Evidence against a link between learning phonotactics and learning phonological alternations

1 Introduction

Languages allow some sound sequences but not others. In English, for example, a sequence of obstruents in coda position should not differ in voicing, preventing sound sequences such as *[pz]#, *[tz]#, or *[gs]#. Languages also exhibit phonological alternations whereby certain morphemes are prone to change under certain conditions. For example, the English plural morpheme varies between [z] ~ [s] ~ [əz] while the past tense morpheme varies between [d] ~ [t] ~ [əd], depending on the features of the preceding stem's final segment.

Infants as young as 10 months old show sensitivity to phonotactic regularities, preferring licit sequences over illicit ones (Friederici and Wessels 1993; Jusczyk et al. 1993). Children, on the other hand, acquire phonological alternations at much later stages. Acquisition data show that children as old as 5 years old still produce incorrect allomorphs (e.g., English in Berko 1958 and Smith 1973; Greek in Kazazis's 1969 cited in Hayes 2004; Hebrew in Berman 1985; Dutch in Kerkhoff 2007; Korean in Do 2018),[1] while some perceptual evidence suggests children's sensitivity to alternation patterns at an even earlier age (Skoruppa et al. 2013; Sundara et al. 2021). The time lag between the acquisition of phonotactics and the acquisition of alternations suggests difficulties involved in acquiring phonological alternations. To master the system of phonological alternations, learners at the very least must figure out various allomorphs which map onto the same meaning (e.g., [-s], [-z], and [-əz] all mean plural in English) and their conditioning environment (e.g., [-z] appears after non-sibilant voiced sounds). Theoretical work within constraint-based phonology (Tesar and Smolensky 1993) proposed another challenge to learning alternations: a prior bias exists against alternations, called the paradigm uniformity bias (Hayes 2004; McCarthy 1998). The paradigm uniformity bias is formalized as undominated output-to-output correspondence constraints (Hayes 2004; Tesar and Prince 2003). Due to this grammatical status, learners initially expect no alternation (Tessier 2012; Kerkhoff 2007; Do 2018). To produce alternating forms, they need to demote the undominated output-to-output

[1] Although see a successful production of alternating forms as early as 15 months among Turkish speaking infants in Aksu-Koç and Slobin (1985) cited in Hayes (2004).

correspondence constraints below the relevant markedness constraints. This can only be accomplished after they have received a sufficient number of alternating forms in the input.

Given the challenges involved in learning phonological alternations, one important goal has been to uncover the factors which help speakers learn alternations. One proposal considers a link between phonotactic knowledge and alternations (Hayes 2004; Jarosz 2006, Jarosz 2011; Pater and Tessier 2005; Tesar and Prince 2007): Phonotactic regularities not only give rise to systematic gaps in languages (e.g., [tz]# is unattested in English), but they also give rise to alternations, thus phonotactic knowledge helps learning patterns of alternations. For example, the English plural morpheme's voice feature alternates in order to avoid phonotactically illicit sequences like *[tz]# or *[pz]#, therefore learners can acquire this alternation based on its phonotactic motivation. Such a link implies that there exists a single learning mechanism for both phonotactics and alternations (P. H. Matthews 1972; Prince and Tesar 2004; Sommerstein 1974), an idea dating back to Chomsky and Halle (1968). In rule-based phonology, alternations are stated as phonological rules, while phonotactic restrictions are captured through Morpheme Structure Constraints (Halle 1959; Kenstowicz and Kisseberth 1977; Stanley 1967). When a phonological rule applies to satisfy Morpheme Structure Constraints, the generalization is represented in the lexicon as well as in the grammar (Kenstowicz and Kisseberth's [1977] Duplication Problem), resulting in representational redundancy.

In constraint-based phonology (Tesar and Smolensky 1993), however, there is no unified grammatical device which correctly predicts the interaction between phonotactics and alternations. In fact, models based on constraint-based phonology (Tesar 1997; Tesar and Smolensky 1998; Hayes & Wilson 2008) presented difficulties in the learning of patterns which exhibit mismatches between phonotactics and alternations (Chong 2017), because learners are initially blind to morphological boundaries of words. Natural languages also show a variety of mismatches between phonotactic regularities and alternations. Phonological processes may occur only in morphologically derived environments, i.e., non-derived environment blocking, (Cho 2001; Iverson and Wheeler 1988; Kiparsky 1993; Oh 1995); or phonological process can be prevented in morphologically derived environments, i.e., derived-environment blocking (Anttila 2009; Burzio 2011; Hall 2006; Łubowicz 2002); different kinds of constraints are applied morpheme-internally and across-morpheme environments. English velar palatalization as in electri[k] ~ electri[s]ity is an example of non-derived environment blocking, where [k] alternates to [s] before some high front vowel-initial suffixes as *-ity*. Since English does allow the [ki] sequence morpheme-internally, there is no phonotactic reason for [k] to alternate [s].[2] The considerations so far are in line with Hale and Reiss's (2008) argument that phonotactic regularities are irrelevant to phonological alternations. Paster (2013) further argues for the separation of learning mechanisms for phonotactics and alternations and attributes the phonotactically motivated alternations to incidental similarity.

Despite such theoretical debates, a unified learning mechanism between phonotactics and alternations has not been a main subject of empirical testing. A major reason for this, as pointed out by Pater and Tessier (2006), is that it is almost impossible to find a natural language with phonological alternations which differ only by their phonotactic motivations. That being said, some empirical evidence has been provided through the use of artificial language learning paradigms in experimental linguistics (see Section 2). Results, however, have been only from participants who are English native speakers. We believe this is problematic. Although English native speakers do not find phonotactic motivations for certain types of alternations in their first language (e.g., no phonotactic regulations in English motivate vowel harmony alternation), they do find other phonotactically motivated alternations. The voicing alternation motivated by a phonotactic constraint against the adjacent heterogeneous voicing features, *[-voice][+voice], is one such example. If learners have constructed abstract knowledge about a relation between phonotactics and alternations from their first language, this knowledge might facilitate the learning of a new type of phonotactically motivated alternation. Thus, better learning of phonotactically motivated alternations observed from native English speakers can still be attributed to first language influence. To see whether a unified mechanism for learning phonotactics and alternations is universally available, we propose to test speakers whose first language does not provide any phonotactic support for alternations. Cantonese is one such example (Bauer 1985; S. Matthews and Yip 2014). See Section 2.

Testing the universality of the connection between phonotactics and alternations is important to understand not only the nature of first language (L1) phonological grammar but also second language (L2) acquisition of alternations (Pater and Tessier 2006). If there is a universal link

[2] See Chong (2017) for more examples showing distinctive phonotactics and alternation patterns across languages.

between the two, it predicts that learners, regardless of their L1, can transfer their newly learned phonotactic knowledge in learning the alternations of the same L2. If the link becomes available only upon receiving supporting evidence from one's L1, then L2 acquisition of alternations will not be facilitated by phonotactics learning when learners' L1 lacks evidence showing phonotactically motivated alternations.

2 Studies on the link between phonotactics and alternations

Artificial language learning studies on the link between phonotactics and alternations are limited in that they have only focused on English native speakers (Pater and Tessier 2006; Chong 2016; Pizzo and Pater 2016; Chong 2017). Results have been mixed. In Pater and Tessier (2006), two artificial languages were created that differed in their phonotactic support for alternations, and they found better learning of phonotactically motivated alternations. Language 1 contained alternations conditioned by the tenseness of vowels, which was consistent with English phonotactics, e.g., /glɪ/ alternated into [glɪt̲] while /lij/ remained [lij]. Language 2 contained alternations conditioned by the frontness of vowels, which was inconsistent with English phonotactics, e.g., /lij/ alternated into [lijt̲] while /vuw/ remained [vuw]. Better learning was observed in Language 1, suggesting a unified mechanism for learning phonotactics and alternations. Some issues with the study design include that phonotactics of Language 1 aligns with that of English, allowing participants to rely on their L1 phonological knowledge to learn a new alternation, whereas the alternation in Language 2 is unnatural and there are no known natural languages showing an alternation conditioned by the frontness of vowels (Pater and Tessier 2006). It is thus possible that the participants did not perform well simply due to their bias against unnatural patterns.

The link between phonotactics and alternations has also been examined from the opposite direction: Pizzo and Pater (2016) wanted to see whether the learning of alternation facilitates the learning of phonotactics by manipulating evidence of alternation while keeping phonotactic patterns constant. Each language contained alternation evidence either for obstruent voicing, e.g., [nemap̲fa] for /nemab̲-fa/ or for place assimilation, e.g., [lobom̲fa] for /lobon̲-fa/. In both languages, the phonotactic constraints motivating the alternations were equally satisfied. After training, participants were tested on morpheme-internal phonotactic judgement, e.g., [mad̲fas] vs. [mat̲fas] for obstruent voicing and [maŋ̲fas] vs. [mam̲fas] for place assimilation. The results showed that the learning of phonotactically-motivated alternations reduced the acceptability of phonotactically illegal sequences, suggesting on facilitation effect of learning alternations to phonotactic judgments. However, such results were found only from an explicit learning condition, involving feedback, but not from an implicit learning condition. Pizzo and Pater (2016) interpreted this inconsistency as weak evidence for the link between phonotactics and alternations. Alternatively, the results might suggest that the link between phonotactics and alternations is unidirectional: Knowledge of phonotactics can inform speakers' knowledge of alternations but knowledge of alternations does not inform speakers' knowledge of phonotactics.

In Chong (2016), English native speakers were trained on palatalization of alveolar stops before a high front vowel in two artificial languages. In Language 1, the constraints against [ti] and [di] were imposed both morpheme-internally and across morpheme boundaries, e.g., /dʒit-i/ surfaced as [dʒidʒi]. In Language 2, the same constraints were only applied across morpheme boundaries but not morpheme-internally, e.g., /tit-i/ surfaced as [tidʒi]. The results showed that participants learned the alternations equally well in both languages, but they failed to learn new phonotactic regularities in Language 1. Thus, the results were inconclusive as to whether newly established knowledge in phonotactics facilitated the acquisition of alternations.

In another study by Chong (2017), alternations consistent with the phonotactics of the lexicon were easier to learn. In the study, two artificial languages with vowel roundedness harmony were created differing in their phonotactic support. Unlike Pater and Tessier (2006), the alternations in these two languages were not motivated by English phonotactics, excluding any potential L1 effects. The result indicated that the vowel harmony alternations were learned more successfully when the same vowel harmony was shown as the phonotactic patterns in the lexicon, e.g., harmonic [nedi-mi] vs. disharmonic [nodi-mi]. Another group of participants were trained on a phonotactic generalization of vowel harmony without exposure to alternations, e.g., [nedi]. When they were tested on novel alternations that match with the phonotactics of the lexicon, they were not able to extend the patterns of phonotactics to predict the correct allomorphs. Thus, the result supported the hypothesis that knowledge in phonotactics, which comes from static generalization of the lexicon, facilitates the acquisition of alternations, but the exposure to both instances of phonotactics and alternations is required. Some modelling work also tested the link between phonotactics and alternations, including Jarosz (2006), Tesar and Prince (2007), and Jarosz (2011), all of which supported the link between phonotactics and alternations.

As stated earlier, one major issue with the previous studies is that the link between phonotactics and alternations has been examined with English native speakers only, leaving room for a first language effect. To test whether a unified learning mechanism for phonotactics and alternations is available to all language users, we need participants whose L1 does not provide any clue for the link between phonotactics and alternations. Cantonese has a wide variety of phonotactic regularities including restrictions on syllable structures, segment sequences, tone-segment combinations, and tone sequences (Barrie 2003; Bauer and Matthews 2003; Do and Lai 2020; Kirby and Yu 2007; S. Matthews and Yip 2011). However, no existing literature has reported alternation patterns in Cantonese that are motivated by phonotactic restrictions of the language, including ones imposed for segment sequences, tone sequences, or a combination of the two. While some tonal phenomena in Cantonese may resemble tonal alternations, e.g., grammatical tones for differentiating lexical categories ([kan˥] 'space (n.)' vs. [kan˧] 'to space (v.)') (Wee 2019), the conventional analyses treat them as unproductive and lexicalized tonal changes (Bauer 1985; S. Matthews and Yip 2014). They are triggered by morphological and semantic factors rather than phonological environment (Bauer 1985; S. Matthews and Yip 2014) and they are associated with colloquial speech (Bauer and Benedict 1997). Syllable fusion is a type of prosodically conditioned alternation in Cantonese, in which two or more syllables within a foot may be optionally blended, resulting in segmental and tonal alternations that are gradient in nature, e.g., kʰeɪ˩ sɐt˧ → kʰe˩ ɐt˧ → kʰɛt˩ 'in fact' (Lee 2003; Wong 2006). Most crucially, these changes are not motivated by phonotactic regularities of the language. Therefore, different from English native speakers, Cantonese speakers do not have solid L1 evidence exhibiting the link between phonotactics and alternations.

Against this background, we test whether the link between phonotactics and alternations is present for Cantonese native speakers. If a unified learning mechanism for phonotactics and alternations exists to all learners regardless of L1 evidence, we predict that Cantonese speakers should learn phonotactically motivated alternations better. If not, we predict that Cantonese speakers will show similar learning performance for phonotactically-motivated alternations and those that are not. To test these predictions, we modified the experiment design in Chong (2017) to suit Cantonese native speakers.

3 Experiment

3.1 Methods

3.1.1 Stimuli

Our experiment examined whether the learning of vowel harmony alternation across morphemes is facilitated when the same phonotactic patterns are found within morpheme boundaries. In our artificial languages, each lexical item was presented as a singular and plural pair. The singular forms consisted of disyllabic stems in the CVCV structure (e.g., kɛnɛ), and the plural forms were formed by attaching a suffix to a stem (e.g., kɛnɛ-mɛ). Eight consonants {p, t, k, p^h, t^h, k^h, m, n} and four vowels {ɛ, eɪ, ɔ, oʊ} were used to create stems and suffixes, all of which are phonemes in Cantonese. All the created CV sequences were legal and attested in Cantonese but the combined disyllabic items as in CVCV were all unattested. The stimuli design ensured that the positional frequency of each phoneme was balanced. The use of diphthongs {eɪ, oʊ} as stems' vowels was unavoidable, but we made sure that both the onset and the offset of each of the selected diphthongs agreed in their rounding and backness features. In total, there were 32 unique stems for each language in the training phase.

We designed three languages differing in their phonotactic support for alternations. Alternations were shown from the vowel of the plural suffix, which alternated between [-mɛ] ~ [-mɔ] to agree its backness and roundedness with the stem-final vowel in all plural forms: [-mɛ] after front and unrounded vowels [ɛ, eɪ], and [-mɔ] after back and rounded vowels [ɔ, oʊ]. The vowel harmony alternation patterns shown across the stem and the suffix boundaries were identical in all languages. What differed between the three languages was their degree of vowel harmony in stems, namely their phonotactic regularities. In the Harmony Language, the two vowels within each stem agreed in backness and roundedness (e.g., kɛnɛ); In the Mixed Language, half of the stems had two vowels which agreed in backness and roundedness (e.g., k^hɛk^heɪ) while the other half did not (e.g., kɔnɛ); In the Disharmony Language, the two vowels in each stem always disagreed in frontness and roundedness (e.g., kɔnɛ). Due to this difference, each language differed in their match between the morpheme-internal and morpheme-external vowel harmony patterns: the Harmony Language showed a match of vowel harmony patterns within (i.e., phonotactics) and across morphemes (i.e., alternations), the Mixed Language showed a half match between the two, whereas the Disharmony Language showed a complete mismatch.

The audio stimuli were recorded in a sound-attenuated booth by a male bilingual speaker of English and Cantonese trained on IPA symbols. To avoid a priming effect from similar-sounding Cantonese lexical items, tone was not included and all the stimuli had primary stress which was placed on the initial syllable of each word. The stimuli were recorded with a Sennheiser MKE2-P-K Lavalier Condenser Microphone and a Marantz Professional PMD661MKII Solid State Recorder at a sampling rate of 44,100Hz with 16-bit resolution. The amplitude of each stimulus was normalized to 70dB using the Scale intensity feature in Praat (Boersma and Weenink 2019). The visual stimuli were retrieved from a set of made-up 'alien' creatures from sporepedia.com (cf. Kapatsinski 2013). A single alien, to represent the singular, and three of them, to represent the plural, were always presented in a pair. This presentation decision was different from Chong (2017) where a singular and a corresponding plural were not presented in a pair.[3]

3.1.2 Procedure

The experiment was conducted on the online platform of Pavlovia (*Pavlovia* 2020) which allowed participants to complete the experiment on their personal computer. Participants were told to learn words from an 'alien' language and were randomly assigned to learn one of the three languages, Harmony, Mixed, and Disharmony languages. The experiment consisted of a pretest, a training block, and two testing blocks. In the pretest, pairs of harmonic and disharmonic stems that only differed in the backness and roundedness of one vowel were presented to the participants in the form of audio stimuli. Participants were instructed to choose the one that sounded better to them. The aim of the pretest was to examine whether participants had an initial preference towards vowel harmony or disharmony prior to the experiment. Then, during the training block, 32 pairs of words with singular and plural forms were shown three times, resulting in a total of 96 training trials. The tokens were presented in a pseudo-random order such that the same word pair would not appear consecutively. During the training block, the participants listened to the audio stimuli accompanied by the visual referent on a computer

[3] Compared to Chong (2017), the current setting could have encouraged participants to focus more explicitly on the patterns of alternation, which in turn derive their attention away from phonotactics. It remains to be seen how much of the discrepancies between the two studies should be attributed to methodological decisions rather than the nature of grammatical differences between participant groups.

screen. The audio stimulus of the singular form was played along with the visual referent, followed by the audio stimulus of the plural form played along with the visual referents. Participants were only allowed to listen to each stimulus once. A focus question was included after every 8 pairs of words by playing a word and asking whether it was the word that they had just heard. Half of the focus questions exhibited the harmony pattern and the other half showed the disharmony pattern.

Then the two testing blocks followed. In the first testing block, participants' knowledge of phonotactics was tested using a force choice task with 16 pairs of novel singular stems. Participants heard two novel singular words: one harmonic stem and one disharmonic stem (i.e., [kɛpɛ] vs. [kɛpɔ]) and were asked to decide which one belonged to the language they had learned. The two words only differed in frontness and roundedness of one of the vowels. After that, in the second testing block, participants' knowledge of alternation was tested using a force choice test with 16 novel singular stems. In each trial, the audio stimulus of the singular word was first played along with its visual referent. Then, the audio files of the three choices for the plural form were played along with the corresponding visual referents. Among the three choices, one had a harmonic suffix (i.e., [-mɛ] for [keɪkɛ] or [-mɔ] for [tʰoʊnɔ]), one had a disharmonic suffix (i.e., [-mɛ] for [tʰoʊnɔ] or [-mɔ] for [keɪkɛ]) and the third choice, [-sa], was a new suffix that was not found in the training block. The stimuli in the testing block were presented in a randomized order.

For each language, two versions of the alternation test with opposite morpheme-internal vowel harmony patterns were created as in Table 1. In the Harmonic stem condition, the two vowels in stems agreed in backness and roundedness (e.g., [keɪkɛ]), while in the Disharmonic stem condition, the two vowels in stems disagreed in backness and roundedness (e.g., [koʊkɛ]). The aim of creating two versions of the alternation test was to examine whether matches of stem phonotactics presented between the training and the testing blocks affect answer choices. If there was an effect of consistency between stem phonotactics in training and testing phases to alternation test, we predicted better performance from the match conditions than from the mismatch conditions.

Table 1. Frequency of vowel harmony of stems for the six conditions in the alternation test.

Languages	**H-H**	**H-DH**	**M-H**	**M-DH**	**DH-H**	**DH-DH**

Training phase	Harmonic stems	32	32	16	16	0	0
	Disharmonic stems	0	0	16	16	32	32
Testing phase (alternation test)	Harmonic stems	16	0	16	0	16	0
	Disharmonic stems	0	16	0	16	0	16
	Phonotactic match between phases	Yes	No	Yes	Yes	No	Yes

H: Harmony; M: Mixed; DH: Disharmony
H-DH indicates that the training session exhibited harmonic stems and the test session exhibited disharmonic stems.

3.1.3 Participants

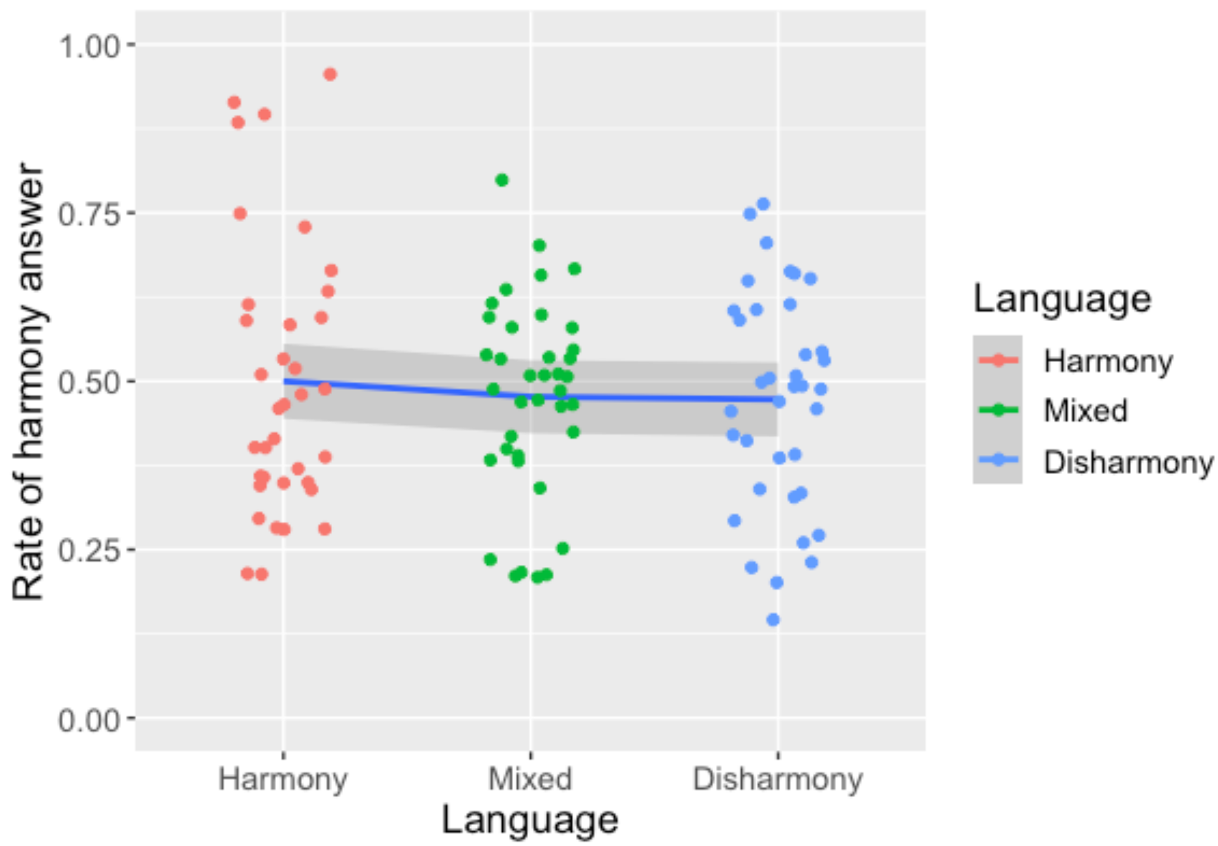
144 self-reported native speakers of Hong Kong Cantonese aged between 18 and 60 were recruited for the present study. Participants were randomly assigned to one of the six conditions in Table 1, i.e., 24 participants per condition. Upon the completion of the experiment, each participant was paid 50 HKD. Out of the 144 responses received, 3 were excluded due to language background (i.e., Cantonese is not a sole dominant language), 17 were excluded due to poor performance in the focus questions, i.e., wrong answers over 15%, and 13 were excluded due to poor performance in the alternation test, i.e., choices of wrong suffixes at the rate of 15% or above. After the exclusion, the results of 111 participants entered the analysis (H-H: 17; H-DH: 17; M-H:16; M-DH:19; DH-H:21; DH-DH:21)[4].

[4] The results of the phonotactics test and the alternation test from all participants (144) did not show significant differences across different language groups. The excluded participants' answers were often categorical, meaning that they consistently chose one type of answer, resulting in large degree of variability of the data within each group.

3.2 Results

Except for the alternation test, where the distinction between two versions of the alternation test is relevant (testing items with harmonic stems vs. disharmonic stems), we combined two versions together and report the results depending only on the language factor for the pre-test and the phonotactics test.

First, the pre-test results were examined to check the existence of a prior bias either toward harmony or disharmony. If any bias exists, the results of the phonotactics test and the alternation test should be analyzed taking the prior bias into account. Figure 1 presents the rate of harmonic stems chosen in the pre-test from the three language groups respectively. Descriptive data showed the average harmony rate at 48% across languages, suggesting no strong initial bias towards vowel harmony or disharmony. The data was further analyzed with a mixed effect logistic regression model in R using lmerTest (Kuznetsova et al. 2017). The contrast coded fixed factor was language with the mixed language as a baseline. The dependent variable was the stem choices (harmonic vs. disharmonic). Random intercepts were included for participants and items. The nonsignificant intercept in Table 2 shows that participants had no preference toward harmony or disharmony patterns in the mixed language, suggesting no bias. In the harmony and disharmony languages (Language_Harmony, Language Disharmony), the differences were not significant from the baseline, indicating that learners did not bring in any prior bias preferring harmony or disharmony.



<Figure 1>

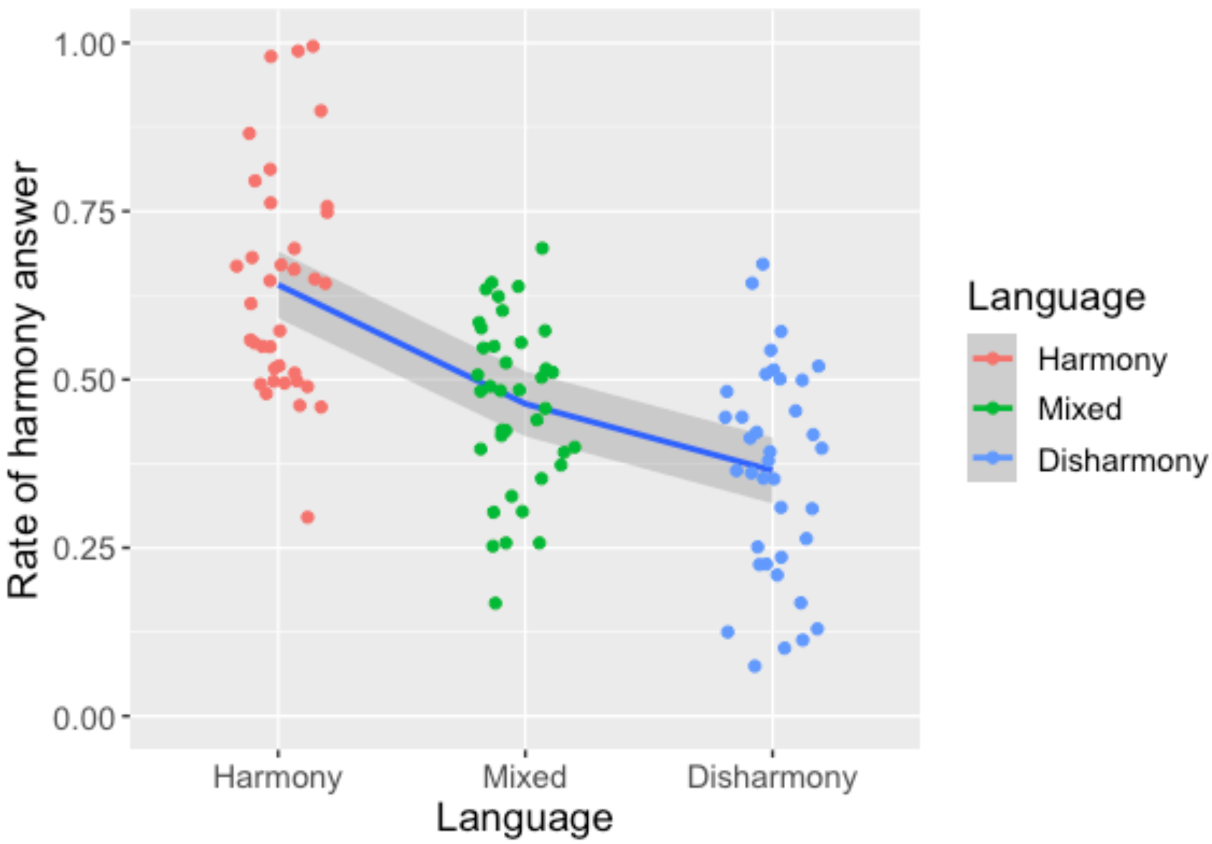
Table 2. Linear mixed effects regression of the rate of choosing harmonic stems in the pre-test.

Fixed effects:	**Estimate**	**Std. Error**	**z-value**	**Pr(>|z|)**
(Intercept)	−0.959	0.179	−0.536	>0.1
Language_Harmony	0.055	0.167	0.570	>0.1
Language_Disharmony	−0.017	0.166	−0.100	>0.1

Our next focus was the phonotactics test. Figure 2 presents the rate of choosing harmonic stems from the three language groups, respectively. If phonotactic learning was successful, we predicted more answers for harmonic stems from the Harmony Language, followed by the Mixed Language, and the Disharmony Language. Figure 2 shows that our prediction was supported at a descriptive level. A mixed effect logistic regression model was built with contrast coded language (mixed language as a baseline) and rate of harmonic answer in pre-test as fixed factors.

The model also included random intercepts for items and participant as well as a random slope for test by participant and a random slope for language by item. The dependent variable was the stem choice (harmonic vs. disharmonic).

As in Table 3, no significant preference towards harmonic or disharmonic stems was found in the mixed language. Crucially, when compared with the Mixed Language, the rate of harmonic stem choices significantly increased in the Harmony Language and it decreased in the Disharmony Language. Such tendency aligns with the phonotactic patterns shown in the input. Furthermore, as shown by the insignificant effect of the rate of harmonic answer in pre-test, a prior bias of vowel harmony or disharmony had no effect on the learning of phonotactic patterns.



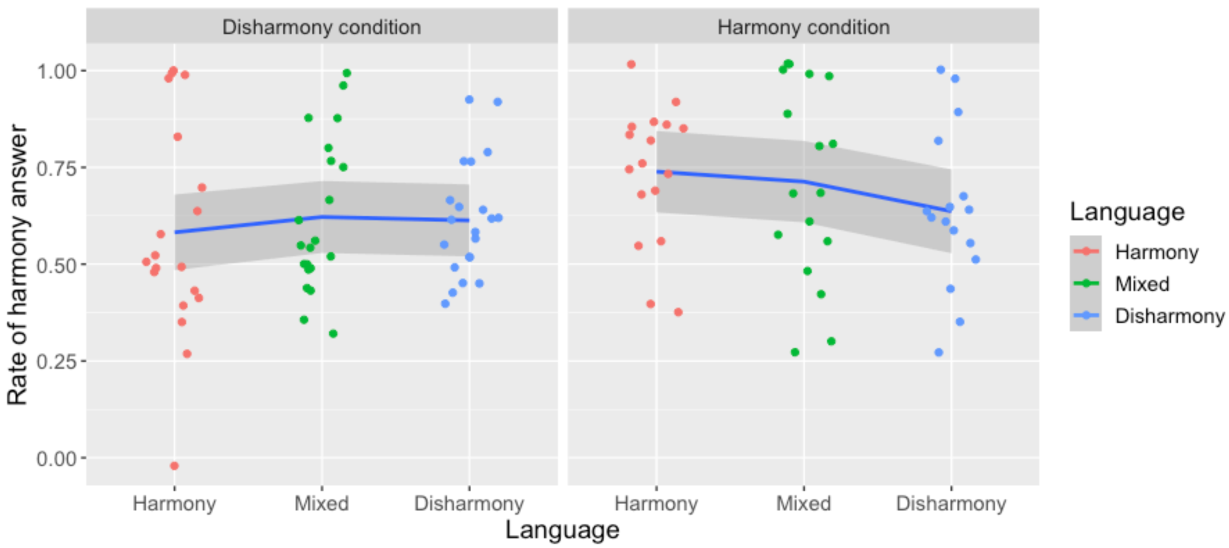
<Figure 2>

Table 3. Linear mixed effects regression of the rate of choosing harmonic stems in the phonotactics test. Bold indicates $p < 0.05$.

Fixed effects:	Estimate	Std. Error	z-value	Pr(>|z|)
(Intercept)	−0.099	0.263	−0.374	**<0.001**
Language_Harmony	0.828	0.189	4.381	**<0.001**

Language_Disharmony	−0.457	0.163	−2.798	**<0.001**
Pre-test	-0.219	0.416	-0.309	0.757

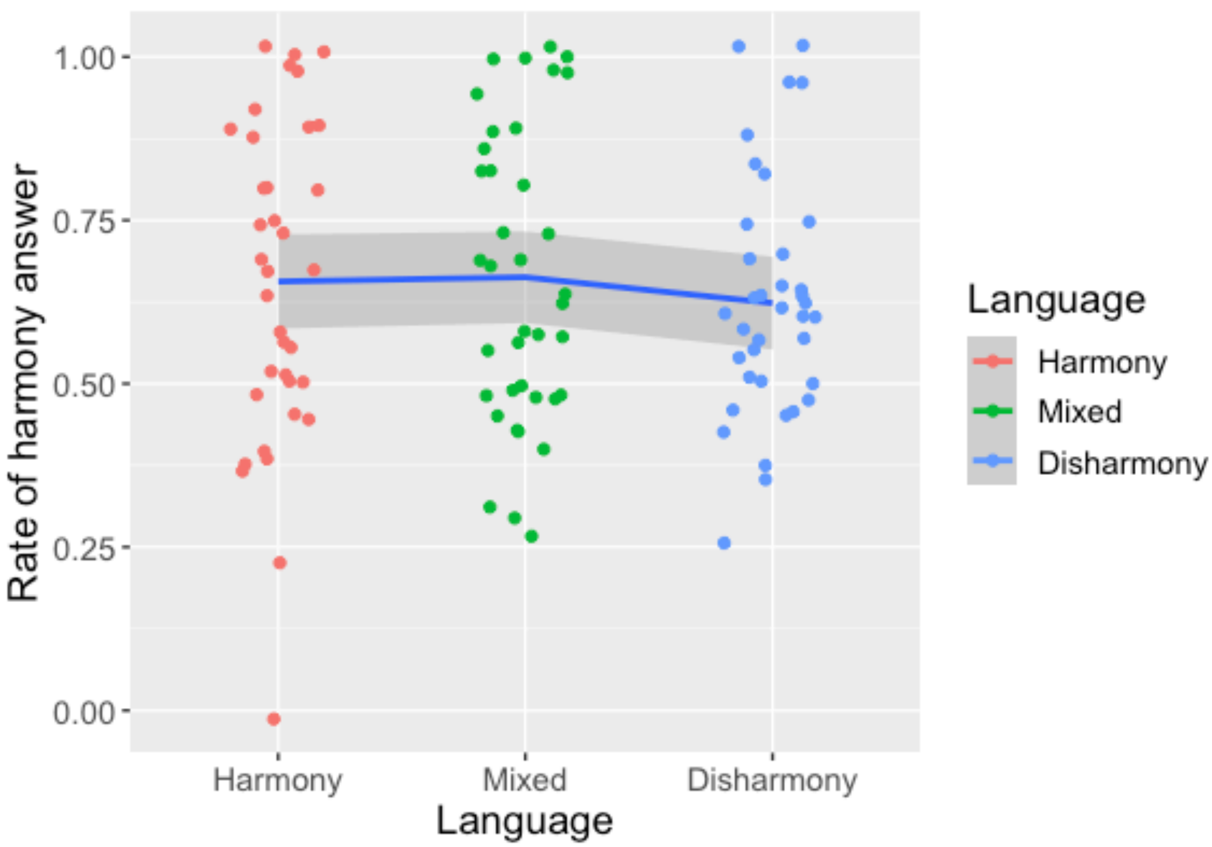
We then analyzed the data of the alternation test, the main interest of our study. First, Figure 3 presents the rate of choosing harmonic suffixes in the alternation test across the six conditions, i.e., H-H, H-DH, M-H, M-DH, DH-H, and DH-DH. Despite some descriptive differences, there is no systematic pattern showing higher rate of harmony alternations in versions with matching phonotactics between training and testing (i.e., Conditions H-H and DH-DH) than in versions with mismatching phonotactics (i.e., DH-H and H-DH).



<Figure 3>

Second, Figure 4 shows the alternation test results grouped by language (Harmony vs. Mixed vs. Disharmony). If the phonotactic learning affected the alternation learning, we predicted better performance in the Harmony Language (match between phonotactics and alternations) than the Disharmony Language, and Mixed Language will be in between. As shown in Figure 4, learners showed overall preference towards harmonic suffixes as the average harmony rate around 60% shows across all languages. To test the statistical significance across languages, we ran a mixed effect logistic regression model with the fixed factors of language (Mixed language as baseline), versions of alternation test (match vs. mismatch), and the interaction between the two. The dependent variable was the suffix choices (harmonic vs. disharmonic). The rate of the novel suffix choices was extremely minor (1.24%, sd= 0.025), thus those choices were excluded from the analysis. Random intercepts were included for items and participants and a random slope for language by item.

As in Table 4, there was no significant effect of the version of alternation test nor its interaction with language, suggesting that whether participants were tested on the same or different types of phonotactic patterns exhibited during training did not affect their performance of the alternation test. On the other hand, as the significant intercept shows, there was overall preference toward harmonic suffixes in the Mixed Language, but crucially there was no significant difference across languages. This indicates independence of alternation learning from phonotactic pattern learning.



<Figure 4>

Table 4. Linear mixed effects regression of the rate of choosing harmonic suffixes in the alternation test. Bold indicates $p < 0.05$.

Fixed effects:	Estimate	Std. Error	z-value	Pr(>|z|)
(Intercept)	0.612	0.260	2.352	**<0.01**

Language_Harmony	-0.147	0.366	-0.401	>0.1
Language_Disharmony	-0.061	0.356	−0.171	>0.1
Alternation test	0.586	0.396	1.480	>0.1
Lg_Harmony x Alternation test	0.181	0.549	0.330	>0.1
Lg_DisHarmony x AlternationTest	-0.431	0.5495	-0.791	>0.1

4 General discussion

Our results suggest that the learning of phonotactic patterns has no effect on alternation learning if one's native language provides no evidence for the link between phonotactics and alternations. In the three artificial languages, each with varying evidence of vowel harmony in the stem phonotactics, Cantonese speaking participants acquired phonotactic patterns matching their dominant patterns in the input, suggesting successful phonotactic learning. However, participants acquired the vowel harmony alternation almost at an equal degree regardless of the learned phonotactic patterns. Such results are markedly different from some previous studies in which English speaking participants learned an alternation pattern more successfully when the same pattern was found in morpheme-internal condition as well (Pater and Tessier 2006; Pizzo and Pater 2016; Chong 2017).

If there is a unified mechanism for phonotactics and alternations available to all learners, the learning of phonotactically-motivated alternations should have been better for both Cantonese and for English speakers. However, this was not borne out from the current study. Instead, our results suggest that the link is language-specific: native language evidence is essential to unify grammatical mechanisms for phonotactics and alternations. If there is no native language evidence, the basic grammatical architecture separates components for phonotactics and alternations, resulting in representational redundancy, as with the assumption in rule-based phonology (see Section 1). If so, leaners in this situation may not learn alternations any better when the same pattern is found in static phonotactics. At the same time, learners will not necessarily find patterns exhibiting phonotactics-alternation mismatches particularly challenging, because the two are stated independently in their grammar.

For the learners with native language support for a link between phonotactics and alternations, our study cannot explain whether the unified learning mechanisms for phonotactics and alternations is part of their innate universal grammar or is created through L1 experience. It is possible that the link between phonotactics and alternation belongs to our innate grammar and can be lost in later stages of language development due to L1 phonology. Or it could be that there is no initial association between phonotactics and alternation but that a link between the two is formed throughout L1 experience. In order to further examine the nature of the link, future investigations should include alternation tests on children in earlier developmental stages whose L1 shows no link between phonotactics and alternations.

References

Aksu-Koç, Ayhan A. & Don Issac Slobin. 1985. The acquisition of Turkish. In Don Issac Slobin (ed.), *The crosslinguistic study of language acquisition: Volume 1: The data*, 839–878. London: L. Erlbaum.

Anttila, Arto. 2009. Derived environment effects in Colloquial Helsinki Finnish. In Paul Kiparsky, Kristin Hanson & Sharon Inkelas (eds.), *The nature of the word: Studies in honor of Paul Kiparsky* (Current Studies in Linguistics 47), 433–460. Cambridge, MA: MIT Press.

Barrie, Mike. 2003. Contrast in Cantonese vowels. *Toronto Working Papers in Linguistics* 20. 1–19. https://twpl.library.utoronto.ca/index.php/twpl/article/view/6229 .

Bauer, Robert S. 1985. The expanding syllabary of Hong Kong Cantonese. *Cahiers de Linguistique Asie Orientale* 14(1). 99–111. https://doi.org/10.1163/19606028_014_01-05 .

Bauer, Robert S. & Paul K. Benedict. 1997. *Modern Cantonese phonology* (Trends in Linguistics, Studies and Monographs 102). Berlin: Mouton de Gruyter.

Bauer, Robert S. & Stephen Matthews. 2003. Cantonese. In Graham Thurgood & Randy J. LaPolla (eds.), *The Sino-Tibetan languages* (Routledge Language Family Series), 146–155. London: Routledge.

Berko, Jean. 1958. The child's learning of English morphology. *WORD* 14(2–3). 150–177. https://doi.org/10.1080/00437956.1958.11659661.

Berman, Ruth A. 1985. The acquisition of Hebrew. In Dan Issac Slobin (ed.), *The crosslinguistic study of language acquisition: Volume 1: The data*, 255–372. London: L. Erlbaum.

Boersma, Paul & David Weenink. 2019. *Praat: Doing phonetics by computer* (version 6.0.49). http://www.praat.org.

Burzio, Luigi. 2011. Derived environment effects. In Marc van Oostendorp, Colin J. Ewen, Elizabeth Hume & Keren Rice (eds.), *The Blackwell companion to phonology: Volume IV: Phonological interfaces* (Blackwell Companions to Linguistics Series), 2089–2114. Malden, MA: Wiley-Blackwell. https://doi.org/10.1002/9781444335262.wbctp0088.

Cho, Taehong. 2001. Effects of morpheme boundaries on intergestural timing: Evidence from Korean. *Phonetica* 58(3). 129–162. https://doi.org/10.1159/000056196.

Chomsky, Noam & Morris Halle. 1968. *The sound pattern of English* (Studies in Language). New York, Evanston & London: Harper & Row.

Chong, Adam J. 2016. Learning consequences of derived-environment effects. *Linguistic Society of America (LSA)* 1. 11–1–15. https://doi.org/10.3765/plsa.v1i0.3709.

Chong, Adam J. 2017. *On the relation between phonotactic learning and alternation learning*. California, Los Angeles: University of California, Los Angeles dissertation. https://escholarship.org/uc/item/7235q340.

Do, Youngah. 2018. Paradigm uniformity bias in the learning of Korean verbal inflections. *Phonology* 35(4). 547–575. https://doi.org/10.1017/S0952675718000209.

Do, Youngah & Ryan Ka Yau Lai. (2020). Incorporating Tone in the Modelling of Wordlikeness Judgements. *Phonology* 37(4). 577-615. http://dx.doi.org/10.1017/S0952675720000287.

Friederici, Angela D. & Jeanine M. I. Wessels. 1993. Phonotactic knowledge of word boundaries and its use in infant speech perception. *Perception & Psychophysics* 54(3). 287–295. https://doi.org/10.3758/BF03205263.

Hale, Mark & Charles Reiss. 2008. *The phonological enterprise* (Oxford Linguistics). Oxford & New York: Oxford University Press.

Hall, T. Alan. 2006. Derived environment blocking effects in Optimality Theory. *Natural Language & Linguistic Theory* 24(3). 803–856. https://doi.org/10.1007/s11049-006-0003-5.

Halle, Morris. 1959. *The sound pattern of Russian: A linguistic and acoustical investigation*. The Hague: Mouton.

Hayes, Bruce. 2004. Phonological acquisition in Optimality Theory: The early stages. In René Kager, Joe Pater & Wim Zonneveld (eds.), *Constraints in phonological acquisition* (pp. 158–203). Cambridge & Madrid: Cambridge University Press.

Hayes, Bruce, & Colin Wilson. 2008. A Maximum Entropy Model of Phonotactics and Phonotactic Learning. *Linguistic Inquiry*, 39(3), 379–440. https://doi.org/10.1162/ling.2008.39.3.379

Iverson, Gregory K. & Deirdre W. Wheeler. 1988. Blocking and the elsewhere condition. In Michael Hammond & Michael Noonan (eds.), *Theoretical morphology: Approaches in modern linguistics*, 325–338. San Diego: Academic Press.

Jarosz, Gaja. 2006. *Rich lexicons and restrictive grammars: Maximum likelihood learning in Optimality Theory*. Baltimore, MD: Johns Hopkins University dissertation. https://rucore.libraries.rutgers.edu/rutgers-lib/37916/.

Jarosz, Gaja. 2011. The roles of phonotactics and frequency in the learning of alternations. In Nick Danis, Kate Mesh & Hyunsuk Sung (eds.), *Proceedings of the 35th Annual Boston University Conference on Language Development (BUCLD): Volume 2*, 321–333. Somerville, MA: Cascadilla Press.

Jusczyk, Peter W., Angela D. Friederici, Jeanine M. Wessels, Vigdis Y. Svenkerud & Ann Marie Jusczyk. 1993. Infants' sensitivity to the sound patterns of native language words. *Journal of Memory and Language* 32(3). 402–420. https://doi.org/10.1006/jmla.1993.1022.

Kapatsinski, Vsevolod. 2013. Conspiring to mean: Experimental and computational evidence for a usage-based harmonic approach to morphophonology. *Language* 89(1). 110–148. https://www.jstor.org/stable/23357723.

Kazazis, Kostas. 1969. Possible evidence for (near-) underlying forms in the speech of a child. *Chicago Linguistic Society (CLS)* 5. 382–388.

Kenstowicz, Michael John & Charles Wayne Kisseberth. 1977. *Topics in phonological theory*. New York: Academic Press.

Kerkhoff, Annemarie Odilia. 2007. *Acquisition of morpho-phonology: The Dutch voicing alternation*. Utrecht Netherlands: Utrecht University dissertation. https://dspace.library.uu.nl/handle/1874/22598.

Kiparsky, Paul. 1993. Blocking in nonderived environments. In Sharon Hargus & Ellen M. Kaisse (eds.), *Studies in lexical phonology* (Phonetics and Phonology 4), 277–313. San Diego: Academic Press. https://doi.org/10.1016/B978-0-12-325071-1.50016-9.

Kirby, James P. & Alan C. L. Yu. 2007. Lexical and phonotactic effects on wordlikeness judgments in Cantonese. In William J. Barry & Jürgen Trouvain (eds.), *16th International Congress of Phonetic Sciences (ICPhS)*, 1389–1392. Saarbrücken: Univ. des Saarlandes.

Kerkhoff, Annemarie Odilia. "Acquisition of morpho-phonology: The Dutch voicing alternation." PhD diss., LOT, 2007.

Kuznetsova, Alexandra, Per B. Brockhoff & Rune H. B. Christensen. 2017. lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software* 82(13). 1–26. https://doi.org/10.18637/jss.v082.i13.

Lee, Kit-mei Gloria. 2003. Syllable fusion in Cantonese connected speech. Pokfulam, Hong Kong SAR: University of Hong Kong MPhil Thesis .

Łubowicz, Anna. 2002. Derived environment effects in Optimality Theory. *Lingua* 112(4). 243–280. https://doi.org/10.1016/S0024-3841(01)00043-2.

Matthews, Peter Hugoe. 1972. *Inflectional morphology: A theoretical study based on aspects of Latin verb conjugation* (Cambridge Studies in Linguistics 6). Cambridge: Cambridge University Press.

Matthews, Stephen & Virginia Yip. 2011. Unbalanced bilingual acquisition as a mechanism of grammatical change. *Bilingualism: Language and Cognition* 14(2). 159–161. https://doi.org/10.1017/S1366728910000593.

Matthews, Stephen & Virginia Yip. 2014. *Cantonese: A comprehensive grammar*, 2nd edn. London: Routledge.

McCarthy, John J. 1998. Morpheme structure constraints and paradigm occultation. *Chicago Linguistic Society (CLS)* 32(2). 123–150. https://scholarworks.umass.edu/linguist_faculty_pubs/46.

Oh, Mira. 1995. A prosodic analysis of nonderived-environment blocking. *Journal of East Asian Linguistics* 4(4). 261–279. https://doi.org/10.1007/BF01440729.

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

Pater, Joe & Anne-Michelle Tessier. 2005. Phonotactics and alternations: Testing the connection with artificial language learning. In Shigeto Kawahara & Kathryn Flack (eds.), *UMOP 31 (University of Massachusetts Occasional Papers in Linguisitcs): Papers in Experimental Phonetics and Phonology*, 1–16. Amherst: GLSA, University of Massachusetts.

Pater, Joe & Anne-Michelle Tessier. 2006. L1 phonotactic knowledge and the L2 acquisition of alternations. In Roumyana Slabakova, Silvina Montrul & Philippe Prévost (eds.), *Inquiries in linguistic development: In honor of Lydia White*, 115–134. Amsterdam & Philadelphia: John Benjamins Publishing Co.

Pavlovia. 2020. https://pavlovia.org/.

Pizzo, Presley & Joe Pater. 2016. Does learning alternations affect phonotactic judgments? *2015 Annual Meeting on Phonology (AMP)* 3. https://doi.org/10.3765/amp.v3i0.3694.

Prince, Alan & Bruce Tesar. 2004. Learning phonotactic distributions. In René Kager, Joe Pater, & Wim Zonneveld (eds.), *Constraints in phonological acquisition*, 245–291. Cambridge & Madrid: Cambridge University Press.

Skoruppa, Katrin, Nivedita Mani, Kim Plunkett, Dominique Cabrol & Sharon Peperkamp. 2013. Early Word Recognition in Sentence Context: French and English 24-Month-Olds' Sensitivity to Sentence-Medial Mispronunciations and Assimilations. *Infancy* 18. https://doi.org/10.1111/infa.12020.

Smith, Neilson V. 1973. *The acquisition of phonology: A case study*. Cambridge: Cambridge University Press.

Sommerstein, Alan H. 1974. On phonotactically motivated rules. *Journal of Linguistics* 10(1). 71–94. https://doi.org/10.1017/S0022226700004011.

Stanley, Richard. 1967. Redundancy rules in phonology. *Language* 43(2). 393–436. https://doi.org/10.2307/411542.

Sundara, Megha, James White, Yun Jung Kim, and Adam J. Chong. "Stem similarity modulates infants' acquisition of phonological alternations." *Cognition* 209 (2021): 104573.

Tesar, Bruce. 1997. Multi-recursive constraint demotion. (Ms., Rutgers University. ROA-197)

Tesar, Bruce & Alan Prince. 2003. Using phonotactics to learn phonological alternations. *Chicago Linguistic Society (CLS)* 39(2). 241–269.

Tesar, Bruce & Alan Prince. 2007. Using phonotactics to learn phonological alternations. *Chicago Linguistic Society (CLS)* 39(2). 209–237.

Tesar, Bruce & Paul Smolensky. 1993. *The learnability of Optimality Theory: An algorithm and some basic complexity results; CU-CS-678-93* [Technical Report]. Boulder, CO: Department of Computer Science, University of Colorado Boulder. https://scholar.colorado.edu/concern/reports/zw12z6295.

Tesar, Bruce, & Paul Smolensky. 1998. Learnability in Optimality Theory. *Linguistic Inquiry* 29:2. 229-268. https://doi.org/10.1162/002438998553734.

Tessier, Anne-Michelle. "Testing for OO-Faithfulness in the acquisition of consonant clusters." *Language Acquisition* 19, no. 2 (2012): 144-173.

Wee, Lian-Hee (2019). *Phonological tone*. Cambridge University Press. https://doi.org/10.1017/9781316410912.

Wong, Wai Yi Peggy. 2006. Syllable Fusion in Hong Kong Cantonese Connected Speech. The Ohio State University PhD Dissertation.