonotactic learning (Chambers et al., 2011; Onishi et al., 2002; Seidl & Buckley, 2005; Seidl et al., 2009; Warker & Dell, 2006). More importantly, these results indicate that the implicit phonotactic learning system considers information beyond the segmental level, when that information is phonological in nature. This suggests that existing models of phonotactic learning (e.g., Warker et al., 2008) should be expanded to include higher level phonological information (see also Bennett, 2012, who found that participants were able to learn a regularity in which a particular vowel was constrained to post-stress syllables). Given previous failures to find learning for phonotactic patterns conditioned on information that is indexical or relating to surface form only, these results are consistent with the claim that phonological information (regardless of the scope) is privileged in phonotactic learning. They also raise intriguing questions about whether and why phonotactic learning may be different from other types of learning in which indexical features are tracked (such as phonetic category learning; Allen & Miller, 2004).

As has been previously demonstrated (Endress & Mehler, 2010; Saffran & Thiessen, 2003), we also found that, across experiments, learning was more consistently observed for participants exposed to patterns involving natural classes of sounds. In Experiment 1, participants in the arbitrary condition recognized particular training items, but their lack of differentiation between legal and illegal test items indicates that they did not learn the phonotactic patterns exemplified by the training stimuli. Similarly, in Experiment 3, although both arbitrary and natural patterns were learned, performance was significantly better for natural patterns in the first block of testing. Previous work has shown that phonotactic learning can occur both at the level of individual segments and at the featural level (Goldrick, 2004). To learn the patterns in our arbitrary conditions, participants needed to track the contexts for each individual consonant (e.g., that /p/, /d/, /s/, and /v/ occurred in the onset of trochaic items and that /b/, /t/, /z/, and /f/ occurred in the coda position—and that the reverse was true of iambic items). Participants in the natural conditions could have engaged in this same strategy of segment-by-segment learning. However, the fact that performance was better in the natural conditions (significantly so both in Experiment 1 and in the first block of Experiment 3, as well as numerically in Experiment 2) suggests that they employed a simpler strategy: encoding patterns along a single featural dimension (voicing) and learning that the positions of voiced and voiceless consonants were constrained by word stress. A more stringent test of this possibility would involve testing whether participants generalize the patterns to unheard segments from the same natural class at test (e.g., k and g). However, we suggest that the natural condition advantage indicates that participants were indeed tracking features in this condition. This is consistent with previous research demonstrating that, although patterns involving arbitrary sets of consonants are learnable (e.g., Chambers et al., 2010; Onishi et al., 2002; Seidl et al., 2009; Warker & Dell, 2006), learning arbitrary patterns becomes less likely (Saffran & Thiessen, 2003) or may not happen at all (Endress & Mehler, 2010) as tasks become more challenging.

One remaining puzzle is why the patterns on iambic items were more readily learned. While Experiments 3 and 4 showed that participants were able to learn the phonotactic patterns on trochaic items, Experiments 1 and 2 demonstrated that learning was easier and/or faster for iambic items. Since this finding was unexpected, we are hesitant to draw strong conclusions at this point; however, the data do allow us to eliminate one possible reason for this asymmetry. One might argue that since the majority of bisyllabic words in English are trochaic, iambic items captured participants' attention during training, and, as a result, they simply ignored the trochaic items. If true, this would in essence mean that participants were attending to first-order, rather than second-order, patterns. However, this is clearly not the case. In Experiment 4, in which the familiarization time was lengthened, participants did learn both sets of patterns. Moreover, participants were equally accurate at recognizing trochaic and iambic *training* items in Experiment 1, indicating that they did indeed attend to the trochaic items during training. Finally, if participants were simply tracking first-order patterns on iambic stimuli in Experiment 1, they should have been successful in the arbitrary condition, since arbitrary first-order patterns are easily learned by both infants and adults (e.g., Chambers et al., 2003; Onishi et al., 2002).

Therefore, participants do appear to have been tracking both word stress types. However, that leaves the question of why it was more difficult for them to learn the patterns instantiated on the trochaic items. One possibility is that learning in our task was not encapsulated from participants' native language knowledge (Finn, Hudson, & Kam, 2008; Warker, 2013) and that this asymmetry has to do with the relationship of our stimuli to naturally occurring phonotactic patterns. In natural languages, there are segmental alternations that are conditioned by stress. For example, across languages, segments in stressed syllables tend to be stronger than those in weak syllables, where weakening or deletion tends to occur (though the reverse can happen as well; Gordon, 2011). In English, coronal stops are weakened to flaps at the onset of unstressed syllables ("city" pronounced as /sɪɾi/), vowels reduce to schwa in unstressed syllables (or are deleted altogether, as in *camera→camra*, Hooper, 1978), and consonants are aspirated (strengthened) in the onset of stressed syllables. In addition, in English (and cross-linguistically), word-final consonants in unstressed syllables tend to be less marked (i.e., coronal, voiceless; Zamuner, 2003). Perhaps the observed asymmetries in learning for our trochaic and iambic items were a result of how our patterns aligned with these natural language distributions.

However, exploration of our stimuli suggests that, if there were any effects of real-world similarity on ease of learning, they are not straightforward. Recall, first of all, that our stimuli included no vowel reduction in either trochaic or iambic items (so this cue was equally inconsistent for both types of items). In addition, although participants were familiarized with different patterns as a result of counterbalancing, we did not find differences across groups that would indicate greater ease of learning for certain consonant assignments. For example, in our stimuli, the natural groups differed in how voicing was assigned to each position. Half of the participants heard voiceless segments in the onset of trochaic items and coda of iambic items (and vice versa for voiced segments). The other half had the opposite assignment. Since voiceless segments are more likely (than voiced) word-finally in unstressed syllables (Zamuner, 2003), this would suggest that trochaic items with voiceless final segments might be easier to learn than those with voiced final segments. However, we observed no consistent asymmetries in performance for learning trochaic items between our natural groups. Likewise, the assignment of segments to position was counterbalanced across groups for our iambic stimuli, and here, too, there were no asymmetries in performance.

Rather than observing such distribution-driven differences in learning within each word type, we observed a more global advantage for learning iambic stimuli (regardless of the specific patterns). There are a number of possible reasons for this. One is that it may have been more difficult for participants to learn that segments were *restricted* to certain positions in trochaic items. Our participants have had a great deal of real-world evidence that all of the segments we used in our stimuli *can* occur in both the onset and coda position of English words (despite differences in the relative frequency with which they do so). Because trochaic words outnumber iambic words in English, this evidence is stronger for trochaic words. As a result, learning to restrict segments to particular positions may have been more difficult for trochaic stimuli. A second possibility is that learning was faster on iambic items because they were more distinct from the majority of English words, leading to greater encapsulation from real-world language knowledge during the task (Warker, 2013). And finally, the asymmetry may reflect a general advantage, at least early in learning, for "less good" forms. For example, Gladfelter and Goffman (2013) reported an iambic (vs. trochaic) advantage in a production task tapping children's novel word learning, and studies of novel word learning in adults similarly show an advantage for words that are more atypical early in the learning process (e.g., lower phonotactic probability; Storkel, Armbruster, & Hogan, 2006). Regardless of the reason, the learning asymmetry is only a relative one, as Experiment 4 demonstrated learning of both types of patterns with additional training.

Importantly, participants were never instructed to attend to stress, and yet they discovered and used the stress cue, despite the fact that items with different stress patterns were randomly intermingled during familiarization. Moreover, the absence of vowel reduction in unstressed syllables (which could have served as a segmental cue) meant that they needed to rely on the global prosodic cues to stress, such as the relative duration, pitch, and amplitude of the two syllables. Although prosodic factors also introduce phonetic changes in the realization of segments (e.g., a /p/ in the onset of a stressed syllable is not phonetically identical to a /p/ in the onset of a weak syllable), attention to these differences would not have been sufficient for learning the patterns. For example, a strategy of linking phonetically weak /p/s to only onset or coda position would not have been beneficial, since they occurred in both positions, as a function of the stress pattern. In previous studies of second-order phonotactic learning, in which consonant position was conditioned on vowel identity, phonetic cues may have been more useful. For example, if /p/ occurs in onset position when followed by /ɪ/, but in coda position when preceded by /æ/, there are phonetic cues that could potentially be used by the learner. These include differences in the realization of /p/ in onset versus coda position and co-articulatory information due to the adjacent vowels. The question of whether listeners use this phonetic variability during phonotactic learning and whether they are tracking context-specific phones or more abstract features/phonemes is an important question for future research. However, this type of variability alone is clearly insufficient to drive learning. Speech rate and talker voice introduce significant variability in the realization of segments, but previous studies have found no evidence of phonotactic learning based on these properties.

Finally, the present findings also have implications for bilingual language acquisition. Since phonotactic regularities are language specific, a person learning two languages may be required to learn different sets of regularities, and in some cases, these sets may even be contradictory. For example, /ŋ/ can begin words in Vietnamese even though it does not in English. Therefore, in order to establish and maintain different phonotactic patterns for each language, the language learner needs to track the contexts in which each set of patterns occurs. If learners attend to properties that distinguish languages, such as more global prosodic properties, they could potentially use these properties to keep phonotactic patterns, even contradictory ones, separate. Recent research has demonstrated that prosodic differences may, indeed, help bilingual learners partition the input in a way that facilitates the acquisition of other linguistic information. For example, infants who are learning English and Spanish, two languages from different rhythmic classes, are able to discriminate the perceptually close /e/ and /ɛ/ contrast at eight months of age (Sundara & Scutellaro, 2011) whereas infants learning Catalan and Spanish, languages from the same rhythmic class, show less robust discrimination abilities of these sounds at the same age (Bosch & Sebastián-Gallés, 2003; cf. Albareda-Castellot, Pons, & Sebastian-Galles, 2011). Similarly, bilinguals' sensitivity to prosody has also been argued to bootstrap their simultaneous acquisition of two different word order systems (Gervain & Werker, 2013): Bilingual English–Japanese 7-month-olds parse speech streams in ways consistent with English or Japanese word order, depending on the prosodic cues present. The present results suggest that prosodic cues could similarly serve to sort the input in a way that allows infants to learn the phonotactic properties of each language individually. More generally, prosodic information may be useful for separating input from multiple languages, allowing for the simultaneous acquisition of other aspects of language structure, including phonetic, lexical, and grammatical properties.

In sum, we demonstrate that word stress can serve as a second-order cue for the learning of phonotactic patterns. This finding has implications for the basic mechanisms of phonotactic learning: The information considered by the learning system extends beyond the level of the segment, as long as it is phonological in nature. Our results additionally reinforce previously observed asymmetries in learning based on phonetic similarity. Learning is facilitated when segments that behave the same way (e.g., occupy the same position) share phonological features. More generally, the current findings further delineate the properties of the system responsible for the acquisition of phonotactic patterns in children and the continual updating of such knowledge in adults.

Notes

1. There are strong relationships in English between the stress pattern of bisyllabic words and their lexical category, with the majority of nouns being trochaic and verbs more likely to be iambic (Kelly, 1992). Whether participants will implicitly categorize our stimuli according to lexical class is not clear. Regardless, the task of learning different phonotactic patterns for the two sets of items remains.
2. Traditional analysis of variance (ANOVA) analyses showed the same patterns of results for all experiments.
3. To confirm our primary analysis, we conducted further modelling in which our categorical labels for stress pattern (trochaic and iambic) for each stimulus item were replaced with pitch and intensity difference scores across syllables. We found the same pattern of results—participants falsely recognized more legal than illegal test items when items had stronger final syllables, but not when they had stronger initial syllables. This was true both when the intensity difference scores ($\beta = -0.02$, $SE = 0.009$, $p < .01$) and the pitch difference scores ($\beta = -0.02$, $SE = 0.007$, $p < .01$) were used (pitch difference scores were rescaled, divided by 10, to reduce the spread for modelling). Furthermore, models that used stress pattern, intensity difference, or pitch difference were found to be statistically equivalent to each other when compared.

Acknowledgements

The authors would like to thank Kavita Schaffer, Katelyn Burden, Amy Xu, Erik Johnson, Olivia Daub, and Danielle Vetter for assistance with data collection, as well as Tania Zamuner and an anonymous reviewer for helpful feedback.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by an operating grant from the 10.13039/501100000038 Natural Sciences and Engineering Research Council of Canada to K.S.W.

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