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Types of statistical knowledge in alternation learning: insights from artificial grammar learning

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1. Introduction

Phonotactics are static probabilistic generalizations about how phonemes can combine in a given language. In English, for example, adjacent sequences of sibilants are restricted, so words like *[**sʃ**ak] *[pa**ʒz**] are not observed. On the other hand, the *alternations* of a language are changes to morphemes that depend on their morphophonological context. For example, in Dutch, final [t] sometimes alternates with [d] under suffixation in intervocalic environments (e.g. [vɛrˈʋɛi**t**]~[vɛrˈʋɛi**d**-en] 'widen').

There is reason to believe that phonotactic knowledge and alternation learning are connected. Crosslinguistically, alternations often serve to remove violations of phonotactic restrictions. For example, alternation of the English plural (e.g. [bɪd-**z**] vs. [fɪʃ-**əz**]) removes sibilant clusters (e.g. *[fɪ**ʃ-z**]), resulting in outputs that respect the general phonotactic restriction against sibilant clusters. This connection between phonotactics and alternations was recognized by Chomsky & Halle (1968), and is also built into frameworks like Optimality Theory (Prince & Smolensky 1993), where both are enforced using the same markedness constraints. Experimental work also suggests that alternations are learned better when they have phonotactic support (e.g. Pater & Tessier 2005, Chong 2021).

Despite the posited connection between phonotactics and alternations, mismatches between the two are also observed crosslinguistically. These include morphologically derived environment effects (Kiparsky 1993, Chong 2019), as well as cases of allomorphy that are not phonologically optimizing (Paster 2009, 2013). For example, in Turkish, velars are deleted intervocalically at a morpheme boundary (e.g. [bebe**k**]~[bebe-in] 'baby-nom/gen'), suggesting the presence of a constraint against intervocalic stops. However, within morphemes (i.e. in the stem phonotactics), intervocalic velars are maintained (e.g. [hara**k**et] 'motion', [si**g**orta] 'insurance'; Inkelas & Orgun 1995). Such cases cannot be straightforwardly accounted for in models where phonotactics and alternations are isomorphic. Instead, they support approaches where phonotactics and alternations are accounted for using separate mechanisms.

Overall, the relationship between phonotactics and alternations is still not well-understood. It is unclear when phonotactics and alternations are allowed to mismatch, and when are they not. If phonotactics and alternations are enforced using separate mechanisms, how and when do the two interact? One possibility is that the influence of phonotactics is conditioned by paradigm-internal frequencies. There is extensive evidence that speakers track paradigm-internal distributions when learning alternations. In particular, speakers *frequency-match*, or apply alternations in a way that matches the proportion at which they occur within that paradigm (Ernestus & Baayen 2003). Going back to the Dutch example, it turns out that across the Dutch lexicon, final [t] is usually non-alternating under suffixation ([vɛrˈʋɛi**t**]~[vɛrˈʋɛi**t**-en] 'reproach'), but alternates with [d] around 25% of the time ([vɛrˈʋɛi**t**]~[vɛrˈʋɛi**d**-en] 'widen'). Ernestus & Baayen (2003) find that speakers, when asked to provide suffixed forms for wug words, apply [t]~[d] alternation at roughly this same rate. This type of frequency-matching behavior has been replicated in extensive work (e.g. Coleman & Pierrehumbert 1997, Zuraw 2000, Albright & Hayes 2003).

The current paper addresses whether phonotactics and paradigm-internal frequencies interact in alternation learning. If phonotactics are constrained by paradigm-internal frequencies, speakers might only draw on phonotactics when paradigm-internal frequencies are uninformative. In other words, if there is ambiguity in whether or not an alternation should apply, learners will draw more heavily on

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their phonotactic knowledge. On the flip side, when paradigm-internal frequencies are highly informative, an alternation is allowed to apply (or not-apply) even if the resulting output contradicts phonotactic generalizations. Under this account, phonotactics and alternations are driven by separate mechanisms, but tend to line up because when an alternation is ambiguous, speakers are biased to apply the alternant that is phonotactically conforming. Over time, this could result in reshaping of the lexicon (e.g. through mislearning of existing words, or the introduction of new words) in way that causes phonotactics and alternations to align.

Studying the link between frequency-matching and phonotactics is difficult in part because phonotactics and paradigm-internal frequency distributions usually align cross-linguistically. As a result, there is limited natural language data that shows how speakers behave when the two factors conflict. To circumvent this issue, we conduct an artificial grammar study where the relationship between phonotactics and paradigm-internal frequencies can be controlled for.

2. Methods

The experiment consisted of a training phase followed by a testing phase. In the training phase, participants learned an artificial language where final [p] sometimes alternates with [k] under suffixation (e.g. dines**p**~dines**k**-a), while other segments are always non-alternating. In the *testing* phase, they were then evaluated on how they applied these p~k alternations to novel words.

2.1. Conditions

Two factors were varied: the rate of alternation in the training phase, and the phonotactic well-formedness of the suffixed forms. First, there were four between-speaker training conditions, varying by the proportion of p~k alternating forms that a participant was exposed to (20%, 40%, 60%, 80%). For example, participants in the 20% condition were exposed to a language with a strong preference for non-alternation, where only 20% of p-final forms underwent p~k alternation. If participants frequency-match, they should apply p~k alternations more when the input has a higher proportion of alternating forms.

Additionally, phonotactic well-formedness of the suffixed forms was varied during the testing phase, using speakers' phonotactic intuitions for English. In the training phase, k-final words were only ever shown with a vowel-initial suffix /-a/ (e.g. dinesp~dinesk-a). However, in the testing phase, k-final words were given with two consonant-initial suffixes, /-wa/ and /-la/. Crucially, when p-final items are suffixed with /-wa/, the alternating and non-alternating variants differ with respect to their (English) phonotactic well-formedness. This is illustrated in (1a-b).

For a stem like [tɪhasp], when the final [p] is non-alternating, the resulting suffixed form has a phonotactically dispreferred onset cluster [pw] (Hammond 1999, Hayes & Wilson 2008). Note that this restriction is not categorical in English, in that [pw] onsets are very rare, but still observed (especially in the context of loanwords like *Puerto Rico*). Even if [p] is syllabified as a coda (e.g. [tɪhasp.wa]), the resulting output still violates phonotactic restrictions against medial CC codas (Borowsky 1986, 1989). The suffix /-la/ is included as a control; when p-final forms are suffixed with /la/, as in (1c-d), the alternating and non-alternating options are neutral with respect to phonotactics, as [pl] and [kl] are equally well-formed onsets. If participants utilize phonotactics in alternation learning, they should apply more alternations when the suffix is /-wa/ (vs. /-la/).

(1) *Example stimuli*

	STEM	SUFFIX=/-wa/	OPTION	PHONOTACTICS
a.	tɪ.ˈhas**p**	tɪ.ˈhas.**pw**a	non-alternating	**marked onset *[pw]**
b.	tɪ.ˈhas**p**	tɪ.ˈhas.**kw**a	p~k alternation	unmarked onset [kw]

	STEM	SUFFIX=/-la/	OPTION	PHONOTACTICS
c.	ga.ˈnar**p**	ga.ˈnar.**pl**a	non-alternating	unmarked onset [pl]
d.	ga.ˈnar**p**	ga.ˈnar.**kl**a	p~k alternation	unmarked onset [kl]

The phonotactic restriction utilized in this study comes from the native language of participants, who are English speakers. We choose to use participants' native language phonotactics for the following reasons. Native language phonotactics are likely to be learned more robustly than completely novel phonotactics taught in an experimental context. Additionally, in experimental settings, it is difficult to confirm whether participants successfully learned a phonotactic restriction, and if they learned the target restriction, rather than other arbitrary generalizations. In contrast, prior experimental work, including Scholes (2016) and Hayes & Wilson (2008), have found that the phonotactic dispreference for *pw onsets is productive for English speakers.

This choice does rely on the assumption that speakers can draw on native language phonotactics in the learning of artificial languages. There is support for this assumption from studies like Pater & Tessier (2005), who conduct an artificial grammar learning study and find that novel alternations are better learned when they are motivated by native language phonotactics. Skoruppa & Peperkamp (2011) is another study that takes advantage of participants' native language knowledge. In this study, native French speakers were taught artificial dialects of French that had a novel vowel (dis)harmony pattern, but otherwise conformed to French phonotactic restrictions.

Work on alternation learning has found effects of learning biases that should also be controlled for. First, speakers show a preference for non-alternation, which can be characterized formally as paradigm uniformity (Steriade 1997), uniform exponence (Kenstowicz 1996), or output-output correspondence (Benua 1995). White (2013) frames this preference as gradient, in that speakers prefer perceptually less salient alternations (with non-alternation being the ideal option). In our experimental design, phonotactics and the non-alternation bias make predictions in the opposite directions. When the suffix is /-wa/, it is the alternating option that reduces phonotactic violations. Therefore, if participants apply more alternations when the suffix is /-wa/, this cannot be explained as a preference for non-alternation.

In addition to this non-alternation preference, speakers have also been found to prefer formally less complex patterns (complexity/analytic bias; Moreton & Pater 2012b). For example, Pycha et al. (2003) find a complexity bias; they test the learning of three different patterns, and find that both vowel harmony and vowel disharmony are learned better than an arbitrary vowel alternation, which would require more features to describe. In the current study, participants learn only a single alternation pattern, so differences in how well participants learn this pattern should not be attributable to complexity bias effects.

Finally, there is also evidence that speakers preferentially learn phonetically motivated patterns (substantive bias; Moreton & Pater 2012a), where an alternation promotes articulatory ease or provides perceptual benefits. For example, Finley & Badecker (2012) tests the learning of different vowel harmony patterns, and finds that a perceptually motivated harmony pattern is learned better than other comparable harmony patterns. The current study minimizes effects of substantive bias by teaching participants an arbitrary alternation pattern (p→k in non-final position) that has no clear phonetic motivation.

2.2. Predictions

As already described in the previous section, if participants frequency-match, they should apply p~k alternations at roughly the same rate as what they were exposed to in the training phase. This is illustrated by the hypothetical results in Fig. 1A. Additionally, if phonotactics can modulate frequency-matching, there should be an effect of suffix type; as illustrated in Fig. 1B, participants should apply more alternations when the suffix is /-wa/ (vs. /-la/).

However, there are also different possibilities for how frequency-matching and phonotactics interact. Phonotactics could have a uniform effect across all rates of alternation, as is shown in Fig. 1B, or phonotactics could be constrained in some way by frequency-matching. Fig. 1C illustrates one possible interaction, where phonotactics has an effect only when the alternation rates are close to chance.

2.3. Stimuli

In the training phase, participants saw 30 p-final words and 30 fillers ending in other non-alternating consonants. In the testing phase, they saw 24 new words (16 p-final words, 8 ending in a consonant other than [p]). Stimuli were all of the shape $C_1V_1.C_2V_2C_3C_4$, with a light initial syllable followed by a heavy syllable with a CC consonant cluster. C_1 and C_2 were always either [h] or a coronal consonant ([t, d, n, s,

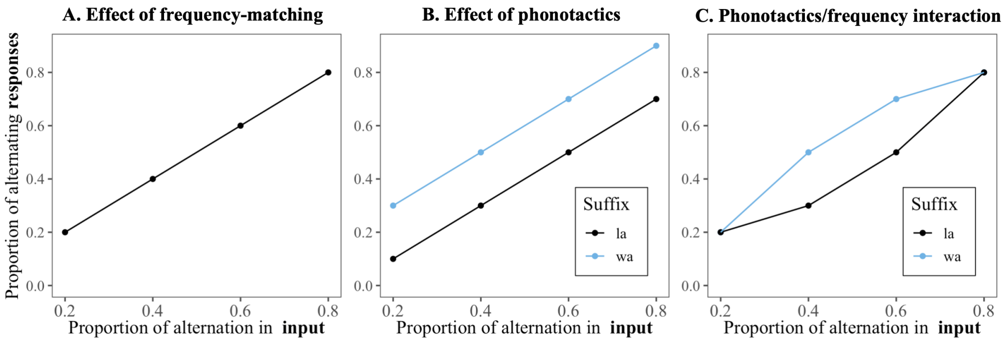

Figure 1: Predicted experimental results

z, ʃ, r]). The final C_3C_4 consonant cluster was one of [sp, rp, mp, lp]. Fillers followed the same structure, except that some filler items did not end in consonant clusters. Instead, all fillers ended in a phonotactically licit English coda (e.g. [st, rt, f, n]). All stimuli had stress on the second syllable, and stress did not shift between the stem and suffixed forms. Stimuli were synthesized using Google Cloud.

2.4. Participants

In total, 150 native English speakers (85 female, 65 male; mean age: 36) were recruited online from Prolific, and paid at a rate of $13/hour. Participants were randomly put into one of the three artificial language groups (fifteen in each). 42 more participants were tested but were excluded due to not completing the experiment, or getting more than 3 responses wrong during the training phase of the study (detailed below in Section 2.5).

2.5. Procedure

The experiment was conducted online using the Labvanced platform (Finger et al. 2017). Participants were told that they would be learning words from a foreign language that is similar to English. They were also asked to pay attention to how words change in different contexts.

Participants were exposed to three suffixes, the vowel-initial /-a/ and two consonant-initial suffixes /-la/ and /-wa/. /-a/ always meant ‘dual’, while /-la/ and /-wa/ meant either ‘bigger’ or ‘many (>2)’. The meanings of /-la/ and /-wa/ were counterbalanced across participants, and the meanings of all three suffixes were indicated visually, as in Fig. 2 below. In the training phase, k-final stems were only shown with the /-a/ suffix, while filler items were shown with all three suffixes. This means that in the training phase, participants were never exposed to the phonotactic restriction against [pw] onsets.

During each training trial, participants saw pairs of stem and suffixed forms, presented both auditorily and orthographically, with accompanying images to indicate the meaning. An schematic example of a training trial is shown in Fig. 2. Immediately after being shown each stem-suffix pair, participants also answered a forced-choice question about what the correct suffixed form for the word was. They were given two options, the correct suffixed form and a suffixed form where either the suffix was wrong, or alternation was incorrectly applied. The order of stimuli presentation was randomized, and participants were exposed to each item twice, resulting in a total of 120 training trials.

In the training phase, participants heard new CVCVCC stimuli, presented in random order. In each trial, the new word was first presented both auditorily and orthographically. Participants were then asked to pick the correct suffixed form in a forced-choice task. As illustrated in Fig. 3, participants were always shown two options, one non-alternating and one with p~k alternation. The suffixed form options were presented orthographically with no audio, and participants were encouraged to say each option out loud. The order in which the options were presented was counterbalanced across trials.

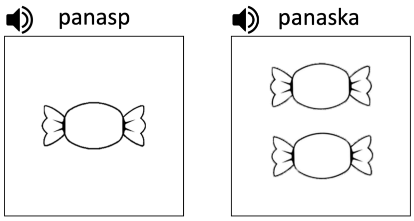

Figure 2: Example testing trial

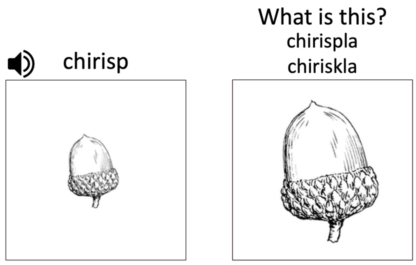

Figure 3: Example training trial

3. Results

Results are visualized below in Fig. 4 below, which shows mean responses across all participants (solid lines) plotted over individual participant responses. Looking first at Fig. 4A, we see that participants were generally frequency-matching, in that they applied more alternations when the input (i.e. training data) has a higher proportion of alternating forms. There was also a general preference for non-alternation; participants applied less p~k alternation than was present in the input across all four input conditions.

In Fig. 4B, which presents results by suffix type, we observe an effect in the expected direction. Specifically, participants applied alternations at a higher rate when the suffix is /-wa/ (vs. /-la/). Notably, this effect is not equal across all rates of alternation, and instead increases as the rate of alternation in the input increases.

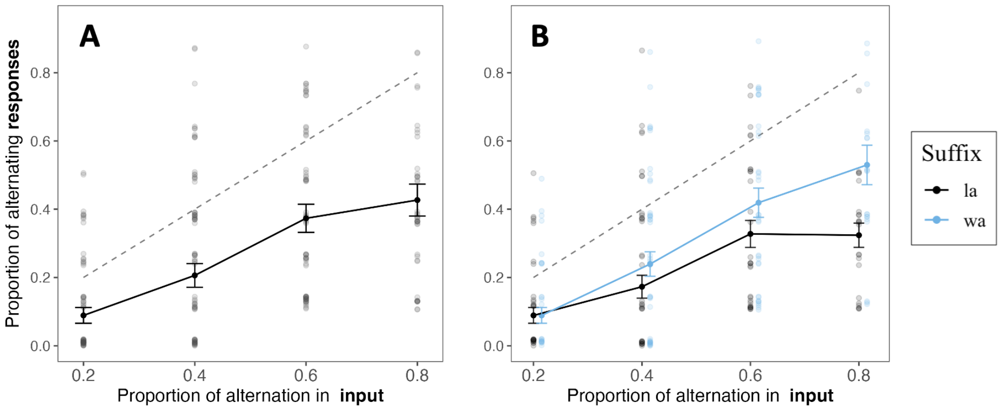

Figure 4: Proportion of p-k alternating responses by distribution of input data (A), and by suffix (B). Dotted line=expected rate if participants perfectly frequency-match.

We also corroborate these findings using a mixed effects logistic regression model, fit in R using the *lme4* package (Bates et al. 2015, R Core Team 2023). The model has a binary dependent variable response (alternating vs. non-alternating) and random intercepts for participant and item. Main effects of alternation rate (continuous variable; the rate of alternation in the input) and suffix (/wa/ vs /la/, baseline set to /la/), as well as their interaction, were included. Additionally, as described in Section 2.5, participants were randomly separated into two blocks which differ in the meaning of suffixes /-wa/ and /-la/. To test for effects of suffix meaning, a main effect of block (1 vs. 2; baseline=1) was also included. Effects were tested for significance using likelihood ratio tests via the *anova()* function in R.

Model results are summarized in Table 1. There is a strongly significant effect of alternation rate, such that as alternation rate increases, the number of alternating responses also increase (β=2.83, z=3.96, p <0.001). While Suffix is not significant (β=-0.052, z=-0.16, p=0.87), the interaction of Suffixxalternation rate is significant (β=1.25, z=2.25, 0.012), in that the effect of suffix increases as the alternation rate increases.

Predictors	Odds Ratios	CI	P
(Intercept)	0.03	0.01 – 0.08	<0.001***
alt_rate	**16.97**	**4.19 – 68.77**	**<0.001*** **
suff [wa]	0.95	0.51 – 1.78	n.s.
suff [wa] × alt_rate	**3.50**	**1.11 – 10.39**	**0.012***
Block [2]	0.96	0.58 – 1.60	n.s.

Table 1: Model results: RESPONSE~ ALT_RATE*SUFFIX + BLOCK + (1|ITEM) + (1|PARTICIPANT)

4. Discussion

The results replicate the substantial literature on frequency-matching; in particular, the significant effect of ALTERNATION RATE suggests that speakers apply more alternations when the input has a higher rate of alternation. Notably, while frequency-matching has been well-substantiated in wug tests (e.g. Coleman & Pierrehumbert 1997, Ernestus & Baayen 2003, Hayes et al. 2009), there is relatively little work on whether speakers frequency-match in the context of artificial grammar learning. Most artificial grammar experiments teach participants categorical patterns; Baer-Henney et al. 2015 is one of the only existing studies to vary the rate at which alternations apply in training.

Across all four alternation rates, participants also on average applied a lower rate of alternation than was present in the input. In fact, even when the input had 80% alternation, participants (on average) only applied alternations to ~40% of the test items. This is unsurprising given the literature on alternation learning, which consistently finds a preference for non-alternation (as discussed in Section 2.1). This preference could be attributed to paradigm uniformity effects (Kenstowicz 1996, Steriade 1997). Task effects such as participant inattention, or other contributors to participants underlearning the alternation pattern, could also have influenced the results.

While there was no main effect of SUFFIX, there was a significant interaction between ALTERNATION RATE and SUFFIX, suggesting while learners utilize phonotactics when learning alternations, they do so in a way that is constrained by paradigm-internal frequencies. This finding is interesting because it shows that to some extent, learners can apply phonotactics to alternation learning, even when the alternation itself is not phonotactically motivated. This is reminiscent of so-called ‘grammatical leakage’ (Martin 2011), where stem-internal phonotactics are active across morpheme boundaries, but have a weaker, gradient effect.

These results also have consequences for models of alternation learning. First, our results show that alternations are not always influenced by phonotactics; this supports a model where the two are independent, rather than enforced using the exact same mechanisms (i.e. the approach taken in classical OT). contradicts models in in which phonotactics and alternations isomorphic. Additionally, probabilistic models of morphophonology tend to focus on frequency-matching, without directly considering phonotactics (e.g. Albright & Hayes 2003). However, results suggest that does interact with frequencies, in a way that should be studied and modeled in more detail.

Notably, the exact nature of how frequency-matching and phonotactics interact remains an open question. One possibility is that learners only utilize phonotactics when there is sufficient evidence for an alternation pattern that can reduce phonotactic violations. When the input had just 20% of p~k alternation, there was strong support for non-alternation. However, as the proportion of p~k alternation increased in the input, there was both increased uncertainty in whether final [p] should alternate with [k], and increased support for an alternation that could be used to reduce phonotactic violations.

Another closely related proposal is that learners are primarily frequency-matching, but draw on phonotactics when there is uncertainty about whether to extend an alternation. When the input had just 20% alternation, there was strong evidence for non-alternation. However, as the amount of the alternation in the input increased, participants' rate of alternation approached chance (y-axis=50%). This made paradigm-internal frequencies less informative, causing participants to rely more on phonotactics. Notably, this proposal predicts that if participants learn a higher rate of alternation, where p~k alternation applies with near-certainty, the effect of phonotactics will also disappear or become smaller. This diverges from the above account, which would predict a stronger effect of phonotactics at higher rates of alternation.

In the current results, almost all participants applied low rates of alternation (<50%), so there is limited information on how speakers behave when they do learn and apply overall higher rates of alternation. Future work is needed to tease apart the two proposals. First, we will aim to replicate the results of the current study in a laboratory setting, which could reduce the effects of participant inattention. Ongoing follow-up studies are also testing how participants behave when trained on a categorical alteration pattern that always applies.

5. Conclusion

The current study tests how phonotactics and frequency-matching interact in the context of artificial grammar learning. Speakers were taught a p~k alternation pattern with varying rates of application. Speakers were also taught three suffixes, two neutral with respect to phonotactics, and one where alternation reduce violations of phonotactic markedness. These results suggest that while alternations and phonotactics do interact, they are not enforced using the same mechanism.

Our results indicate that both frequency-matching and phonotactics are active in alternation learning. However, phonotactics do not always influence alternation rates, and are instead constrained by paradigm-internal frequencies. In particular, the effect of phonotactics was not present when the input had lower rates of alternation (20%, 40%), and only emerged as the rate of alternation in the input increased. These results are challenging for approaches such as classical OT, where phonotactics and alternations are enforced suing the same set of constraints, meaning that phonotactics should always have an effect on alternation learning. From the current study, it remains unclear exactly how phonotactics and frequency-matching interact, and future research should help clarify the relationship between these two factors.

References

Chomsky, Noam & Morris Halle. 1968. *The sound pattern of English*. New York: ERIC.

Borowsky, Toni. 1986. *Topics in the lexical phonology of english*. University of Massachusetts Amherst dissertation.

Borowsky, Toni. 1989. Structure preservation and the syllable coda in English. *NLLT* 7(2). 145–166.

Kiparsky, Paul. 1993. Blocking in nonderived environments. In Sharon Hargus & Ellen M. Kaisse (eds.), *Studies in lexical phonology*, 277–313. Academic Press.

Prince, Alan & Paul Smolensky. 1993. *Optimality theory: constraint interaction in generative grammar*. Wiley Online Library.

Benua, Laura. 1995. Identity effects in morphological truncation. In Suzanne Urbanczyk Jill N. Beckman & Suzanne Urbanczyk (eds.), *University of massachusetts occasional papers 18: papers in optimality theory*, 77–136. Amherst: GLSA.

Inkelas, Sharon & Cemil Orhan Orgun. 1995. Level ordering and economy in the lexical phonology of turkish. *Language* 71(4). 763–793. `https://doi.org/10.2307/415744`.

Kenstowicz, Michael. 1996. Base-identity and uniform exponence: alternatives to cyclicity. In Jacques Durand & Bernard Laks (eds.), *Current trends in phonology: models and methods*, 363–394. Salford: University of Salford.

Coleman, John & Janet Pierrehumbert. 1997. Stochastic phonological grammars and acceptability. In *3rd meeting of the ACL special interest group in computational phonology: proceedings of the workshop*, 49–56. Association for Computational Linguistics.

Steriade, Donca. 1997. Lexical conservatism. *Linguistics in the morning calm*. 157–179.

Hammond, Michael. 1999. *The phonology of english: a prosodic optimality-theoretic approach*. OUP.

Zuraw, Kie Ross. 2000. *Patterned exceptions in phonology*. UCLA dissertation.

Albright, Adam & Bruce Hayes. 2003. Rules vs. analogy in English past tenses: A computational/experimental study. *Cognition* 90(2). 119–161.

Ernestus, Mirjam Theresia Constantia & R Harald Baayen. 2003. Predicting the unpredictable: interpreting neutralized segments in Dutch. *Language* 79(1). 5–38.

Pycha, Anne, Pawel Nowak, Eurie Shin & Ryan Shosted. 2003. Phonological rule-learning and its implications for a theory of vowel harmony. In *Proceedings of the 22nd west coast conference on formal linguistics*, vol. 22, 101–114. Cascadilla Press Somerville, MA.

Pater, Joe & Anne-Michelle Tessier. 2005. Phonotactics and alternations: testing the connection with artificial language learning. *University of Massachusetts Occasional Papers in Linguisitcs* 31. 1–16.

Hayes, Bruce & Colin Wilson. 2008. A maximum entropy model of phonotactics and phonotactic learning. *Linguistic Inquiry* 39(3). 379–440.

Hayes, Bruce, Péter Siptár, Kie Zuraw & Zsuzsa Londe. 2009. Natural and unnatural constraints in Hungarian vowel harmony. *Language*. 822–863.

Paster, Mary. 2009. Explaining phonological conditions on affixation: evidence from suppletive allomorphy and affix ordering. *Word structure* 2(1). 18–37.

Martin, Andrew. 2011. Grammars leak: modeling how phonotactic generalizations interact within the grammar. *Language* 87(4). 751–770. https://doi.org/10.1353/lan.2011.0096.

Skoruppa, Katrin & Sharon Peperkamp. 2011. Adaptation to novel accents: feature-based learning of context-sensitive phonological regularities. *Cognitive Science* 35(2). 348–366. https://doi.org/10.1111/j.1551-6709.2010.01152.x.

Finley, Sara & William Badecker. 2012. Learning Biases for Vowel Height Harmony. *Journal of Cognitive Science* 13(3). 287–327.

Moreton, Elliott & Joe Pater. 2012a. Structure and substance in artificial-phonology learning, part {II}: Substance. *Language and linguistics compass* 6(11). 702–718.

Moreton, Elliott & Joe Pater. 2012b. Structure and substance in artificial-phonology learning, part I: Structure. *Language and linguistics compass* 6(11). 686–701.

Paster, Mary. 2013. Rethinking the 'duplication problem'. *Lingua* 126. 78–91. https://doi.org/https://doi.org/10.1016/j.lingua.2012.11.015.

White, James C. 2013. *Bias in phonological learning: evidence from saltation*. UCLA dissertation.

Baer-Henney, Dinah, Frank Kügler & Ruben Van De Vijver. 2015. The Interaction of Language-Specific and Universal Factors During the Acquisition of Morphophonemic Alternations With Exceptions. en. *Cognitive Science* 39(7). 1537–1569. https://doi.org/10.1111/cogs.12209.

Bates, Douglas, Martin Mächler, Ben Bolker & Steve Walker. 2015. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* 67(1). 1–48. https://doi.org/10.18637/jss.v067.i01.

Scholes, Robert J. 2016. *Phonotactic grammaticality*. Vol. 50. Berlin/Boston: De Gruyter.

Finger, Holger, Caspar Goeke, Dorena Diekamp, Kai Standvoß & Peter König. 2017. Labvanced: a unified javascript framework for online studies. In *International conference on computational social science (cologne)*, 1–3.

Chong, Adam J. 2019. Exceptionality and derived environment effects: a comparison of korean and turkish. *Phonology* 36(4). 543–572.

Chong, Adam J. 2021. The effect of phonotactics on alternation learning. *Language* 97(2). 213–244.

R Core Team. 2023. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org/.