Journal of Memory and Language 92 (2017) 142–157

Contents lists available at ScienceDirect

Journal of Memory and Language

journal homepage: www.elsevier.com/locate/jml

# Learning metathesis: Evidence for syllable structure constraints

Sara Finley *

*Pacific Lutheran University, United States*

ARTICLE INFO

*Article history:*
Received 19 August 2015
revision received 17 June 2016

*Keywords:*
Phonology
Artificial grammar learning
Metathesis
Syllable structure

ABSTRACT

One of the major questions in the cognitive science of language is whether the perceptual and phonological motivations for the rules and patterns that govern the sounds of language are a part of the psychological reality of grammatical representations. This question is particularly important in the study of phonological patterns – systematic constraints on the representation of sounds, because phonological patterns tend to be grounded in phonetic constraints. This paper focuses on phonological metathesis, which occurs when two adjacent sounds switch positions (e.g., *ca**st*** pronounced as *ca**ts***). While many cases of phonological metathesis appear to be motivated by constraints on syllable structure, it is possible that these metathesis patterns are merely artifacts of historical change, and do not represent the linguistic knowledge of the speaker (Blevins & Garrett, 1998). Participants who were exposed to a metathesis pattern that can be explained in terms of structural or perceptual improvement were less likely to generalize to metathesis patterns that did not show the same improvements. These results support a substantively biased theory in which phonological patterns are encoded in terms of structurally motivated constraints.

© 2016 Elsevier Inc. All rights reserved.

## Introduction

One of the goals of the cognitive science of language is to understand the relationship between human cognition and the rules and patterns that are found across languages of the world. In the search for understanding this relationship, questions arise in regards to the extent to which patterns in languages are arbitrary, or are grounded in perceptual and cognitive principles. A phonological pattern is grounded if it can be explained in terms of phonetic grounding (e.g., increases the perceptibility of a word) or structural improvements (e.g., improves the syllable structure of a word), and is arbitrary if the pattern cannot be explained in these terms (Anderson, 1981).

On the one hand, linguistic patterns are typically analyzed using features and representations that are highly specific to language and language structure (e.g., vowel height) (Berent, Balaban, Lennertz, & Vaknin-Nusbaum, 2010; Goldsmith, 1993; Kiparsky, 1973), and include the structural improvements that result from the phonological rule/pattern (e.g., a reduction in markedness[1]) (Prince & Smolensky, 2004). On the other hand, linguistic patterns are often analyzed using highly abstract, symbolic constructions (e.g., reduplication as /AB/ → [ABAB]) (Chomsky & Halle, 1968). Phonological patterns can be considered abstract in two ways. First, phonological patterns refer to an 'underlying' form, or input, that may never be pronounced by a language user. Second, the representation makes use of symbols that include a wide range of elements (e.g., high vowels, or final position). The use of abstract

* Address: Department of Psychology, Pacific Lutheran University, 12180 Park Ave S, Tacoma, WA 98447, United States.
*E-mail address:* finleysr@plu.edu

[1] Markedness is defined as the extent to which a phonological unit is dispreferred due to articulatory, perceptual and other cognitive constraints.

http://dx.doi.org/10.1016/j.jml.2016.06.005
0749-596X/© 2016 Elsevier Inc. All rights reserved.

symbols opens the possibility for patterns to apply not only to linguistic units, but to non-linguistic units as well (Finley & Christiansen, 2011) (e.g., the element in final position is repeated). This raises the question as to whether symbolic rules are formed from general cognitive mechanisms, rather than from domain specific language generators (Chater & Christiansen, 2010; Monaghan, Chater, & Christiansen, 2005; Monaghan, Christiansen, & Chater, 2007), and whether the structural constraints that motivate linguistic patterns duplicates both domain-general cognitive constraints and considerations from language change, and therefore need not be included in the linguistic grammar (Blevins, 2004; Hale & Reiss, 2000). This issue is especially relevant for phonological patterns, which tend to be abstractions from more universal phonetic principles (Hyman, 1976). For this reason, this paper will focus on phonological patterns, specifically metathesis.

Phonological metathesis occurs when two adjacent sounds switch places (e.g., pronouncing '*cast*' as '*cats*', in which the /t/[2] and the /s/ switch).[3] Because many cases of metathesis are diachronic, or historical in nature, some cases of metathesis may appear to be arbitrary. Within the Metathesis in Language Database (Hume, 2016), several languages are listed as having no clear motivation,[4] either phonetic or phonological, and can be considered to be arbitrary. For example, in Georgian, the thematic suffix /-av/ metathesizes with sonorants, (e.g., /k'l + av/ → [k'vla] 'you kill them'), without any clear phonetic or phonological motivation (Hume, 2016).

Seemingly arbitrary patterns can also arise from the fact that metathesis involves abstract symbol manipulation (e.g., /A/ + /B/ → [BA]). Cases of 'mirror image' metathesis (Hume, 2004) in which one language shows one direction of metathesis (e.g., Hungarian, where /h/ metathesizes with /r/, /hr/ → [rh], as in /tehernek/ 'load-DAT' → [terhek], *[tehrek]'load-PL') and another language shows the opposite direction of metathesis (e.g., Pawnee, where /rh/ becomes [hr], /ti-ir-hisak-hus/ → [tihrisaksu] 'he is called'), appear to be arbitrary because it is not clear what kind of perceptual or structural motivation could produce both directions of metathesis. Accounting for metathesis using abstract symbol manipulation allows for both directions of metathesis to occur (i.e., both /AB/ → [BA] and /BA/ → [AB]) without reference to structural or perceptual motivation.

While some cases of 'mirror image' metathesis appear to be arbitrary, other cases of 'mirror image' metathesis can be grounded in the perceptual constraints of the specific language. Because languages vary with respect to both the phonetic realization of sounds and syllable structure constraints, the optimal order of sounds may vary depending on how perceptual constraints interact in a given language. For example, Old English metathesis involves /sk/ becoming [ks] (e.g., /aske/ → [akse] 'ash') following a stressed syllable, while Colloquial French metathesis involves /ks/ becoming [sk] on the final, stressed syllable (e.g., /fiks/ → [fisk] 'fish'). Differences in stress assignment between these two languages result in differences in the perceptibility of /s/ word finally,[5] and result in 'mirror image' metathesis that is perceptually motivated by different language-specific perceptual constraints (Blevins & Garrett, 2004). Thus, even though the abstract symbols allow for both directions of metathesis to apply, phonetic and phonological constraints ground the phonological patterns, so that they are no longer arbitrary.

Hume (2004) argues that Optimality Theory (OT) (Prince & Smolensky, 2004) is ideal for accounting for perceptual and structural grounding of metathesis. In OT, language-specific differences are formalized as differences in constraint rankings. Markedness constraints govern the perceptual and structural makeup of a word. For example, *Coda is a formalization of the preference for onset consonants (the start of a syllable, as in [ba]) over coda consonants (the end of a syllable, as in [ab]). Faithfulness constraints, on the other hand, allow for violations of markedness constraints in favor of preserving the underlying form of a word. When markedness constraints outrank faithfulness constraints, structural changes occur, but when faithfulness constraints outrank markedness constraints, the underlying form is preserved. In order to induce metathesis, the markedness constraints that drive metathesis must outrank the faithfulness constraints that preserve the linear order of sounds in a word (i.e., Linearity). In languages with metathesis, Linearity must be ranked below the markedness constraints that motivate metathesis.[6] The result is that metathesis applies only when a markedness constraint would otherwise be violated; spurious metathesis would result in spurious violations of Linearity, and would therefore not be accepted in the language.

The OT analysis outlined above implies that metathesis cannot be arbitrary, but as noted above, there are cases of arbitrary metathesis. In OT, arbitrary patterns can be accounted for in a variety of ways, including 'ad hoc' constraints that target the specific pattern (Hayes, 1999). An ad hoc constraint for an arbitrary metathesis pattern might be something like 'Switch-CC', requiring consonants to change places from the input to the output. Because this kind of arbitrary, ad hoc constraint applies without structural considerations, metathesis applies more generally, regardless of whether metathesis results in structural improvements.

The existence of both grounded and arbitrary phonological processes poses the question of whether grounded patterns are privileged in terms of typology and learnability. According to the substantively biased theory of learning (Finley & Badecker, 2007; Wilson, 2006), language users

[2] Transcriptions of phonological forms are in IPA format.

[3] Note that for the purposes of this paper, only consonant-consonant metathesis is discussed, but languages do employ consonant-vowel metathesis (Blevins & Garrett, 1998).

[4] Note that the term 'motivation' is used to refer to the phonetic and structural pressures that drive metathesis. This term is used throughout the Metathesis Database (Hume, 2016).

[5] Final stress in French lengthens the /s/, increasing the confusability of the surrounding /k/ segment, so the /s/ is moved out of final position in order to preserve perceptibility of /k/.

[6] In the case of an artificial grammar learning experiment, this markedness constraint (e.g., Maximize Onsets) could be already learned or be learned during the course of the experiment. Both make the same prediction about generalizing to contexts that do not meet the structural requirements.

are biased toward phonological patterns that are grounded in phonetic or structural improvements. Substantively biased learning combines language specific components (such as syllable structure) with domain general cognitive mechanisms (such as memory and attention) to form the set of patterns that learners are most likely to learn. The substantively biased theory of learning predicts that phonological patterns that are phonetically or phonologically grounded will be easiest to learn. It also predicts that learners will formulate constraints in terms of phonetic and phonological grounding, if possible. According to the substantively biased theory of learning, learners' formalization of metathesis constraints will be different depending on the presence or absence of structural or perceptual improvement; arbitrary metathesis patterns are learned with a more general set of constraints than a metathesis patterns governed by syllable structure.

The substantively biased theory of learning necessarily relies on 'substance'– phonetic and structural grounding. This is contrasted with the substance free approach to phonology. This theory of phonology advocates that the substance that grounds phonological patterns (e.g., perceptual and cognitive constraints) does not play any role in the characterization of phonological patterns (Hale & Reiss, 2000).[7] The substance-free approach to phonology predicts that both a grounded and an arbitrary metathesis pattern should receive the same formal analysis (e.g., /A/ + /B/ → [BA]). The substance free approach to phonology is consistent with evolutionary approaches to phonology that assert that the phonetic grounding for phonological patterns is a part of the historical development of the language, and is not a part of the mental representation of the phonological grammar (Blevins, 2004; Blevins & Garrett, 1998).

Much insight into the debate between substantively biased and substance-free approaches to phonology has been gleaned from artificial grammar learning experiments (Moreton, 2008). In these experiments, naïve language users are trained on a novel phonological pattern and then tested on their learning and generalization of that pattern. For example, in Moreton's (2008) study, participants were more likely to learn a phonological pattern that contained phonetically grounded constraints than a pattern that could only be explained in terms of language change,[8] even when controlling for typological frequency.

Several learning experiments have shown biases for typologically preferred patterns, further suggesting that learners make use of the factors that influence the typology of language patterns across languages of the world (Carpenter, 2005; Finley, 2012; Finley & Badecker, 2009b; Finley & Badecker, 2012; White, 2014; Wilson, 2003, 2006). However, these studies have not directly addressed whether the learned patterns contain the perceptual or structural grounding for these novel patterns. In addition, the evidence that learners prefer phonetically grounded over arbitrary patterns appears to be mixed (Moreton & Pater, 2012). One reason for these mixed results is that phonetically grounded phonological patterns are more likely to be described in simple terms (e.g., constraints involving a single phonological feature), while arbitrary phonological patterns may require more complex representations (e.g., constraints that require multiple features), making it difficult to tease apart whether the differences in learning are due to complexity or to phonetic grounding. For example, Saffran and Thiessen (2003) found that nine month old infants were more likely to learn constraints on word forms that involved a single feature (e.g., all words start with a voiced stop) than constraints on word forms that involved more than one feature (e.g., all words start with coronal and velar voiced stops and labial voiceless stops). It is possible that arbitrary phonological patterns are easier to learn when such arbitrary phonological patterns make use of simple representations (Moreton, Pater, & Pertsova, 2015). Because the metathesis rule is equally complex regardless of whether the pattern is grounded or arbitrary, it is possible to control for both formal complexity and arbitrariness. In the present study, two sets of learners with similar language backgrounds (i.e., adult English speakers) were trained on a metathesis pattern that shared the same level of formal complexity across two conditions, but the pattern varied in terms of arbitrariness and grounding; the metathesis pattern either improves syllable structure (via the Maximal Onset Principle, described below) or a does not improve syllable structure (through violation of *CODA).

A general linguistic tendency is to prefer onsets to codas, and to maximize onsets to avoid codas where possible. This principle is referred to as the Maximal Onset Principle (Selkirk, 1982). Across a syllable boundary, English speakers will parse two adjacent consonants as a complex onset rather than as a coda (if allowed by syllable structure constraints). For example the word 'apron' is parsed as [e.prIn] rather than [ep.rIn] in order to satisfy the Maximal Onset Principle and to avoid a coda. In contrast, English speakers parse 'captain' as [cæp.tIn] rather than *[cæ.ptIn] because the /pt/ is not a valid onset in English. A metathesis pattern that results in a complex onset (e.g., /el/ + /pa/ → [e.pla], *[el.pa]) is a pattern that is grounded in structurally-based markedness constraints, while a metathesis pattern that results in a coda when one could have been avoided (e.g., /ep/ + /la/ → [el.pa], *[e.pla]) is arbitrary. Note that this difference in motivation relies on English syllabification principles. If English did not allow complex onsets, then metathesis would result in a coda in both cases (e.g., /el/ + /pa/ → [ep.la]).

The hypothesis tested in the present study is that in phonologically grounded cases, learners will only extend the pattern to cases that show the same perceptual motivation; in arbitrary cases, learners will generalize more freely. This type of differential generalization can be used to test the hypothesis that learners make use of the grounding of the phonological pattern when generalizing to novel items. A theory of substantively biased learning would be supported if learners were more likely to

[7] Note that a rule-based analysis such as /C1C2/ → [C2C1] can also be encoded without reference to any phonological grounding, suggesting that this issue is not specific to OT.

[8] Moreton refers to this difference as a contrast between analytic bias and channel bias. Analytic bias is, for the purposes of this paper, identical to substantive bias. Channel bias refers to constraints on linguistic typology that are based in the evolution of the language over several generations, and are therefore outside of the minds of current language learners or language users.

generalize a novel metathesis pattern when it improves syllable structure constraints. A theory of substance-free learning would be supported if learners show generalization to novel metathesis patterns regardless of the whether the novel metathesis satisfies structural constraints.

## Experiment 1

The goal of Experiment 1 was to explore whether learners make use of syllable structure improvements to help learn a novel metathesis pattern.

### *Method*

#### *Participants*

All participants were adult monolingual native English speakers who had not studied any language with a regular metathesis pattern. Forty-eight participants were recruited from the University of Rochester community, whose gender and age were representative of the university population. All participants were paid $10 for their participation and followed standard informed consent and debriefing procedures. Participants were randomly assigned, but evenly distributed across four experimental conditions: Onset-L, Onset-R, Coda-L, and Coda-R, where 'R' and 'L' indicated the liquid consonant that was present in all bisyllabic forms used in the training set. No participants were excluded in this study, as all participants met the requirements and appeared to follow directions.

#### *Design*

Participants were exposed to a miniature language that demonstrated a metathesis pattern. Metathesis was presented to the learner as a result of the concatenation of two independent syllables. In this 'triad presentation' (Davidson, Smolensky, & Jusczyk, 2004; Finley, 2011b; Finley & Christiansen, 2011), participants heard a VC syllable followed by a CV syllable and the concatenation of these two (e.g., $/V_1C_1/ + /C_2V_2/ \rightarrow [V_1C_2C_1V_2]$, /ep/ + /la/ → [elpa]). This triad design allows the learner to be exposed to the underlying form in a clear and unambiguous way. While phonological processes in natural languages do not always have a clear underlying form, many processes occur as a result of morphological derivation (e.g., Hungarian metathesis, noted above), making the inference of the underlying form relatively straightforward. In all items, one consonant was a liquid (/l/, /r/) and the other consonant was a non-coronal stop (/p, k, b, g/). Non-coronal stops were used because English phonotactic constraints restrict syllables from beginning with */tl/ and */dl/. All vowels were drawn from the set /i, e, o, u/.

All training items across all conditions used this same triad format. The difference across conditions was the type of liquid (/l/ vs. /r/) and the placement of the liquid ($C_1$ vs. $C_2$). In the Onset conditions, the liquid appeared in $C_1$ and the stop appeared as $C_2$ (e.g., /el/ + /pa/ → [epla]). When the liquid appears in $C_1$, after metathesis applies, the syllable structure is improved because the onset of the second syllable is maximized. In the Onset-L Condition, $C_1$ was always /l/ (e.g., /el/ + /pa/ → [epla]), and in the Onset-R Condition, $C_1$ was always /r/ (e.g., /er/ + /pa/ → [epra)]. In the Coda conditions, the stop occurred in $C_1$ and the liquid appeared as $C_2$ (e.g., /ep/ + /la/ → [elpa]). When the liquid appears in $C_2$, syllable structure is not improved because the onset of the second syllable is not maximized, and the first syllable has a coda.

In the R conditions, the liquid was always /r/ (e.g., /er/ + /pa/ → [epra]), and participants were tested on /l/ in the New Segment items at test (discussed below). In the L conditions, the liquid was always /l/ (e.g., /el/ + /pa/ → [epla]), and participants were tested on /r/ in the New Segment items. The difference between these two conditions largely served as a control, as there were no hypothesized differences between the L and the R conditions. Examples of the training and test items can be found in Table 1.

Following exposure, participants were given a two-alternative forced-choice test. Participants were asked to compare two sets of three items: one involving metathesis: $/V_1C_1/ + /C_2V_2/ \rightarrow [V_1C_2C_1V_2]$, and the other involving no-change (i.e., a faithful representation of the input): $/V_1C_1/ + /C_2V_2/ \rightarrow [V_1C_1C_2V_2]$. For example, learners were asked to choose which of two sets of three belonged to the language: /ep/ + /la/ → [elpa] or /ep/ + /la/ → [epla]. The first two syllables in the first set were always identical to the first two syllables in the second set (e.g., /ep/ + /la/); the difference between the two sets was the bisyllabic word, which was either a faithful concatenation of the first two syllables (e.g., [epla]) or a concatenation in which the two consonants have undergone metathesis (e.g., [elpa]). Order of concatenation (no change vs. metathesis) was counterbalanced across items.

There were four different types of test items: Old items, New items, New Segment items, and New Position items. Old items appeared in the training set, New items did not appear in the training set, but had all of the properties of the training set (the same liquid consonant appeared in

**Table 1**
Examples of training and test stimuli, Experiments 1 and 2 (items undergoing metathesis presented first; faithful items presented second).

| Condition | Training/Old items | New items | New Segment items | New Position items |
|---|---|---|---|---|
| Onset-R | ur bi ubri vs.<br>ur bi urbi | ar ge agre vs.<br>ar ge arge | el ga egla vs.<br>el ga elga | ep ri erpi vs.<br>ep ri epri |
| Onset-L | al be able vs.<br>al be albe | el ga egla vs.<br>el ga elga | ar ge agre vs.<br>ar ge arge | uk le ulke vs.<br>uk le ukle |
| Coda-R | op ri orpi vs.<br>op ri opri | ep ri erpi vs.<br>ep ri epri | uk lo ulko vs.<br>uk lo uklo | ar ge agre vs.<br>ar ge arge |
| Coda-L | ik lo ilko vs.<br>ik lo iklo | uk le ulke vs.<br>uk le ukle | ep ri erpi vs.<br>ep ri epri | el ga egla vs.<br>el ga elga |

the same position as in the training). Selecting the metathesis (as opposed to the no-change/faithful) option demonstrates that the participant has learned the general metathesis pattern. Note that selecting the metathesis option on these items is critical for understanding the interpretation of the New Segment and New Position items.

New Segment items contained the liquid that had not appeared during training (/r/ in the L conditions, and /l/ in the R conditions), but the position of the liquid remained constant. New Position items contained the same liquid that appeared in training, but the position of the liquid was reversed from what appeared in training. Selecting the metathesis item (as opposed to the no-change/faithful) option demonstrates that the participant is able to apply the general metathesis pattern to novel segments. For example, a learner exposed to a metathesis pattern in which /l/ switches with /p/ (e.g., /lp/ → [pl]), could represent the pattern very generally (e.g., adjacent consonants switch), or very specifically (e.g., /l/ and /p/ switch). If the learner extends the metathesis to segments that were not heard in training, it suggests that the learner formed a general rule rather than a specific rule. Previous results in the artificial grammar learning literature suggest that learners are able to make generalizations about novel segments for patterns that can be easily applied to multiple segments in a category, especially when the two sounds are phonetically very similar (Cristia, Mielke, Daland, & Peperkamp, 2013; Finley, 2011a; Finley & Badecker, 2009a; White, 2014), which is the case with the present metathesis pattern. Thus, it is expected that learners will be able to generalize to novel segments in both the Onset and the Coda conditions.

The New Position test items were critical for testing the hypothesis that learners who are exposed to an arbitrary metathesis pattern with no structural improvements (e.g., a coda) will be more likely to generalize the pattern to items that create a different syllable structure (e.g., an onset) compared to learners who are exposed to a grounded pattern with structural improvements (e.g., maximal onsets). Selecting the metathesis option demonstrates that the participant has learned a metathesis pattern general enough to apply to a novel syllable structure. If learners in the Onset condition represent the metathesis pattern as a way to satisfy the Maximal Onset Principle, then these learners will be less likely to extend the pattern when metathesis does not result in an onset, thereby supporting the substantively biased theory of learning. The substantively biased theory of learning hypothesizes that learners in the Onset condition will show fewer metathesis responses for New Position items compared to learners in the Coda conditions.

*Stimuli*

An adult female native English speaker recorded all stimuli. While the speaker was aware that the stimuli were to be used for an artificial grammar learning study, the speaker was unaware of the hypothesis of the study. Each token was spoken four times in list format. A single token was chosen from the second or third element of the set in order to keep the prosody as uniform as possible. The first and last elements were avoided to avoid the intonation of first and last elements in a list. The speaker was told to pronounce each item as clearly and accurately as possible (without reducing vowels). Stress on the disyllabic words was placed on the final syllable, but the speaker was not given any cues to syllabification. Monosyllabic items were recorded separately from bisyllabic items (e.g., /ep/ and /le/ were recorded from one list, while /epla/ and /elpa/ were recorded from a second list), and the triads were constructed in Praat (Boersma & Weenink, 2015) through concatenation of sound files. Approximately 400 ms of silence was placed between each monosyllabic item in the training set, with 750 ms ISI between each item. Approximately 1000 ms of silence was placed between each set of three items in the test phase. All stimuli were normalized to 70 dB.

*Procedure*

Participants were told that they would be listening to words from a language they had never heard before, and their task was to listen to the way the novel language sounded, but that they need not try and memorize the forms. Participants were told that the words would be presented in sets of three, with two words followed by the combined form, as in 'tooth', 'brush' and 'toothbrush'. The training consisted of 24 triads repeated five times each. Following training, participants completed a two-alternative forced-choice test that contained 40 items, 10 for each test item conditions described above. Participants were told that they would hear two sets of three words; two words followed by the combined form. One of the sets belongs to the language, and the other set does not belong to the language. If participants believed the first set of words belonged to the language, they were to press the 'a' key; if they believed the second set of words belonged to the language, they were to press the 'l' key. Participants were instructed to respond as quickly and accurately as possible, and to listen to both sets of words before responding, but no time limit was given for responses. For this reason, reaction time was not a reliable measure of learning, as participants waited to make a selection after hearing both options, even if the participant immediately believed the first option was grammatical. The experiment took approximately 15 min to complete.

*Results*

Fig. 1 reports the means and standard errors of the proportion of items in which participants chose the metathesis option (as opposed to the no change/faithful option) in the two alternative forced choice test. Because the results did not differ for L and R conditions (see below), and for ease of reading, the figure combines these conditions. The Onset Conditions showed high rates of metathesis responses for Old (mean = 0.90, *SD* = 0.15), New (mean = 0.95, *SD* = 0.08), and New Segment (mean = 0.87, *SD* = 0.20) items, but lower rates of metathesis responding for New Position items (mean = 0.59, *SD* = 0.28). In contrast, the Onset Conditions showed relatively high rates of metathesis responses for all four test conditions: Old

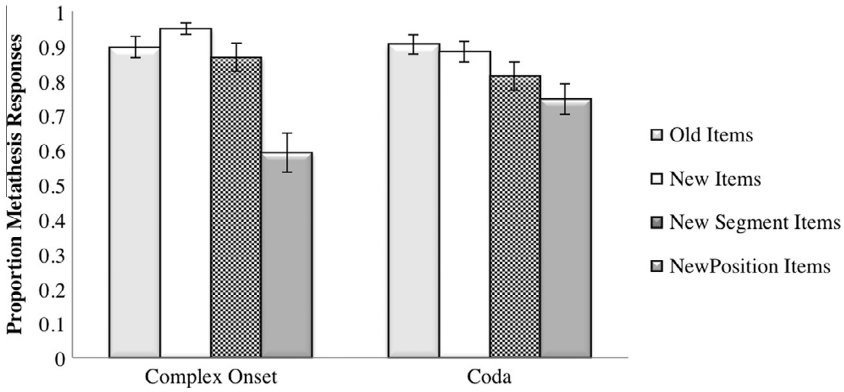


**Fig. 1.** Experiment 1 results: means and standard errors.

(mean = 0.90, $SD$ = 0.14), New, (mean = 0.88, $SD$ = 0.15), New Segment (mean = 0.81, $SD$ = 0.20), and New Position (mean = 0.75, $SD$ = 0.22) items.

The data were analyzed using a generalized linear mixed effects logistic regression fit by the Laplace approximation using the lme4 package in R (R Development Core Team, 2011) with Coda/Onset and Test Condition as crossed factors, with Old items serving as the reference for comparison. The alpha for significance was $p < .05$, based on $z$ scores ($z > 1.96$). For simplicity, and because a logistic regression (with random slopes for items, and random intercepts for subjects) comparing the L and R conditions was not significantly different ($\beta = 0.43$, $SE = 0.44$, $z = 0.96$, $p = .33$), L and R variables were not used as fixed variables in the model. The model was created with the maximal set of random slopes and intercepts for subjects and items that would successfully converge (Barr, Levy, Scheepers, & Tily, 2013).[9] When the baseline was Old items, this maximal model included random slopes and intercepts for subjects. Ten items for each of the four test conditions, for each of the 48 participants were analyzed. Results for this model are shown in Table 2. For space considerations, only comparisons that specifically relate to the hypotheses in question are noted in the text.

Overall, participants made fewer metathesis responses for New Position items (mean = 0.67, $SD$ = 0.26) compared to Old items (mean = 0.90, $SD$ = 0.14). However, there was a significant interaction[10] of Old vs. New Position and Coda vs. Onset, suggesting that this difference was larger for the Onset condition compared to the Coda condition, in line with the hypothesis that learners in the Onset condition would be less likely to choose the metathesis pattern for New Position items. This was confirmed through a significant difference between the New Position items for Onset (mean = 0.59, $SD$ = 0.28) and Coda conditions (mean = 0.75, $SD$ = 0.22) (this statistic was based on the comparison between Onset and Coda conditions when New Position serves as the reference for comparison).

**Table 2**
Summary of mixed effect model, Experiment 1.

| | $\beta$ | $SE$ | $z$ |
|---|---|---|---|
| Intercept (Baseline = Old) | 3.08 | 0.41 | 7.49*** |
| Intercept (Baseline = New Segment) | 1.82 | 0.20 | 9.14*** |
| Coda vs. Onset (Baseline = Old) | 0.063 | 0.57 | 0.11 |
| New vs. Old | 0.34 | 0.38 | 0.89 |
| NewSeg vs. Old | −0.47 | 0.35 | −1.34 |
| NewPos vs. Old | −2.37 | 0.34 | −6.92*** |
| Coda vs. Onset × New vs. Old | −0.87 | 0.52 | −1.68 |
| Coda vs. Onset × NewSeg vs. Old | −0.38 | 0.49 | −0.78 |
| Coda vs. Onset × NewPos vs. Old | 1.12 | 0.48 | 2.33* |
| *New position comparisons* | | | |
| Coda-L | 1.81 | 0.54 | 3.58*** |
| Coda-R | 1.91 | 0.53 | 3.58*** |
| Onset-L | 0.44 | 0.37 | 1.18 |
| Onset-R | 0.87 | 0.50 | 1.75† |
| Coda vs. Onset | 1.05 | 0.46 | 2.26* |

† $0.05 < p < .10$.
* $p < .05$.
** $p < 0.01$.
*** $p < .001$.

In order to determine whether the responses to New Position items were significantly different from chance (0.50), the intercept of separate models was recorded for each condition: (Coda-L, Coda-R, Onset-L, and Onset-R) with random intercepts for subjects and items. By running a model with only the New Position items, the intercept shows the significance of the reference condition; changing the reference condition for each condition gives the significance as compared to 50% chance for each test condition.[11] While both Coda-L (mean = 0.76, $SD$ = 0.22) and Coda-R (mean = 0.72, $SD$ = 0.22) conditions showed a significant intercept (suggesting a significant difference from chance), the Onset-L condition (mean = 0.58, $SD$ = 0.30) did not show a significant intercept, and the Onset-R condition (mean = 0.60, $SD$ = 0.26) showed a

[9] When Old items served as the baseline, the model with random intercepts for both subjects and items failed to converge, but there was no significant difference between a model with random intercepts for subjects and a model with random intercepts for items ($\chi^2 = 1$).

[10] The comparison between the model with no interaction effects and the model with an interaction effect was significant ($\chi^2(3) = 23.56$, $p < .001$). Note that the kappa estimate for assessing colinearity was 16.01 (HLPLab, 2011).

[11] While $z$ scores were not adjusted for multiple comparisons in the table, all significant responses are still significant after Bonferroni correction.

marginally significant intercept. These results are in line with the finding that learners were more likely to extend the metathesis pattern to New Position items in the Coda conditions compared to the Onset conditions, thus supporting the substantively-biased theory of learning.

To test whether participants successfully extended the metathesis pattern to novel segments, the full model described above was run with the New Segment items as the reference point, with the intercept comparing New Segment items to chance. The significant intercept suggests that participants in Experiment 1 were able to generalize to novel segments.

### *Discussion*

Participants were more likely to extend to the metathesis pattern to New Position items in the Coda conditions compared to the Onset conditions. This supports the hypothesis that the perceptual and structural improvements that ground phonological patterns are a part of the learned representation of a novel phonological pattern.

One potential issue with Experiment 1 is that participants may have formed an ambiguous (ambisyllabic) syllable parse, in which the complex onsets from Experiment 1 were parsed as both a coda of the first syllable and an onset and the onset of the second syllable (Kahn, 1976; Treiman & Danis, 1988; Treiman & Zukowski, 1990). If this were the case, then the /p/ in a word like [epla] would be both the coda of the initial syllable and an onset of the final syllable. While the distributional cues for stops and liquids may provide sufficient cues to syllabification in general, the artificial nature of the stimuli could have reduced reliability of regular distributional cues, and lead participants to interpret the stimuli using an incorrect parse. An incorrect parse of the stimuli could explain the generalization to New Position items for the Coda conditions; if learners perceived the New Position items as having a coda, then they would be more likely to accept these items, not because they learned a general pattern, but because they learned something along the lines of 'metathesis creates codas'. Because this study is testing how learners represent novel phonological patterns, it is important to better understand how learners represented the patterns in Experiment 1. Experiment 2 attempts to address this concern by disambiguating the beginnings and ends of syllables in the stimuli.

## Experiment 2

Experiment 2 contained the same stimuli as Experiment 1, with one major modification: 150 ms of silence was spliced in between each intended onset and coda so that the learner was sure to parse the syllables as the experimenter intended. While previous experiments have shown that 25 ms of silence may be sufficient to induce a word boundary (Peña, Bonatti, Nespor, & Mehler, 2002), those studies used silence to divide CVCV syllables that are less likely to be subject to an ambisyllabic analysis. A 150 ms gap ensured the intended parsing of syllable boundaries, which becomes complicated by potentially ambisyllabic consonant clusters, as were present in the current experiment.

### *Method*

#### *Participants*

All participants were fluent speakers of English who had not participated in Experiment 1, and had not been significantly exposed to a language with a regular metathesis pattern. Participants were drawn from a combination of participants from the Elmhurst College Psychology and the Waldorf College participant pools. There were 52 total participants evenly distributed across four conditions, of similar demographics to those of Experiment 1.

#### *Design*

The design of Experiment 2 was identical to Experiment 1.

#### *Stimuli*

The stimuli were identical to Experiment 1, except that all stimuli were spliced with 150 ms of silence between syllables to better specify where the syllable boundaries were in the stimuli. All ISIs remained the same for Experiment 1 and Experiment 2. An independent coder verified all syllable boundaries. Because the stimuli included added silence, it was extremely difficult to create stimuli that sounded as natural as the stimuli in Experiment 1 – in many cases, the stimuli sounded quite unnatural. This may have affected the results, discussed below.

#### *Procedure*

The procedure was identical to Experiment 1.

### *Results*

Mean and standard errors of the proportion of metathesis responses (as opposed to a 'no change'/faithful response) are presented in Fig. 2. For ease of interpretation, L and R conditions have been combined in the figure. As in Experiment 1, a mixed effects regression model comparing L and R conditions (with random slopes and intercepts for subjects and items) was not significant, $\beta = 0.17$, $SE = 0.29$, $z = 0.58$, $p = .56$, and were therefore combined in the full analysis.

The data were analyzed in the same manner as Experiment 1, except that the maximal model included random intercepts for subjects and items; the results of this analysis are provided in Table 3. For space considerations, only comparisons related to the hypotheses are noted in the text.[12] There was a significant intercept when the reference point was Old items, suggesting that overall, participants selected the metathesis option significantly greater than chance for Old items. There was also a marginally significant difference between the Coda (mean = 0.74, $SD = 0.19$) and

[12] Note that the kappa estimate for assessing colinearity was 16.00 (HLPLab, 2011). The comparison between the model with an interaction term and without was significant ($\chi^2(3) = 25.34$, $p < .001$).

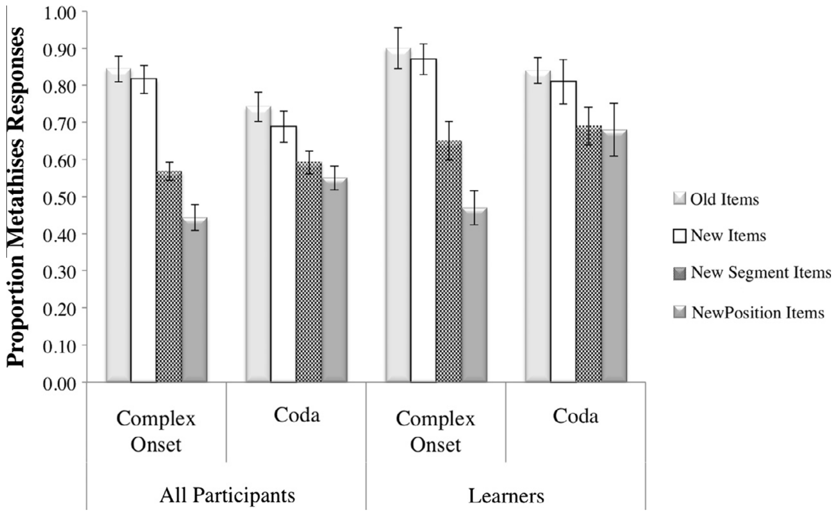


**Fig. 2.** Experiment 2 results: means and standard errors.

**Table 3**
Summary of mixed effect model, Experiment 2.

| | All participants | | | Leaners only | | |
|---|---|---|---|---|---|---|
| | *β* | *SE* | *z* | *β* | *SE* | *z* |
| Intercept (Baseline = Old) | 2.01 | 0.28 | 7.28*** | 1.95 | 0.20 | 9.97*** |
| Intercept (Baseline = NewSegment) | 0.39 | 0.24 | 1.60 | 0.57 | 0.22 | 2.60** |
| Coda vs. Onset (Baseline = Old) | −0.73 | 0.37 | −1.95† | −0.36 | 0.28 | −1.29 |
| New vs. Old | −0.16 | 0.26 | −0.62 | −0.11 | 0.27 | −0.40 |
| NewSeg vs. Old | −1.61 | 0.24 | −6.75*** | −1.47 | 0.24 | −6.23*** |
| NewPos vs. Old | −2.33 | 0.24 | −9.60*** | −2.15 | 0.23 | −9.16*** |
| Coda vs. Onset × New vs. Old | −0.13 | 0.34 | −0.40 | 0.010 | 0.39 | 0.026 |
| Coda vs. Onset × NewSeg vs. Old | 0.81 | 0.32 | 2.54* | 0.71 | 0.35 | 2.00* |
| Coda vs. Onset × NewPos vs. Old | 1.33 | 0.32 | 4.11*** | 1.30 | 0.35 | 3.71*** |
| *New position comparisons* | | | | | | |
| Coda-L | −0.025 | 0.41 | −0.060 | 0.85 | 0.54 | 1.58 |
| Coda-R | 0.64 | 0.42 | 1.53 | 1.05 | 0.46 | 2.74* |
| Onset-L | −0.26 | 0.41 | −0.64 | −0.13 | 0.18 | −0.73 |
| Onset-R | −0.42 | 0.41 | −1.01 | −0.32 | 0.40 | −0.80 |
| Coda vs. Onset | 0.60 | 0.34 | 1.74† | 0.96 | 0.22 | 4.36*** |

† $0.05 < p < .10$.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Onset conditions for Old items (mean = 0.85, *SD* = 0.18), suggesting that learners in the Onset Condition may have found the learning task somewhat easier. There was an overall significant difference between Old (mean = 0.79, *SD* = 0.19) and New Position (mean = 0.49, *SD* = 0.29) items, but with a significant interaction for the Coda vs. Onset and Old vs. New Position, suggesting a that the difference between Old and New Position items was larger for the Onset conditions compared to the Coda conditions, in line with the hypothesis that learners in the Onset condition will be less likely to choose the metathesis pattern for New Position items. However, the difference between Onset (mean = 0.43, *SD* = 0.25) and Coda conditions (mean = 0.55, *SD* = 0.31) for New Position items was only marginally significant.

In addition, the intercept was recorded for a model comparing responses to New Position items all four conditions (Coda-L, Coda-R, etc.) with random intercepts for subjects and items. No conditions showed significant intercepts for New Position items, suggesting a general failure to generalize to the New Position items in Experiment 2. Note that the Coda conditions were generally above 50% chance, while the Onset conditions were generally below 50% chance, explaining the marginal difference between Onset and Coda for New Position items.

The intercept when the reference point was New Segment items was not significantly different from chance, suggesting that the participants in Experiment 2 failed to generalize to novel segments.

While the comparison between Onset and Coda for New Position items in Experiment 2 did not reach statistical significance, the trends in the data remained the same as Experiment 1, suggesting that the results of Experiment 1 were not due to syllable parsing alone. It is possible that the failure to find significance was a result of general difficulty in learning the pattern for some participants. To test this, Experiment 2 was reanalyzed using only participants who scored above 50% in the overall experiment, coded as 'learners'. This reanalysis involved removal of one participant from the Onset-R condition, two participants from the Onset-L condition, six participants from the Coda-L condition, and three participants from the Coda-R condition.[13] Note that all of these participants scored at or above chance on New items. The results of the analysis are provided in Table 3.[14] As in the previous analysis, there was a significant interaction between the New Position vs. Old items comparison and the Onset vs. Coda comparison. Unlike the previous analysis, there was a significant difference between the Onset (mean = 0.47, *SD* = 0.24) and Coda (mean = 0.68, *SD* = 0.29) conditions for New Position items. In addition, the difference between Onset (mean = 0.90, *SD* = 0.12) and Coda (mean = 0.84, *SD* = 0.15) conditions was no longer significant for Old items, which was expected, as only participants who learned the pattern are included in this analysis. Further, the intercept when the reference point was New Segment items was significantly different from chance, suggesting that the learners in Experiment 2 were able to generalize to novel segments. This reanalysis provides a replication of Experiment 1.

### Discussion

Experiment 2 replicated the results of Experiment 1 when participants who did not choose the metathesis option on more than 50% of trials were excluded. This suggests that the results of Experiment 1 were not due to syllable parsing alone.

In Experiment 1, participants in the Onset conditions did not choose the metathesis option for New Position items at a rate significantly different from chance. The New Position items in Experiments 1 and 2 pitted a complex onset (e.g., [epla]) against a coda (e.g., [elpa]). The Onset option in New Position items was the result of a faithful parse (e.g., /ap/ + /le/ → [a.ple]), while the coda option resulted from metathesis (e.g., /ap/ + /le/ → [al.pe]). If learners in the Onset conditions preferred maximized onsets to metathesis, one would expect that learners would choose the metathesis option at a rate below chance, but no preference emerged. This pattern of responses suggests that participants in the Onset conditions of Experiments 1–2 did not simply select the complex onset option, but were willing to apply metathesis even if it did not create a complex onset.

[13] Note that the general results were the same when we included participants who scored above 50% on Old, New and New Segment items (excluding New Position items). This analysis included the same participants as the analysis shown, as well as two participants from the Onset-R condition, and one participant each from the Coda-L and Coda-R conditions.

[14] The new model also showed no differences between L and R conditions ($\chi^2$ = 0.0022, *SD* = 0.30, *z* = 0.007, *p* = .99). Note that the kappa estimate for assessing colinearity was 14.22 (HLPLab, 2011). The comparison between the model that included an interaction and the model that did not was significant, $\chi^2(3) = 19.13$, $p < .001$.

The prosodic structure of the stimuli may have prevented learners in the Onset conditions from forming a preference for onsets in New Position items. Metathesis often applies in order to increase the perceptual salience of the sounds in a word (Hume, 2004). Training items in the Onset conditions resulted in a coda consonant in the input (e.g., /al/), becoming a part of the onset of a stressed syllable (e.g., /a**ple**/, where the stressed syllable is in bold). This means that the training in the Onset conditions was ambiguous between creating a maximal onset and having all consonants in a stressed syllable.

This ambiguity is removed in Experiment 3 by moving the stress of the bisyllabic item from the final syllable to the initial syllable. In training, participants in the Onset condition are trained on items in which metathesis results in a maximal onset in the unstressed position (the second syllable), thereby removing any ambiguity of perceptual prominence.

## Experiment 3

In Experiment 3, participants were exposed to the same general metathesis pattern as Experiment 1, except that stress was placed on the initial syllable, rather than the final syllable in the bisyllabic form. Creating stress on the initial syllable should remove any ambiguity that the onset is the motivation for metathesis, rather than a stressed position (e.g., /el/ /pa/ → /**e**.pla/). Since the stressed position is no longer a possible motivator for metathesis, learners should only choose items that create a complex onset. This predicts that learners in the Onset condition in Experiment 3 will select the metathesis option (e.g., /ep/ /le/ → **el**.pe) at a rate lower than chance (50%).

In addition, the potential ambisyllabicity was removed during the creation of the stimuli, as the speaker was instructed to clearly articulate the syllable boundary, which was then verified by an independent coder.

### Method

#### Participants

All participants were fluent speakers of American English who had not participated in Experiments 1–2, and had not been significantly exposed to a language with a regular metathesis pattern, with similar demographics to those of Experiments 1–2. Participants were drawn from the Pacific Lutheran University Psychology participant pool. Twenty-one participants participated in the Coda condition and 18 participants participated in the Onset condition. Five participants were excluded because they were not native English speakers.

#### Design

The design of Experiment 3 was similar to Experiment 1. However, because the L and R conditions did not yield significantly different responses in Experiments 1 and 2, participants were only trained on the L conditions.

*Stimuli*

The items in Experiment 3 were identical to Experiment 1, recorded by a female speaker of American English (different from Experiments 1 and 2), except that stress was placed on the initial syllable, and the talker made an effort to separate the first and second syllables in the bisyllabic forms. An independent coder verified all syllable boundaries.

*Procedure*

The procedure was identical to Experiments 1 and 2.

*Results*

Means and standard errors of the proportion of metathesis responses (as opposed to 'no change'/faithful responses) are presented in Fig. 3. The Onset condition showed relatively high rates of metathesis responses for Old (mean = 0.92, $SD$ = 0.13), New (mean = 0.89, $SD$ = 0.15) and New Segment (mean = 0.85, $SD$ = 0.18) items, but low rates of metathesis responses for New Position items (mean = 0.34, $SD$ = 0.30). The Coda condition showed relatively high rates of metathesis responses for Old (mean = 0.81, $SD$ = 0.20), New (mean = 0.83, $SD$ = 0.22) and New Segment (mean = 0.83, $SD$ = 0.18) items, but with rates of metathesis responses for New Position items only numerically above chance (mean = 0.57, $SD$ = 0.29).

The data were analyzed in the same fashion as for Experiments 1–2. The maximal model included random slopes and intercepts for items.[15] Results for this model are shown in Table 4. For space considerations, only the comparisons of interests are noted in the text. There was a significant difference between the Coda and Onset conditions for Old items, suggesting that learners in the Onset condition may have found the learning task somewhat easier. There was also an overall significant difference between New Position (mean = 0.47, $SD$ = 0.32) and Old (mean = 0.86, $SD$ = 0.17) items. There was a significant interaction between Old vs. New Position items and Onset vs. Coda comparisons, suggesting that the difference between Old and New Position items was mediated by the Onset condition, in line with the hypothesis that learners in the Onset condition would be less likely to choose the metathesis pattern for New Position items. This was confirmed by a significant difference between Onset and Coda conditions for New Position items.

The intercept was recorded for a model comparing responses to New Position items for both conditions (Coda, Onset) with random intercepts for subjects and items. Metathesis responses were selected at a rate significantly below chance in the Onset condition, while metathesis responses in the Coda condition were not selected at a rate significantly above chance.[16]

[15] Note that the kappa estimate for assessing colinearity was 16.61 (HLPLab, 2011). The comparison between the model that included an interaction and the model that did not was significant, $\chi^2(3) = 24.05$, $p < .001$.

[16] Note that with a Bonferroni correction applied, the Onset condition is only marginally significant, $p = .054$.

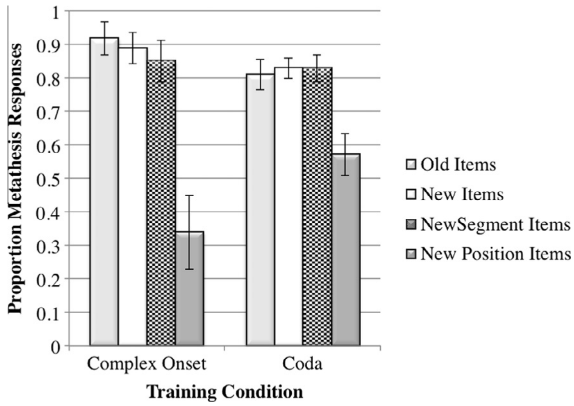


**Fig. 3.** Experiment 3 results: means and standard errors.

**Table 4**
Summary of mixed effect models, Experiment 3.

| | $\beta$ | $SE$ | $z$ |
|---|---|---|---|
| Intercept (Baseline = Old) | 2.33 | 0.26 | 8.87*** |
| Intercept (Baseline = NewSegment) | 1.83 | 0.22 | 8.44*** |
| Coda vs. Onset (Baseline = Old) | −0.81 | 0.32 | −2.50* |
| New vs. Old | 0.25 | 0.35 | 0.69 |
| NewSeg vs. Old | 0.50 | 0.34 | 1.48 |
| NewPos vs. Old | 2.94 | 0.31 | 9.62*** |
| Coda vs. Onset × New vs. Old | 0.50 | 0.45 | 1.12 |
| Coda vs. Onset × NewSeg vs. Old | 0.61 | 0.43 | 1.40 |
| Coda vs. Onset × NewPos vs. Old | 1.81 | 0.39 | 4.65*** |
| *New position comparison* | | | |
| Coda | 0.50 | 0.37 | 1.36 |
| Onset | −0.86 | 0.39 | −2.13* |
| Coda vs. Onset | 1.00 | 0.22 | 4.63*** |

† $0.05 < p < .10$.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

In addition, the intercept when the reference point was New Segment items was significantly different from chance, suggesting that the participants in Experiment 3 were able to generalize to novel segments.

*Discussion*

Experiment 3 replicated the difference between Onset and Coda for New Position items found in Experiments 1–2. Learners in the Coda condition were more likely to extend the metathesis pattern to a novel position compared to learners in the Onset condition. However, this was carried by the fact that learners in the Onset condition selected the metathesis (coda) option significantly less than chance for New Position items, suggesting a preference for items containing a complex onset. In addition, participants in the Coda condition did not select the metathesis option in New Position items at a rate greater than chance. This difference is predicted by the stress change in Experiment 3. In the Onset condition, metathesis resulted in a complex onset in an unstressed syllable, highlighting the importance of an onset over a coda, even in a prominent (stressed) position. In the Coda condition, metathesis resulted a coda in a stressed position (e.g., /ep/ + /la/ → [**el**pa]), a prominent position that may be the target for metathesis. This may have created some phonetic motivation for the metathesis that would drive some speakers away from generalizing the metathesis to the novel (onset) position (e.g., /el/ /pa/ → /**e**pla/), which may have driven some participants to select the metathesis option at a rate lower than 50% chance. Of the 21 participants in the Coda condition, 13 (62%) selected the metathesis option more than half the time, one (5%) selected the metathesis item exactly half of the time, and seven (33%) selected the metathesis item less than half of the time. This suggests that while the majority of participants showed the same pattern as Experiment 1 (where 19 (79%), of the 24 participants in the Coda conditions chose the metathesis option more than half of the time), a strong proportion of participants in the Coda condition of Experiment 3 may have learned a metathesis pattern that resulted in consonants placed in stressed position.

Experiment 3 demonstrated that stress assignment plays an important role in how syllables are parsed, and therefore, the structural constraints that learners use to represent the novel metathesis pattern. Experiments 1–3 tested the role of syllable structure constraints without consideration of syllable contact. Syllable contact laws govern how syllabification interacts with sonority. Syllable contact is a measure of the change in sonority at a syllable boundary (Vennemann, 1988). For example, sonority rises at the syllable boundary in [ep.la]: the coda /p/ is an obstruent (low sonority), and the onset /l/ is a sonorant (high sonority). Sonority falls at the syllable boundary in [el.pa]: the coda /l/ is a sonorant (high sonority) and the onset /p/ is an obstruent (low sonority). Most languages prefer falling sonority across a syllable boundary (Clements, 1988; Gouskova, 2004). In Leti, a language that does not allow complex onsets, metathesis is more likely to occur when the result is falling sonority across a syllable boundary (e.g., /urun/ → [urnu] 'beautiful') (Hume, 1998). In English, speakers tend to parse /epla/ as [e.pla] with the onset maximized, meaning that the first syllable has only a vowel (a high sonority) and the second syllable starts with /p/, low sonority. Because English allows complex onsets, the change from /elpa/ to [e.pla] creates a better English syllable than the change from /epla/ to [el.pa]. Thus, it may be possible to explain the results of Experiments 1–3 in terms of syllable contact, rather than onset maximization. Experiment 4 controls for onset maximization and syllable contact in order to fully explore the effects from Experiments 1–3.

## Experiment 4

Experiment 4 explored the possibility that learners made use of syllable contact to represent a novel metathesis patterns, rather than in terms of maximization of onsets. Participants were exposed to a metathesis pattern in which metathesis only improved or degraded the syllable contact, but did not change the syllable structure. While metathesis often improves syllable contact (Hume, 2001, 2004), the result is always improvement in perceptibility, rather than syllable contact alone. Recent studies have argued that syllable contact may be a placeholder for a range of perceptual effects that happen to pattern along the theoretical sonority hierarchy (Henke, Kaisse, & Wright, 2012), suggesting that even in cases where metathesis follows syllable contact laws (as in Leti (Hume, 1998)), they may be governed by more general constraints based in syllable structure (e.g., onset maximization and avoidance of codas) and perceptual constraints. Thus, it is expected that participants in Experiment 4 will learn a general metathesis pattern rather than a pattern couched solely in terms of syllable contact.

In Experiment 4, learners were exposed to a metathesis pattern in which a stop consonant (e.g., /p, t, k/) was switched with the sonorant nasal /m/. Participants in the Increased Sonority condition were exposed to a metathesis pattern that increased sonority at the syllable boundary and improved syllable contact (e.g., /em/ + /pa/ → [ep.ma]), while participants in the Decreased Sonority condition were exposed to a metathesis pattern that decreased sonority at the syllable boundary and did not improve syllable contact (e.g., /ep/ + /ma/ → [em.pa]).

It is important to note that neither the Increased nor the Decreased Sonority conditions involved metathesis that improved perceptibility or syllable structure. Metathesis in the Increased Sonority condition results in a stop in coda position. Coda stops are perceptibly weak (Steriade, 2001), and tend to be subject to phonological processes that enhance overall perceptibility (e.g., deletion or metathesis). In contrast, metathesis in the Decreased Sonority condition results in a nasal in coda position. Nasal codas are also subject to degraded perceptibility. The major difference between the Decreased and Increased Sonority conditions is syllable contact rather than syllable structure or perceptibility. If learners make use of syllable contact in learning metathesis, then learners should be more likely to extend the metathesis pattern to New Position items in the Increased Sonority condition (which degrades syllable contact) compared to the Decreased Sonority condition (which improves syllable contact). However, if learners make use of syllable structure and/or perceptual constraints, then learners should extend the metathesis pattern to New Position items in both conditions equally.

### Method

#### Participants

All participants were fluent speakers of English who had not participated in Experiments 1–3, from the Pacific Lutheran University Psychology participant pool, and had not had significant exposure to a language with a regular metathesis pattern. There were 42 participants (21 in each condition) who participated for course credit, whose gender and age were representative of the university population. Two participants were excluded from analysis because these participants failed to follow directions.

**Table 5**
Examples of training and test stimuli, Experiment 3.

| Condition | Training/Old items | New items | New Position items |
|---|---|---|---|
| Increased Sonority | em da edma vs.<br>em da edma<br>um ko ukmo vs.<br>um ko ukmo | am be abme vs.<br>am be ambe<br>im pu ipmu vs.<br>im pu impu | ob mi ombi vs.<br>ob mi obmi<br>ag mu amgu vs.<br>ag mu agmu |
| Decreased Sonority | ed ma emda vs.<br>ed ma edma<br>uk mo umko vs.<br>uk mo ukmo | ob mi ombi vs.<br>ob mi obmi<br>ag mu amgu vs.<br>ag mu agmu | am be abme vs.<br>am be ambe<br>im pu ipmu vs.<br>im pu impu |

*Design*

The design of Experiment 4 was similar to Experiments 1–3, with the following changes. Participants in the Increased Sonority condition were exposed to a metathesis pattern that resulted in an increase in sonority at the syllable boundary (e.g., /em/ + /do/ → [edmo]), while participants in the Decreased Sonority condition were exposed to a metathesis pattern that resulted in a decrease in sonority at the syllable boundary (e.g., /ed/ + /mo/ → [emdo]). In addition, Experiment 4 did not make use of New Segment test items, thus simplifying the design to include only Old, New and New Position items.

*Stimuli*

The stimuli were created in the same manner as Experiments 1–3, except that a different female speaker was used. Stress in bisyllabic items was placed on the initial syllable. In addition, the set of consonants included the stops /p, t, k, b, d, g/ and the nasal /m/. Participants in the Decreased Sonority condition were exposed to sequences of the form: /$VC_{stop}$/ + /mV/ → [$VmC_{stop}V$] (e.g., /ip/ + /me/ → [impe]) sequences. Participants in the Increased Sonority condition were exposed to sequences of the form: /Vm/ + /$C_{stop}V$/ → [$VC_{stop}mV$], (e.g., /im/ + /pe/ → [ipme]). Examples of training and test stimuli for Experiment 4 are provided in Table 5.'

*Procedure*

The procedure was identical to Experiments 1–3.

*Results*

Mean proportion and standard error of metathesis responses (as opposed to a 'no change' response) are presented in Fig. 4. The rate of metathesis responses was relatively high for the Increased Sonority condition: Old (mean = 0.84, *SD* = 0.22), New (mean = 0.87, *SD* = 0.21), and New Position (mean = 0.70, *SD* = 0.29) items. A similar pattern was found Decreased Sonority condition: Old (mean = 0.82, *SD* = 0.21), New (mean = 0.74, *SD* = 0.14), and New Position (mean = 0.67, *SD* = 0.26) items.

The data in Experiment 4 were analyzed in the same manner as Experiments 1–3, with the maximal model having random slopes and intercepts for subjects and random intercepts for items. The full list of results[17] is provided in Table 6. For space considerations, only comparisons related to the hypotheses are discussed in the text. Overall, there was a significant difference between Old (mean = 0.83, *SD* = 0.21) and New Position items (mean = 0.68, *SD* = 0.27),

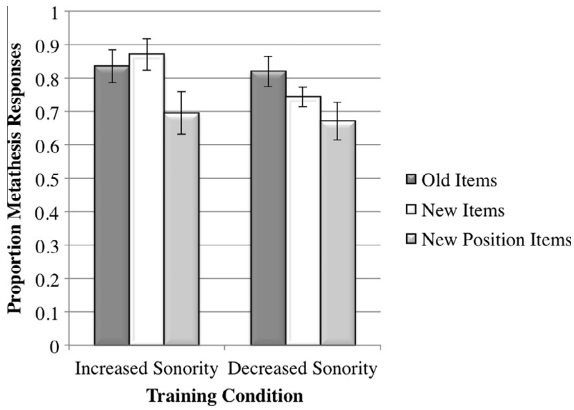


**Fig. 4.** Experiment 4 results: means and standard errors.

**Table 6**
Summary of mixed effect models, Experiment 4.

| | $\beta$ | *SE* | *z* |
|---|---|---|---|
| Intercept | 1.77 | 0.32 | 5.46*** |
| Increased vs. Decreased | 0.52 | 0.57 | 0.91 |
| New vs. Old | −0.36 | 0.37 | −0.97 |
| NewPos vs. Old | −0.83 | 0.36 | −2.32* |
| Increased vs. Decreased × New vs. Old | 0.67 | 0.53 | 1.28 |
| Increased vs. Decreased × NewPos vs. Old | −0.16 | 0.51 | −0.32 |
| *New position comparisons* | | | |
| Increased | 1.11 | 0.39 | 2.86** |
| Decreased | 1.07 | 0.38 | 2.82** |
| Increased vs. Decreased | 0.036 | 0.54 | 0.066 |

† $0.05 < p < .10$.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

[17] The colinearity estimate was 12.15. The comparison between the model that included an interaction and the model that did not was not significant, $\chi^2(2) = 2.04$, $p = .35$.

but unlike Experiments 1–3, the interaction with conditions was not significant, suggesting that the reduction in metathesis responses from Old to New Position items was relatively even across conditions. This is in line with the hypothesis that learners did not base their representations of the novel metathesis pattern on syllable contact laws.

The intercept was recorded for a model comparing responses to New Position items for both Increased and Decreased Sonority conditions with random intercepts for subjects and items. Both Increased (mean = 0.70, $SD$ = 0.29) and Decreased (mean = 0.67, $SD$ = 0.26) Sonority conditions showed significant intercepts, suggesting that learners were selecting the metathesis response greater than 50% chance, but there were no significant differences between Increased and Decreased Sonority conditions, further supporting the conclusion that the metathesis pattern was not learned in terms of syllable contact.

### *Discussion*

The results of Experiment 4 demonstrate that English-speaking learners will generalize a novel metathesis pattern to a novel structure, even if that novel structure does not improve syllable contact. This suggests that learners in Experiments 1–3 made use of syllable structure, rather than syllable contact to encode the novel metathesis pattern.

## General discussion

Taken together, the four experiments in the present paper provide evidence that English-speaking learners make use of syllable structure constraints when learning a novel metathesis pattern. Experiments 1–3 showed that learners who were trained on a grounded metathesis pattern that resulted in a complex onset were less likely to generalize the pattern to items that did not create a complex onset, compared to learners trained on an arbitrary metathesis pattern that resulted in a coda. Experiment 4 demonstrated that the results of Experiments 1–3 were not due to syllable contact constraints. It is possible that syllable contact constraints are useful for speakers under circumstances that create perceptual or structural improvement. Winters (2001) showed that English speakers preferred consonant-consonant metathesis when the perceptibility of the two consonants improved, suggesting that syllable contact law and sonority may serve as a cover constraint for perceptibility (Henke et al., 2012). In addition, Berent and colleagues have shown a robust tendency for language users (independent of language background) to be sensitive to typological generalizations about sonority, even when there is only scant evidence for those generalizations in the native language (Berent & Lennertz, 2010; Berent, Lennertz, Smolensky, & Vaknin-Nusbaum, 2009; Berent et al., 2010; Zhao & Berent, 2015). While Berent et al. (2009) found that English speakers prefer nasal-stop clusters to stop-nasal clusters, a seemingly contradictory result from Experiment 4, the clusters used in Berent et al. (2009) were illegal in English, while the consonants used in the present study crossed a syllable boundary and were therefore legal in English.

A possible alternative explanation for the results in Experiments 1–3 is that learners in the Onset condition only learned that the language required complex onsets, and did not learn a metathesis pattern. For this to occur, participants must learn the structural constraints of the output, rather than the structural change. This possibility would be evidence of output-based learning rather than process-based learning, but would still support the hypothesis that learners make use of structural constraints when learning. Many languages make use of multiple repair strategies in order to satisfy a single markedness constraint (e.g., *Coda) (Wilson, 2001). If learners first place the relevant markedness constraint in a high-ranked position before re-ranking faithfulness constraints, it could help to explain why some phonological processes appear to be stored in terms of a structural constraint along with several repair options. While it is not clear how to fully test this alternative explanation, there are several reasons to doubt that this occurred. First, in Experiment 1, learners in the Onset condition did not select the metathesis option at a rate lower than chance, suggesting no strong preference for complex onsets in the New Position items. Second, given that the other conditions showed evidence for learning the metathesis pattern, it is unlikely that failure to learn metathesis only occurs when metathesis results in a complex onset.

The present experiment made use of American English speakers. In English, onsets are maximized and codas are tolerated. For many languages, however, complex onsets are ungrammatical. As noted above, metathesis in Leti is motivated by avoidance of complex onsets (Hume, 1998). If learners make use of their own language-specific constraints when learning novel phonological patterns, speakers of a language that avoids complex onsets should show the opposite pattern of generalization of the metathesis pattern compared to English speakers. In addition, languages that tolerate complex consonant clusters and violations of sonority sequencing principles (such as several Slavic languages like Polish and Russian) may show different patterns of learning and generalization of metathesis. A question for future research is how learners with various L1 backgrounds learn novel phonological patterns differently.

The results of the present study demonstrate that learners can encode syllable structure constraints when learning novel phonological patterns, supporting a framework like Optimality Theory (Prince & Smolensky, 2004) in which metathesis (and other phonological patterns) are governed through an interaction between markedness constraints (constraints on the structure of language) and faithfulness constraints (constraints limiting changes from the input to the output). This is in line with several other artificial grammar learning experiments showing support for OT, such as the transitivity principle (Guest, Dell, & Cole, 2000). Because markedness constraints can specify the kind of phonological structures that motivate metathesis (e.g., Maximize Onsets, *Coda), metathesis only applies when the relevant markedness constraints would be violated otherwise. However, arbitrary metathesis must apply as an 'ad hoc' constraint that applies generally, regardless of what markedness constraints might be violated. If ad hoc constraints are easily created, there is a question of why these constraints are not applied to all patterns. If learners are biased toward patterns that are grounded in terms of markedness constraints or structural improvements, then learners may require more evidence in order to create an ad hoc metathesis constraint. If markedness constraints are learned along with the L1 grammar, then creating new rankings based on learned constraints should be easier than posing a novel constraint. This may explain why synchronic metathesis patterns are typically grounded in some kind of perceptual or structural improvement, and those without such phonetically based improvements tend to be highly constrained by morphology (Blevins & Garrett, 1998; Hume, 2004).

If learners in the present study made use of constraints such as those found in OT, learning the metathesis pattern would result in lowering of the ranking for Linearity over a high-ranked markedness constraint. One concern is that lowering the Linearity constraint could induce errors elsewhere in speech, meaning that creating an ad hoc constraint to satisfy the experiment might be both easier and less risky. However, speakers readily adapt to the speech around them (Bradlow & Bent, 2008; Dell, Reed, Adams, & Meyer, 2000), and this adaptation can result in changes in production (referred to as phonetic convergence) (Kim, Horton, & Bradlow, 2011), suggesting that the phonological system is highly adaptable, and allows for the possibility of temporary changes to constraint rankings. More research is needed to understand how learners adapt to novel speakers, novel languages, and novel rules.

While the present experiments support an abstract approach to phonology such as the ones advocated for in OT, it is important to explore other approaches to phonology, specifically the role of frequency. Hume (2004) argues that speakers tend to prefer metathesis patterns that produce a sequence that is more frequent in the language. In order to test the hypothesis that learning was based in terms of frequency of adjacent consonants rather than syllable structure, $\log_2$ frequencies were computed for the sound sequences in Experiments 1–3 using ngram data compiled from Google Books corpus (Norvig, n.d.). While the onset clusters were numerically more frequent than the clusters in the Coda condition, the difference was not significant (Coda mean = 30.07, $SD = 1.92$, Onset Mean 31.38, $SD = 2.19$, $t(22) = 1.56$, $p = .13$), suggesting that the results of Experiments 1–3 are unlikely to be due to frequency alone. The same statistics were taken for Experiment 4, with the same result; Increased Sonority clusters were numerically more frequent than Decreased Sonority, but the difference between the two conditions' frequencies were not statistically significant (Decreased Sonority mean = 26.70, $SD = 4.25$, Increased Sonority mean 27.86, $SD = 1.54$, $t(10) = .63$, $p = .54$), suggesting that if the trend of frequency differences alone were enough to cause the differences in Experiments 1–3, then these differences should have been seen in Experiment 4 as well, as the trends pulled in the same direction (though without statistical significance).

The data in the present experiments may shed some light on the distinction between abstract and exemplar models of phonological processes. In exemplar models of phonology, speakers store the phonetic details of every instance of every utterance both heard and spoken (Pierrehumbert, 2001), including talker specific details (Nygaard, 1998). Generalization from stored instances to novel instances is based on the similarity of the known instance to the novel instance. While exemplar theories do not specifically spell out how generalization to novel items occurs, an exemplar model should predict that the Coda and Onset conditions should generalize to New Position items at the same rate, since the perceptual difference from onset to coda are equivalent regardless of direction (e.g., onset to coda or coda to onset). Because generalization of the metathesis pattern in the New Condition items was different for Onset and Coda positions, it suggests that similarity alone (as predicted by exemplar models) cannot account for the data. This supports a view in which phonological representations share an abstract level of processing (Cohen-Goldberg, 2015). This abstract level of processing has been supported in several areas of research, where learners of novel artificial languages (Finley, 2013; Linzen & Gallagher, 2014) and native English speakers (Cohen-Goldberg, 2015) generalize beyond the lexical statistics.

While exemplar models do not make the correct prediction about the differences between Onset and Coda conditions, they do make the correct prediction that as differences between the training items and test items increase, generalization should decrease. Across all experiments, there was a general, reliable tendency for rates of metathesis responding to decrease from Old to New Position items. Even when learners reliably extend the metathesis pattern to new segments and new positions, metathesis responses are always greatest to familiar items. This suggests that factors like similarity and frequency must play some role in representation and generalization. A question for future research is to incorporate the ideas from exemplar theories into an abstract model of phonology (Cohen-Goldberg, 2015).

If metathesis in the Coda condition was based on an arbitrary, ad-hoc rule, while metathesis in the Onset condition was based on a grounded rule (i.e., metathesize in order to create a complex onset), one might argue that the metathesis rule in Coda condition was actually less complex than the metathesis rule in the Onset condition. For example, a general rule can be classified as 'first order' (e.g., /k/ is an onset), while a restricted rule can be classified as 'second order' (e.g., /k/ is an onset when the vowel is /i/). Previous research has shown that second order rules take longer to learn than first order rules (Warker & Dell, 2006). It is possible that second order rules may not necessarily be more difficult to learn if the conditions of the second order rule are part of the prior knowledge base, or if learners are biased to find specific types of patterns. Learning a pattern may be easier if the pattern is expected, compared to rules that are unexpected or unnatural. Evidence that learners make use of biases when forming conditional learning has come from artificial learning of vowel harmony, where vowels agree in a specific feature value.

Learners were more likely to learn a restricted round harmony vowel pattern that fit with the perceptual biases of the language user and the typology of harmony languages compared to a restricted harmony pattern that went against perceptual biases (Finley, 2012).

*Implications for domain general cognition*

The results of the present study have important consequences for a domain general theory of language and cognition. In a domain general view of cognition, phonological processes operate under similar principles as other cognitive processes, but appear different due to modality specific constraints (Frost, Armstrong, Siegelman, & Christiansen, 2015); the difference between views might be expressed in the level of abstraction to which the domain general rules apply. While metathesis is discussed as a purely phonological pattern, the process of switching elements is not specific to sounds. For example, in arranging files in an office, one might alternate the color of files (e.g., red and green) in order to create ease in sorting. This structural constraint might result in files being 'switched' around to achieve this structural parsimony. In a domain general view, the abstract rule of /A/ + /B/ → [BA] can apply regardless of modality, and modality specific constraints must be represented at a level of abstraction specific to the modality. A domain general account of the present study would require that domain specific constraints on syllable structure and perceptibility interact with domain general constraints on linearity of structure. This implies that the LINEARITY constraint in Optimality Theory could operate at a domain general level. It also implies that there may be different types of generalization from a spoken metathesis pattern to a visual analogue, depending on the perceptual motivation for the spoken constraint. While some research has explored transfer of phonological processes to visual modalities (Finley & Christiansen, 2011), more research could be done to understand how phonological systems interact with domain general cognitive processes.

*Conclusions*

The present paper made use of an artificial grammar learning paradigm in which learners were more likely to generalize a novel metathesis pattern to items that involved a structural improvement (maximization of onsets). These results support a theory of substantively biased learning, where language users make use of perceptual and cognitive constraints when learning novel phonological patterns. The use of these constraints results in a bias toward learning phonetically and cognitively grounded patterns.

## Acknowledgments

I am grateful to Patricia Reeder, Neil Bardhan, Elizabeth Jennings, Emily Kasman, Caitlin Hilliard, Kathryn Schuler, Matthew Goldrick, Jochen Trommer, Jennifer Cole, Abby Stringer, Stine Lindvig, Nicole Wirth, Magdiel Habila, Michael Medina, John Alderede, and to members of the Northwestern Phonatics group and the University of Rochester Aslin-Newport lab, as well as participants at the 2014 LAGB workshop. This research was supported in part by NIH grant DC00167 to E. Newport, HD37082 to R. Aslin & E. Newport, and NIH training grant T32DC000035.

## A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jml.2016.06.005.

## References

Anderson, S. (1981). Why phonology isn't "natural". *Linguistic Inquiry, 12*, 493–539.
Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68*(3), 255–278. http://dx.doi.org/10.1016/j.jml.2012.11.001.
Berent, I., Balaban, E., Lennertz, T., & Vaknin-Nusbaum, V. (2010). Phonological universals constrain the processing of nonspeech stimuli. *Journal of Experimental Psychology: General, 139*(3), 418–435. http://dx.doi.org/10.1037/a0020094.
Berent, I., & Lennertz, T. (2010). Universal constraints on the sound structure of language: Phonological or acoustic? *Journal of Experimental Psychology: Human Perception and Performance, 36*(1), 212–223. http://dx.doi.org/10.1037/a0017638.
Berent, I., Lennertz, T., Smolensky, P., & Vaknin-Nusbaum, V. (2009). Listeners' knowledge of phonological universals: Evidence from nasal clusters. *Phonology, 26*(01), 75–108.
Blevins, J. (2004). *Evolutionary phonology: The emergence of sound patterns*. Cambridge: Cambridge University Press.
Blevins, J., & Garrett, A. (1998). The origins of consonant-vowel metathesis. *Language, 74*, 508–556.
Blevins, J., & Garrett, A. (2004). The evolution of metathesis. In B. Hayes, R. Kirchner, & D. Steriade (Eds.), *Phonetically based phonology* (pp. 117–156). Cambridge: Cambridge University Press.
Boersma, P., & Weenink, D. (2015). *Praat: Doing phonetics by computer*.
Bradlow, A., & Bent, T. (2008). Perceptual adaptation to non-native speech. *Cognition, 106*(2), 707–729.
Carpenter, A. (2005). Acquisition of a natural vs. and unnatural stress system. In A. Brugos, M. R. Clark-Cotton, & S. Ha (Eds.), *BUCLD 29 proceedings* (pp. 134–143). Somerville, MA: Cascadilla Press.
Chater, N., & Christiansen, M. H. (2010). Language acquisition meets language evolution. *Cognitive Science, 34*, 1131–1157.
Chomsky, N., & Halle, M. (1968). *The sound pattern of English*. New York: Harper and Row.
Clements, G. (1988). The sonority cycle and syllable organization. *Phonologica*, 63–76.
Cohen-Goldberg, A. (2015). Abstract and lexically specific information in sound patterns: Evidence from /r/-sandhi in rhotic and non-rhotic varieties of English. *Language and Speech, 58*(4), 522–548.
Cristia, A., Mielke, J., Daland, R., & Peperkamp, S. (2013). Constrained generalization of implicitly learned sound patterns. *Journal of Laboratory Phonology, 4*(2), 259–285. http://dx.doi.org/10.1515/lp-2013-0010.
Davidson, L., Smolensky, P., & Jusczyk, P. (2004). The initial and final states: Theoretical implications and experimental explorations of richness of the base. In R. Kager, J. Pater, & W. Zonnefeld (Eds.), *Constraints in phonological acquisition* (pp. 321–368). Cambridge: Cambridge University Press.
Dell, G. S., Reed, K. D., Adams, D. R., & Meyer, A. S. (2000). Speech errors, phonotactic constraints, and implicit learning: A study of the role of experience in language production. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 1355–1367.
Finley, S. (2011a). Generalization to novel consonants in artificial grammar learning. In *Proceedings of the 33rd annual conference of the Cognitive Science Society* (pp. 3268–3273). Austin, TX: Cognitive Science Society.
Finley, S. (2011b). Perceptual biases in consonant deletion. In *Proceedings of the XVII international congress of phonetic sciences* (pp. 675–678).
Finley, S. (2012). Typological asymmetries in round vowel harmony: Support from artificial grammar learning. *Language and Cognitive*

*Processes, 27*(10), 1550–1562. http://dx.doi.org/10.1080/01690965.2012.660168.
Finley, S. (2013). Generalization to unfamiliar talkers in artificial language learning. *Psychonomic Bulletin & Review, 20*(4), 780–789. http://dx.doi.org/10.3758/s13423-013-0402-7.
Finley, S., & Badecker, W. (2007). Towards a substantively biased theory of learning. *Berkeley Linguistics Society, 33*, 142–154.
Finley, S., & Badecker, W. (2009a). Artificial language learning and feature-based generalization. *Journal of Memory and Language, 61*(3), 423–437.
Finley, S., & Badecker, W. (2009b). Right-to-left biases for vowel harmony: Evidence from artificial grammar. In A. Shardl, M. Walkow, & M. Abdurrahman (Eds.). *Proceedings of the 38th north east linguistic society annual meeting* (Vol. 1, pp. 269–282). Amherst, MA: GLSA.
Finley, S., & Badecker, W. (2012). Learning biases for vowel height harmony. *Journal of Cognitive Science, 13*, 287–327.
Finley, S., & Christiansen, M. H. (2011). Multimodal transfer of repetition patterns in artificial grammar learning. In *Proceedings of the 33rd annual conference of the cognitive science society* (pp. 330–335).
Frost, R., Armstrong, B. C., Siegelman, N., & Christiansen, M. H. (2015). Domain generality versus modality specificity: The paradox of statistical learning. *Trends in Cognitive Sciences, 1–9*. http://dx.doi.org/10.1016/j.tics.2014.12.010.
Goldsmith, J. (1993). Harmonic phonology. In J. Goldsmith (Ed.), *The last phonological rule* (pp. 20–60). Chicago: The University of Chicago Press.
Gouskova, M. (2004). Relational hierarchies in optimality theory: The case of syllable contact. *Phonology, 21*(2), 201–250.
Guest, D. J., Dell, G. S., & Cole, J. S. (2000). Violable constraints in language production: Testing the transitivity assumption of optimality theory. *Journal of Memory and Language, 42*(2), 272–299.
Hale, M., & Reiss, C. (2000). Substance abuse" and "dysfunctionalism": Current trends in phonology. *Linguistic Inquiry, 31*(1), 157–169.
Hayes, B. (1999). Phonological restructuring in Yidiny and its theoretical consequences. In B. Hermans & Marc vanOostendorp (Eds.), *The derivational residue in phonological optimality theory* (pp. 175–205). Amsterdam: John Benjamins.
Henke, E., Kaisse, E., & Wright, R. (2012). Is the sonority sequencing principle an epiphenomenon? In S. Parker (Ed.), *The sonority controversy* (pp. 65–100). Berlin: Mouton de Gruyter.
HLPLab (2011). https://hlplab.wordpress.com/2011/02/24/diagnosing-collinearity-in-lme4/.
Hume, E. (1998). Metathesis in phonological theory: The case of Leti. *Lingua, 104*, 147–186.
Hume, E. (2001). Metathesis: Formal and functional considerations. In E. Hume, N. Smith, & J. van de Weijer (Eds.), *Surface syllable structure and segment sequencing* (pp. 1–25). Leiden, NL: HIL Occasional Papers.
Hume, E. (2004). The indeterminacy/attestation model of metathesis. *Language, 80*(2), 203–237.
Hume, E. (2016). Metathesis in Language. Retrieved March 3, 2016, from http://metathesisinlanguage.osu.edu/.
Hyman, L. (1976). Phonologization. *Linguistic studies offered to Joseph Greenberg* (Vol. 2, pp. 407–418). .
Kahn, D. (1976). *Syllable-based generalizations in English phonology*. New York: Garland.
Kim, M., Horton, W., & Bradlow, A. (2011). Phonetic convergence in spontaneous conversations as a function of interlocutor language distance. *Journal of Laboratory Phonology, 2*, 125–156.
Kiparsky, P. (1973). Abstractness, opacity, and global rules. In O. Fujimura (Ed.), *Three dimensions of linguistic theory* (pp. 57–86). Tokyo: TEC.
Linzen, T., & Gallagher, G. (2014). The timecourse of generalization in phonotactic learning. In J. Kingston, C. Moore-Cantwell, J. Pater, & R. Staub (Eds.), *Proceedings of phonology 2013* (pp. 1–12). Washington, DC: Linguistic Society of America.
Monaghan, P., Chater, N., & Christiansen, M. H. (2005). The differential role of phonological and distributional cues in grammatical categorisation. *Cognition, 96*, 143–182.
Monaghan, P., Christiansen, M. H., & Chater, N. (2007). The phonological-distributional coherence hypothesis: Cross-linguistic evidence in language acquisition. *Cognitive Psychology, 55*(4), 259–305.
Moreton, E. (2008). Analytic bias and phonological typology. *Phonology, 25*(01), 83–127. http://dx.doi.org/10.1017/S0952675708001413.
Moreton, E., & Pater, J. (2012). Structure and substance in artificial-phonology learning, Part II: Substance. *Language and Linguistics Compass, 6*(11), 702–718. http://dx.doi.org/10.1002/lnc3.366.
Moreton, E., Pater, J., & Pertsova, K. (2015). Phonological concept learning. *Cognitive Science*. http://dx.doi.org/10.1111/cogs.12319.
Norvig, P. (n.d.). Ngrams2 via Google Books ngram data.
Nygaard, L. C. (1998). Talker-specific learning in speech perception. *Perception & Psychophysics, 60*(3), 355–376.
Peña, M., Bonatti, L. L., Nespor, M., & Mehler, J. (2002). Signal-driven computations in speech processing. *Science, 298*, 604–607.
Pierrehumbert, J. B. (2001). Exemplar dynamics: Word frequency, lenition and contrast. In J. L. Bybee & P. Hopper (Eds.), *Frequency and the emergence of linguistic structure* (pp. 137–157). John Benjamins Publishing Company.
Prince, A., & Smolensky, P. (2004). *Optimality theory: Constraint interaction in generative grammar*. Cambridge: Blackwell.
R Development Core Team, R. (2011). R: A Language and Environment for Statistical Computing. (R. D. C. Team, Ed.) R Foundation for Statistical Computing. R Foundation for Statistical Computing. http://dx.doi.org/10.1007/978-3-540-74686-7.
Saffran, J. R., & Thiessen, E. D. (2003). Pattern induction by infant language learners. *Developmental Psychology, 39*(3), 484–494. http://dx.doi.org/10.1037/0012-1649.39.3.484.
Selkirk, E. (1982). The syllable. In H. van der Hulst & N. Smith (Eds.), *The structure of phonological representations (Part II)* (pp. 337–383). Foris Publication.
Steriade, D. (2001). *The phonology of perceptibility effects: The P-map and its consequences for constraint organization. Ms., UCLA.*
Treiman, R., & Danis, C. (1988). Syllabification of intervocalic consonants. *Journal of Memory and Language, 27*(1), 87–104.
Treiman, R., & Zukowski, A. (1990). Towards an understanding of English syllabification. *Journal of Memory and Language, 29*, 65–85.
Vennemann, T. (1988). *Preference laws for syllable structure and the explanation of sound change: With special reference to German, Germanic, Italian and Latin*. Berlin: Mouton de Gruyter.
Warker, J. A., & Dell, G. S. (2006). Speech errors reflect newly learned phonotactic constraints. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*(2), 387–398. http://dx.doi.org/10.1037/0278-7393.32.2.387.
White, J. (2014). Evidence for a learning bias against saltatory phonological alternations. *Cognition, 130*(1), 96–115.
Wilson, C. (2001). Consonant cluster neutralisation and targeted constraints. *Phonology, 18*, 147–197.
Wilson, C. (2003). Experimental investigations of phonological naturalness. *WCCFL, 22*, 101–114.
Wilson, C. (2006). Learning phonology with substantive bias: An experimental and computational study of velar palatalization. *Cognitive Science, 30*, 945–982.
Winters, S. (2001). VCCV perception: Putting place in its place. *Ohio State University Working Papers in Linguistics, 55*, 70–81.
Zhao, X., & Berent (2015). Universal restrictions on syllable structure: Evidence from Mandarin Chinese. *Journal of Psycholinguistic Research, 5*, 1–17.