

Substantive Bias and Variation in the Acquisition of /n/~/l/ Alternation

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1 Introduction

As a way to understand language universals, it has been proposed that some linguistic patterns are recurring across languages, because of learning biases, i.e., a tendency that learners are predisposed to learn certain phonological patterns over others (Moreton, 2008). The two widely studied learning biases in phonology are structural bias, a bias against structurally complex patterns, and substantive bias, a bias that favors phonetically natural or motivated patterns (Moreton & Pater, 2012a, b). For structural bias, experimental evidence is robust. A wide variety of phonological-learning experiments support the structural bias hypothesis, showing that a pattern with a single feature is easier to learn than ones with more features (See Moreton & Pater 2012a for a review). Contrary to structural bias, experimental evidence for substantive bias has been varied. Some studies found convincing evidence for substantive bias, showing that natural patterns are learned better than unnatural ones and participants are more likely to generalize natural patterns than unnatural ones toward broader natural classes (Finley, 2012; Do, 2013; White, 2014; van de Vijver & Baer-Henney, 2014). Other studies found mixed results showing that substantive bias is at work only under certain conditions (Wilson, 2006). There are also studies which found no difference in the learning of natural and unnatural patterns (Pycha et al., 2003; Seidl & Buckley, 2005; Lysvik, 2018). Moreton and Pater (2012) attributed the mixed experimental support for substantive bias to the weakness of substantive bias in phonological learning than structural bias. However, no agreement has been made as to the reasons behind the relative weakness of substantive bias.

The objective of this study is to find out why the effect of substantive bias has been weak or not systematic in phonological learning. A few possible explanations have been already proposed. Glewwe (2019) argued that substantive bias is often strong when the naturalness is grounded in perception but not in production, which could be attributed to some primacy of perception in the definition of naturalness. Greenwood (2016) found that unnatural patterns were harder to acquire when the input had reduced ‘perceptual clarity’, which becomes an issue for clear transmission. For example, the effect of substantive bias was found only in casual speech, thus with low clarity, but not in careful speech. Do & Havenhill (2021) uncovered that the effect of substantive bias is sensitive to methodological choices of artificial language learning paradigms; Learning a phonological pattern that is primarily grounded on articulatory basis was substantively biased only when production practice was involved in learning and such a production effect emerged from variable pattern learning conditions, not from categorical learning conditions. Lysvik (2020) argued that there is a large degree of individual variation in learning phonetically grounded vs. ungrounded patterns, which results in the mixed support for the substantive bias hypothesis.

We note that across the aforementioned findings, whether the substantive bias effect emerges or not is related to patterns’ (*un*)certainty. For example, Greenwood (2016)’s finding suggests that substantive bias exists only when the pattern is learned in casual conditions or learning contexts which lack clarity. Glewwe (2019) proposed that naturalness effect better emerges in a passive perception process rather than an active production process. Learning through passive perception can be regarded as a learning involving lower degree of certainty in comparison to learning with active production because production practice requires explicit repetition of heard forms. Do & Havenhill (2021) directly found the effect of production practice when the pattern was learned in variation (i.e., higher level of patterns’ uncertainty) but not categorically. The large degree of individual variation found in Lysvik (2020) suggests higher uncertainty in predicting global tendencies about substantively biased learning. Baer-Henney et al. (2015) explored the relative role of

* This paper has been improved thanks to the helpful comments from Sara Finley, Tong Xiuli Shelley, Jonathan Havenhill and the AMP 2021 audience, particularly Shigeto Kawahara and Eleanor Glewwe.

L1 and substantive bias (See review of Baer-Henney et al. (2015) in Section 2.2), and the results showed that the effect of substantive bias was strong in a condition with more variable input and with less training. This also suggests that when there is more *uncertainty* involved in the input, either in forms of variation or insufficient training, such uncertainty could increase the effect of substantive bias. Beyond linguistics, psychological studies have revealed stronger effects of cognitive biases when an event under consideration involves higher uncertainty (Kahneman & Tversky, 1972; Tversky & Kahneman, 1973, 1974; Sherman & Corty, 1984; Cosmides & Tooby, 1996; Griffin et al., 2001). If we subscribe to the idea that phonological learning biases can be considered as a type of cognitive biases, the same idea can be applied to the prediction of substantive bias: when speakers learn sound patterns under higher level of uncertainty, the subsequent learning outcomes show stronger effect of learning biases.

To explore the effect of substantive bias under uncertainty, this study tests the learning of *variable* phonological patterns. Due to its probabilistic distribution, variable phonological patterns should provide higher uncertainty to learners compared to absolute and categorical ones. Considering the findings from the previous studies, we predict that the effect of substantive bias is stronger in variable than in categorical pattern learning condition. To test our hypothesis of the potential effect of uncertainty on substantive bias, we examined the learning of the the /n/ ~ /l/ alternation in phonetically motivated vs. unmotivated context by Hong Kong Cantonese (HKC hereafter) native speakers. We designed four artificial languages by varying patterns' phonetic motivation and its variability. We found that the learning is substantively biased when the alternation patterns were shown in variation, but not as categorical patterns, confirming our prediction.

Section 2 will first review work on substantive bias in categorical and variable learning conditions respectively. Section 3 will provide the phonetic basis of /n/ ~ /l/ alternation and describe the alternation in Hong Kong Cantonese as well as other Chinese varieties. Section 4 will describe the experiment method, and the results and analyses. Discussion and conclusion will be covered in Section 5.

2 Substantive bias in categorical vs. variable learning conditions

This section reviews artificial language learning (ALL) studies on substantive bias in learning categorical and variable patterns respectively.

2.1 Substantive bias in learning categorical phonology The majority of ALL studies on substantive bias investigated the acquisition of categorical patterns. In these studies, all critical items always underwent the target phonological processes. Of these, some have found convincing evidence for substantive bias (Hayes et al., 2009; Finley, 2012; Shapp, 2012; White, 2014). For example, in Finley (2012), participants learned a rounding harmony pattern in which stem vowels triggered rounding harmony on the suffix vowel (e.g. [kini-mi], [tudu-mu]). In one condition, the stem vowels were exclusively mid vowels, a better trigger of rounding harmony, while in the other they were high vowels (Kaun, 2004). The results showed that participants in the mid vowel condition learned the rounding harmony better than those in the high vowel condition, supporting an effect of substantive bias rooted in perceptual motivation.

Some studies on categorical pattern learning have found partial effects of substantive bias (Wilson, 2006; Baer-Henney, 2015). For instance, Wilson (2006) found an asymmetry in the generalization of velar palatalization (/k/→/tʃ/, /g/→/dʒ/). Participants who were exposed to palatalization before /e/, i.e., phonetically not-well motivated context, generalized to /i/, i.e., phonetically better motivated context, but those who exposed to palatalization before /i/ did not generalize to /e/ context. This result suggests that if two sounds alternate in a phonetically not-well motivated context, they should also alternate in a better motivated context, but not vice versa, supporting the substantive bias hypothesis. However, additional results show inconsistencies. All participants were also taught that velar stops did not palatalize before /a/. Participants who were exposed to palatalization before /i/ did not generalize to the /a/ context, which is predicted by substantive bias. However, participants who were exposed to palatalization before /e/ extended not only to the /i/ context, but also to the /a/ context. Such tendency is not predicted by substantive bias, because velar stops and palate-alveolar affricates are more dissimilar before /a/ than before /e/. In addition, some studies on categorical pattern learning have failed to find supporting evidence for substantive bias (Pycha et al., 2003; Peperkamp & Dupoux, 2007; Finley, 2008; Finley & Badecker, 2009; Do et al., 2016; Lysvik, 2018; Glewwe et al., 2018).

2.2 Substantive bias in learning variational phonology There are ALL studies on variable linguistic

pattern learning, while the majority of them are from the study of morphosyntax (Singleton & Newport, 2004; Kam & Newport, 2005, 2009; Culbertson & Newport, 2015; Schuler et al., 2016). Only a few ALL studies have examined phonological variation. Baer-Henney et al. (2015) explored the interaction of L1 phonotactics and substantive bias in variable phonological pattern learning by manipulating phonetic naturalness and L1 phonotactic relevance simultaneously. They tested the learning of two types of alternation by native German speakers. The first type of alternation was a vowel backness harmony (backness of the stem vowel determines backness of the suffix vowel), which was grounded on phonetic naturalness but had no relevance in the phonotactics of native German speakers. The second type exhibited a tenseness-backness relation, whereby tenseness of the stem vowels determines backness of the suffix vowel. This pattern was phonetically unnatural but it reflected a phonotactic property of German. They also varied the degree of regularity (65% vs. 85%) and the length of training (two vs. three training blocks). The results of the production task showed that vowel backness harmony was learned better when the alternation was less regular (65% compared to 85%) and the training was shorter (two blocks compared to three blocks); tenseness-backness pattern was learned better when the alternation was more regular (85%) and the training was longer (three blocks). In other words, the acquisition of a less stable pattern was facilitated by substantive bias rather than L1, and the influence of L1 was stronger in the acquisition of a more stable pattern. Therefore, it can be inferred that the uncertainty of input, as with lower regularities or with shorter training, affected the strength of substantive bias. However, it is worth noting that the effect of substance in this study can be attributed to structural bias. The unnatural tenseness-backness pattern is also more structurally complex. The vowel backness harmony relates to two instances of the same features [backness], while the tenseness-backness pattern relates to one instance of [tenseness] and one instance of [backness].

Mooney & Do (2018) found a substantive bias in learning phonological variation from adult native English speakers. In the study, participants were exposed to either a language with more frequent (67%) rounding harmony and less frequent (33%) disharmony pattern or a language with the opposite proportions of harmony and disharmony. The results showed that learners in both languages modulated the probabilistic distribution of variables toward the natural harmony pattern. The degree of modulation was higher from the language with more unnatural patterns. The authors proposed that patterns should be unnatural enough to activate the learner to adjust their proportions. Do & Mooney (2021) further conducted the experiment with Cantonese-native preschoolers. The results in general were in parallel with the findings of Mooney & Do (2018), while a stronger substantive bias was found among children.

Taken together, in comparison to the results of ALL on categorical pattern learning, the studies on variable pattern learning consistently found evidence for substantive bias, although the number of studies on this topic is very limited. ALL studies on substantive bias found mixed results in categorical pattern learning and evidence is insufficient to conclude the role of substantive bias in variable pattern learning. If the substantive bias was found only in casual rather than careful speech (Greenwood, 2016), and the substantively biased learning was observed only when the pattern was variable (Do & Havenhill, 2021), and the effect of substantive bias was strong in a condition with more variable input (Baer-Henney et al. (2015)), we hypothesize that the substantive bias effect is stronger in the learning of more uncertain phonological patterns. To test this hypothesis, we investigated the learning of a variable alternation pattern in HKC, namely /n~/l/ alternation. The variation of /n~/l/ alternation is chosen as the target pattern because it is widely attested in natural languages (Tu, 1989; Li, 2011; Coblin, 2009; Matthews & Yip, 2011; Bu, 2018) and the pattern has clear phonetic groundings as reviewed in the following section.

3 Background on /n~/l/ alternation

This section provides the phonetic basis of /n~/l/ alternation and describes the alternation in HKC as well as other Chinese varieties.

3.1 Acoustic and articulatory basis The alternation between /n/ and /l/ is grounded on acoustic and articulatory similarities. In terms of acoustics, both /n/ and /l/ have transitions to a following vowel which involves sudden shifts in amplitude and spectral configuration. Both of them also leave voicing and pitch unperturbed (Greenlee & Ohala, 1980). Moreover, /n/ and /l/ both have anti-formants (anti-resonances). Nasal formants have a lower amplitude than oral formants due to the additional constriction in the nasal cavity and the presence of side cavities. When producing nasal consonants at more anterior places of articulation (i.e. /n/), the oral cavity acts as a side cavity. The resonances within the side (oral) cavity absorb resonances from the nasal tube, and the side cavity resonance is referred as anti-formants. Similarly, laterals involve a lowering

of one or both sides of the tongue, but a pocket of air remains on top of the tongue, which serves as an anti-formant-producing side branch (Fant, 1960; Stone, 1991). In addition, /n/ and /l/ both have very low first formant centered at about 250Hz. Note that their slight differences are in F2 and F3. /n/ has higher second and third formant values than /l/. When laterals appear immediately before high front vowels, a smaller oral cavity is formed. The smaller the cavity, the higher the formant frequency (Fant, 1960; Johnson, 2012). Therefore, /l/ followed by high front vowels has higher F2 and F3, becoming more acoustically similar to /n/; /n/ followed by non-high front vowels has lower F2 and F3, making it more acoustically similar to /l/.

Articulatorily, /n/ and /l/ have similar place of articulation, alveolar ridge, while they differ in the degree of constriction. To produce /n/, tongue tip presses against the alveolar ridge to prevent air pass through the mouth (Roach, 1998). In comparison, /l/ is produced with a central obstruction, so that air escapes along the sides of the tongue. To make a /l/, although the tongue tip is at a similar place in the mouth as it is for /n/, the area right behind the tongue tip is not touching the side of upper teeth. The tongue tip is lowered at the side (Ladefoged & Maddieson, 1996). Ultrasound imaging showed a more retracted tongue root for /l/ and a more advanced tongue root for /n/ (Tabain et al., 2020). Therefore, when /l/ is followed by high front vowels, the tongue position undergoes fronting and raising, which makes its place of articulation more similar to that of /n/; When /n/ is followed by non-high front vowels, the tongue moves towards the centre of the oral cavity, which makes its place of articulation similar to that of /l/.

In terms of directionality of alternation, there is no stronger phonetic support toward one direction over another (/n/ to /l/ or /l/ to /n/). On the one hand, /l/ is more marked compared to /n/ in onset position, because less sonorous onsets are less marked (de Lacy, 2006), but on the other hand, /n/ is slightly more difficult than /l/ in terms of articulation, because the greater constriction degree in producing /n/ requires more effort to produce (Kirchner, 1998).

Taken together, /n/ and /l/ are acoustically and articulatorily similar in several aspects, triggering the alternation. The relative markedness between the two is hard to define when pure phoneme level articulatory or acoustic properties are concerned. It is the conditioning phonological environment that is relevant to motivated vs. unmotivated alternation patterns: /l/ followed by high front vowels is similar to /n/, thus /l/ is likely to alternate to [n] in this context; /n/ followed by non-high front vowels is similar to /l/, thus /n/ is likely to alternate to [l] in this context.

3.2 /n~/l/ alternation in HKC and other Chinese varieties In HKC, /n/ and /l/ are two phonemes (Zee, 1999). Syllable-initial /n/ and /l/ have minimal pairs, for instance, [nam21] ‘male’ and [lam21] ‘blue’; [nou22] ‘angry’ and [lou22] ‘to show’ (Ng, 2017). However, there had been a sound change, replacing syllable-initial /n/ with /l/ in HKC. Such change has been adopted by more than 80% of the population born in and after the 1970’s (To et al., 2015). Older speakers in less formal speech registers tend to do so (Matthews & Yip, 2011). In To et al. (2015), where they examined several phonetic variations in HKC, it was found that over 90% of the participants in the child group (94.2%) and adult (94.6%) pronounced /n/ as /l/. The authors proposed that the change appears to be close to completion. Ng (2017) investigated syllable initial /n~/l/ variation in various phonological environments by HKC speakers. In Ng (2017)’s study, the participants often pronounced initial /n/ as /l/ (with the range from 52% to 100%), and such change was context free. In perception, however, /n/ and /l/ are still distinguishable. Since both /n/ and /l/ are still found in speech, it was argued that the merger of initial /n/ and /l/ in HKC has not yet completed.

/n~/l/ alternation is not restricted to HKC in Chinese. In fact, the alternation has been found in other Chinese varieties. In Southwestern Mandarin, /n/ and /l/ usually merge to /n/. For example, in Changsha dialect, syllable-initial [n] and [l] have completely merged into a pure nasal (Shi, 2011). In Lower Yangtze Mandarin, they usually merge to /l/ (Norman, 1988). For example, in Nanjing, syllable-initial [n] and [l] have all become /l/ (Shi & Liang, 2017). Synchronically, in Chengdu, [n] and [l] are allophones of /n/. [n] and [l] keep contrast before high front vowels and they are in free variation elsewhere (Li, 2011). Similarly, in south Guiyang, /n/ and /l/ contrast only before /i/. They are in free variation elsewhere (Tu, 1989). Wuhan prefers the initial /n/ over /l/. [n] and [l] are in free variation and they are allophones of /n/. But in 1930’s, [n] was preferred over [l] before high front vowels, with free variation elsewhere (Coblin, 2009). The alternation patterns in Chengdu, Guiyang and Wuhan suggest that /n/ and /l/ tend to keep contrast before high front vowels. Bu (2018)’s survey of six Chinese varieties (Yangzhou, Hefei, Chengdu, Chongqing, Xiamen, Guangzhou) showed that the merge of /l/ and /n/ as one single phoneme tend to incline towards [l] as its surface value than [n]. [l] seems to be favored among the varieties with synchronic surface level free variation, like Guangzhou and Yangzhou where the new native speakers manifest a clear tendency toward the [l] realization regardless of vowels.

In sum, /n/ and /l/ in some Chinese varieties diachronically merge into either /n/ or /l/. And synchronic /n~/l/ variation has an asymmetry towards surface [l]. The preservation of initial /n/ specifically before high front vowels is more common than the preservation before any other vowels, because /n/ before high front vowels is acoustically and articulatorily dissimilar to /l/.

3.3 Hypothesis and predictions If substantive bias affects phonological learning and its effect is stronger when the input involves higher uncertainty, as shown in Baer-Henney et al. (2015), Mooney & Do (2018), and Do & Mooney (2021), we hypothesize that variable pattern learning condition will show stronger substantive bias effect than in categorical pattern learning context. In other words, the effect of substantive bias will be strong when the phonetically motivated vs. unmotivated patterns are shown as variable patterns than when the patterns are shown as categorical patterns. Phonetic grounding in this study refers to the motivation of conditioning environment for the /n/ ~ /l/ alternation. Specifically, the alternation tested in this study is /n/ → /l/ which occurs before different vowels: As mentioned in Section 3.1, the change from /n/ to /l/ before non-high front vowels is phonetically motivated, while the change from /n/ to /l/ before high front vowels is phonetically unmotivated. Note that in the current HKC, the change from /n/ to /l/ is not context sensitive, i.e., the alternation is applied to all phonological contexts, regardless of the following vowels. Therefore, participants were expected to redefine the phonological context of /n/ to /l/ alternation, by subdividing a context free rule to context-sensitive rules.

To test our hypothesis, HKC native speakers were randomly assigned to one of the four artificial languages: a categorically natural language (CNL), a categorically unnatural language (CUL), a variably natural language (VNL), and a variably unnatural language (VUL). In CNL and CUL, the input pattern was categorical: In CNL, /n/ always changed to /l/ before non-high-front vowels ([-high] or [-front]), so that the patterns were 100% phonetically motivated. While in CUL, the patterns were 100% phonetically unmotivated. In VNL and VUL, the input pattern was variable. In VNL, the majority of /n/ changed to /l/ before non-high-front vowels (67%) and the remaining 33% of /n/ changed to /l/ before high front vowels, hence the dominant pattern was phonetically motivated. In VUL, the dominant pattern was phonetically unmotivated. The four languages are illustrated in (1) below.

(1) The four artificial languages

CNL: categorical n → l alternation only before non-high-front vowels

n → l/ __ u, ε

n → n/ __ i, y

CUL: categorical n → l alternation only before high front vowels

n → l/ __ i, y

n → n/ __ u, ε

VNL: dominant n → l alternation before non-high-front vowels

n → l/ __ u, ε (67%) with n → n/ __ u, ε (33%)

n → l/ __ i, y (33%) with n → n/ __ i, y (67%)

VUL: dominant n → l alternation before high front vowels

n → l/ __ i, y (67%) with n → n/ __ i, y (33%)

n → l/ __ u, ε (33%) with n → n/ __ u, ε (67%)

By comparing CNL and CUL, we can investigate whether substantive bias plays a role in categorical pattern learning. By comparing VNL and VUL, the same question can be asked, but in variable pattern learning context. If patterns' uncertainty increases the role of substantive bias, we predict that the substantive bias effect will be stronger in VNL vs. VUL, compared to CNL vs. CUL. Learners in both categorical and variable learning conditions may modulate the probabilistic distribution of variables toward the phonetically motivated pattern (n → l/ __ non-high-front vowels), if the learning is substantively biased, but the degree of departure from the input will be stronger in variable pattern learning conditions.

4 Methodology

4.1 Stimuli Participants were exposed to singular ~ plural pairs which exhibited /n/ to /l/ alternation in certain prevocalic contexts. To make the /n/ ~ /l/ alternation learning implicit, the items also showed rounding harmony among vowels. The singular form was C₁V₁C₂ik or C₁V₁C₂uk. All the chosen phonemes were

attested in HKC. For the target stimuli, the onset consonant was always /n/. For fillers, the onsets consisted of /s, k, k^h/. Vowels following the onsets (V₁) consisted of the four Cantonese monophthongs /i, y, u, ε/. C₂ were chosen from /p, p^h, t, t^h, k, ts, ts^h, s/.

In plurals, the initial consonant /n/ changed to /l/ before certain vowels and remained unchanged before other vowels. In this way, the change from /n/ to /l/ occurred at the word-initial position, to avoid misperception of /n/ or /l/ due to a preceding vowel (Kurowski & Blumstein, 1995). For fillers, the initial consonant consistently remained unchanged. For the rounding harmony, a suffix /i/ or /y/ was attached depending on V₂. The suffix was /i/ when V₂ was /i/ and it was /y/ when V₂ was /u/, reflecting a height-conditioned rounding harmony. Table 1 illustrates the stimuli. The visual stimuli¹ were a cartoon monster and three monsters creating singular~plural pairs.

Table 1. Stimuli

		C ₁	V ₁	C ₂		
Singular	Target	n	i, y, u, ε	p, p ^h , t, t ^h , k, ts, ts ^h , s	ik	uk
	Filler	s, k, k ^h				
Plural	Target	n, l			ik-i	uk-y
	Filler	s, k, k ^h				

In the training phase, there were 96 items (48 target items; 48 fillers) in each language. For target items in categorical pattern learning languages (CNL and CUL), a half of them (24 items) exhibited the change from /n/ to /l/ in plurals and another half of target items showed non-alternation of initial /n/. Specifically, in CNL, where the /n~/l/ alternation was phonetically motivated, the initial /n/ changed to /l/ only before non-high front vowels /u/ and /ε/ (24 items) and /n/ was preserved before high front vowels /i/ and /y/ (24 items). In CUL, where the /n~/l/ alternation was phonetically unmotivated, the initial /n/ changed to /l/ only before high front vowels /i/ and /y/ (24 items) and /n/ remained unchanged before non-high front vowels /u/ and /ε/ (24 items). VNL and VUL involved variable pattern learning. In VNL, the majority of /n~/l/ alternations were phonetically motivated, thus /n/ changed to /l/ more often before non-high front vowels /u/ and /ε/ (16 items, 67%) than before high front vowels /i/ and /y/ (8 items, 33%). For the 24 items with non-alternation of /n/, the majority of /n/ was preserved before high front vowels /i/ and /y/ (16 items, 67%) and the minority of /n/ was preserved before non-high front vowels /u/ and /ε/ (8 items, 33%). In VUL, the majority of /n~/l/ alternations were phonetically unmotivated, thus /n/ changed to /l/ more often before high front vowels /i/ and /y/ (16 items, 67%) and /n/ changed to /l/ less often before non-high front vowels /u/ and /ε/ (8 items, 33%). For the 24 items with non-alternation of /n/, the majority of /n/ was preserved before non-high front vowels /u/ and /ε/ (16 items, 67%) and the minority of /n/ was preserved before high front vowels /i/ and /y/ (8 items, 33%). In order to match transitional probability, the frequencies of the vowel following initial /n/ (V₁) were balanced. Across the four languages, the four vowels /i/, /y/, /u/, /ε/ which appeared in the training phase each occurred 24 times. For the second consonant (C₂), across the four languages, each of them occurred 12 times. The initial consonants /s, k, k^h/ of fillers each occurred 16 times. Besides, half of singulars ended with /ik/ and another half ended with /uk/. The attestedness of stimuli were balanced across the four languages.

In the test phase, there were 48 items (32 target items; 16 fillers). Among the target items, there were 8 unseen items with /ɔ/ and /a:/ (each vowel occurs 4 times) as new V₁ which can examine participants' generalization of initial /n/→/l/. In addition, there were 16 old singulars with /n/ followed by high front vowels² /i, y/ (each vowel occurs 8 times) and 8 old singulars with /n/ followed by non-high front vowels /u, ε/ (each vowel occurs 4 times). The frequency of the occurrence of segments and the transitional probability were balanced in the test as well. In total, each V₁ /i, y, u, ε, ɔ, a:/ occurred 8 times; each C₂ /p, p^h, t, t^h, k, ts, ts^h, s/ appeared 6 times; and the initials /s, k, k^h/ of fillers each occurred 5, 5, 6 times respectively. Half of singulars ended with /ik/ and another half ended with /uk/.

¹ The monsters were from Sporepedia (2009).

² For the singulars with /n/ followed by high front vowels, there were no unseen items in the testing phase. In HKC, there were only two high front vowels /i/ and /y/, thus the two high front vowels must appear in the training phase for the variability of stimuli.

4.2 Participants 107 native speakers of HKC aged 18 or older participated in the experiment and completed the task. Upon the completion of the task, each participant was paid 50 HKD. No participants reported any speech or hearing disorders. In order to make sure that participants were able to distinguish initial /n/ and /l/, the following criterion was applied. From the AXB task (see Section 4.3), we selected participants who chose at least 4 correct answers out of 6 questions. In order to make sure that the participants focused on the test, we further chose the participants who had at least 5 correct answers out of 8 focus questions (see Section 4.3). Also, we chose the participants whose accuracy rate on fillers were 50% or above. Participants' data was discarded when they did not meet any one of the aforementioned criteria. In total, 23 participants' data was discarded. Of the remaining 84 participants (28 males, 56 females), 19 of them learned CNL; 22 learned CUL; 20 learned VNL; and 23 learned VUL.

4.3 Procedure A computer-based task was created through PsychoPy version 3.0 (Peirce et al., 2019) and was conducted online via Pavlovia (2021). Before the experiment, participants filled in a questionnaire about their age, gender and native language created through Qualtrics (2021). The experiment consisted of three parts: a training phase, a testing phase and an AXB test. For each participant, the stimuli were randomized within each phase. Neither orthography nor feedback were provided, making the experimental procedure an implicit learning task. In the beginning of the training phase, participants saw an instruction page explaining that they were going to learn a new language and would be asked how to name plural forms in this language. Then, they went through two practice items. For each item, while they saw the corresponding visual stimuli, they heard the names of the singular monster and then the plural form. After the practice session, the training phase consisting of 48 target items and 48 fillers began. They heard the singular form and saw the corresponding picture, followed by the plural form for each item. To ensure the participants focused on the learning, there were eight focus questions which asked participants about the color of a monster they just saw.

After training, participants entered the testing phase, which consisted of 24 seen target items, 8 unseen target items, 8 seen fillers and 8 unseen fillers ($n=48$). Before the test, they were given two practice items, both without initial /n~/l/ alternation. Participants heard the names of monsters, both in a singular form, and they were asked to choose the plural form from two options, showing either vowel rounding harmony or disharmony between V_2 and the suffix. For target items, the two options showed either initial /n/ or /l/, with the correct suffix (height rounding harmony). For fillers, the two options exhibited either height rounding harmony or disharmony, with the initial consonant unchanged. Across all of the items, half of the correct answers were given as the first option, and the other half as the second option.

After the testing phase, participants took an AXB test which was used to assess their perceptual ability to distinguish initial /n/ and /l/ occurring before /i, y, u, ε, ə, a:/. They first took a practice trial presenting the three sounds /p^hi/, /sa:/, /sa:/. Then they took six AXB tests presenting three sounds with the same vowel context, but with either the first or the third initial sound identical to the second one. In the six AXB tests, when the first syllable was unattested in HKC (/n/ or /l/ followed by /i/, /y/ or /u/), the second syllable was /pɔ/ which is attested in HKC. When the first syllable was attested in HKC (/n/ or /l/ followed by /ε/, /ɔ/ or /a:/), the second syllable was /p^hi/ which is unattested in HKC. In this way, either the first or the second syllable was unattested in HKC, thus the attestedness of all AXB items would not affect participants' perception. The AXB test was presented after the learning and testing sessions in order not to show participants that the focus of the experiment is on /n/ and /l/.

4.4 Results The average accuracy rates of vowel harmony among fillers were high overall, showing 81.3%, 75.9%, 81.9% and 81.8% accuracy respectively for CNL, CUL, VNL, and VUL. This indicates that the participants successfully learned height-conditioned vowel harmony. No significant accuracy difference was found on fillers between CNL vs. CUL ($t(37.22)=0.972$, $p=0.337$) and VNL vs. VUL ($t(39.63)=0.015$, $p=0.988$).

Now we analyze the consonant alternations, a main focus of the current study. The alternation rates among all the target items were below 50%, i.e., 35.9% (CNL), 36% (CUL), 41.1% (VNL) and 30.3% (VUL) respectively. Even in categorical learning conditions, where all critical items always alternated before non-high front vowels (CNL) or high front vowels (CUL), the tendency to alternate was low. This could presumably be due to half of the non-alternating items in the other phonological contexts, i.e., high front vowels in CNL and non-high-front vowels in CUL, which could also suggest a strong bias against alternation across the experimental conditions (Wilson, 2003, 2006; Tessier, 2012; Do, 2018). We then compared the alternation rates within categorical vs. variable pattern learning conditions. As in Figure 1 (seen target items)

and Figure 2 (unseen target items), the alternation rates between the two categorical languages (CNL vs. CUL) were not significantly different. For the two variational languages (VNL vs. VUL), on the other hand, the alternation rates in VNL and VUL seem significantly different with VNL showing higher alternation rates.

Figure 1. Alternation rates on target seen items

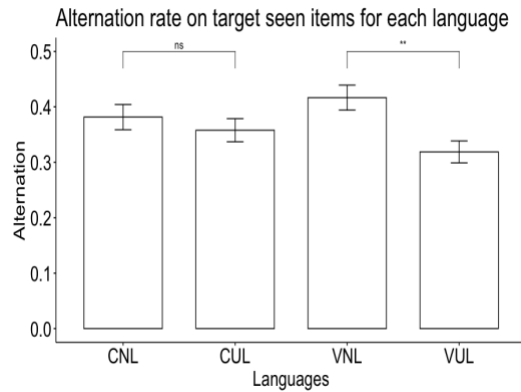
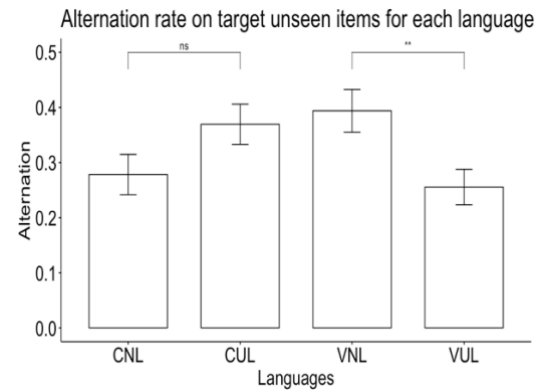


Figure 2. Alternation rates on target unseen item



To test the statistical significance of the results in the categorical learning, logistic regressions were performed using the `glmer` function of the `lme4` package (Bates et al., 2015) in R (R Core Team, 2018). The alternation of initial /n/ on critical items of the binary-forced-choice task were converted to binary values (0 = non-alternation; 1 = alternation). Two dummy coded factors, Languages (CNL vs. CUL and VNL vs. VUL) and Vowel Context (motivated vs. unmotivated) were our interests. Languages and Vowel Context, as well as their interaction were included as the independent variables. Random intercepts for Participants and Items were included. ‘CUL’ was assumed as a baseline of Languages and ‘Unmotivated’ was assumed as a baseline of Vowel Context. The results in Table 2 show a strong bias against alternation ($\beta = -1.0391$ $p < .01$). It also shows that Languages, Vowel Context and their interactions were not significant in categorical learning.

Table 2. The results of a logistic regression model for the alternation rates in categorical learning

	Estimate	SE	z value	p(z)
Intercept	-1.0391	0.3257	-3.190	0.00142 **
Languages (CUL)	0.1834	0.3417	0.537	0.59143
Vowel Context (Unmotivated)	0.3964	0.3455	1.147	0.25133
Languages (CUL): Vowel Context (Unmotivated)	-0.1293	0.2583	-0.500	0.61673

The same model was built for the results of learning the two variable languages (VNL and VUL). The results in Table 3 show that the general alternation rate was significantly lower for VUL in comparison with VNL ($\beta = -1.0312$, $p < .01$). The alternation rate for Unmotivated patterns was not significantly different from Motivated patterns ($\beta = 0.1228$, $p = 0.682$). However, it further shows that there was a significant interaction between Language and Vowel context, showing that the alternation was especially higher in VUL when the vowel context was unmotivated ($\beta = 0.6857$ $p < .01$).

Table 3. The results of a logistic regression model for the alternation rates in variable learning

	Estimate	SE	z value	p(z)
Intercept	-0.5218	0.3101	-1.683	0.09244 .
Languages (VUL)	-1.0312	0.3634	-2.838	0.00455 **
Vowel Context (Unmotivated)	0.1228	0.2996	0.410	0.68190
Languages (VUL): Vowel Context (Unmotivated)	0.6857	0.2543	2.696	0.00701 **

An additional analysis of pairwise comparisons was conducted for the two factors Languages and Vowel Context in Table 3, using the `emmeans` package (Lenth et al., 2020). The results are in Table 4. As shown,

the alternation difference between Language VNL and VUL was significant, while no significant difference was found between motivated and unmotivated vowel contexts, confirming our observation in Table 3.

Table 4. Pairwise comparisons of Languages and Vowel Context

Contrast	odds.ratio	SE	z ratio	p value
VNL vs. VUL	1.99	0.669	2.047	0.0407 *
Motivated vs. Unmotivated	0.628	0.171	-1.711	0.0872

Taken together, the regression analyses show that (1) There was a strong bias against alternation in categorical learning context; (2) Languages, Vowel Context and their interactions were not significant in categorical learning; (3) Languages and the interaction between Languages and Vowel Context were significant factors in variable learning context, showing the hesitance of applying the alternation especially when the dominant patterns were phonetically unmotivated.

5 General discussion and conclusion

The current experiment presents evidence for the effect of pattern's uncertainty in activating the substantive bias effect in phonological learning. The main findings include (1) there was a high rate of non-alternation across languages; (2) when patterns were variable, participants who learned the dominant natural language were more likely to apply /n/ to /l/ alternation compared to those who learned the dominant unnatural language; (3) substantive bias was evidenced only in variable learning.

The alternation rates were low across the four languages, all rates were below 50%. Considering the training data, 50% of them showed /n~/l/ alternation and another 50% showed no alternation of /n/. The distributions of specific alternations were different in categorical and in variable learnings, but the overall alternation proportions in each language were always 50%. And all fillers showed no alternation of the consonants, so in a language as a whole only 25% of data exhibited /n~/l/ alternation across all of the four artificial languages. Previous studies revealed a strong bias against alternation, even when 75% of the training data showed alternation (Coetzee, 2009; White, 2014; Do, 2018). Therefore, the low alternation rates in the current study are not unusual. Additionally, in most of the previous research on phonological alternation using artificial language learning paradigm, the target pattern was not attested in Participants' L1 (e.g., Finley, 2012; Shapp, 2012; White, 2014), which is different from the current study. The current task of revising a context free alternation rule, i.e., /n/ to /l/ alternation, to context-sensitive alternation rules, i.e., $n \rightarrow l_ \{i, y\}$ or $n \rightarrow l_ \{u, \epsilon\}$ was challenging, which may lead to the non-alternation bias across languages. Although the overall alternation rates were low, crucially, different alternation rates between natural and unnatural languages were found from variable learning, but not from categorical learning. Specifically, the variably natural language (VNL) showed significantly higher alternation rate than the variably unnatural language (VUL), despite the same alternation rate in the two languages. This result suggests that participants learned and generalized the alternation pattern in a substantively biased way when variation was involved in learning. Therefore, for the design of ALL studies on substantive bias, the methodological choice deserves more attention. The results further imply that through the course of sound change, phonologically variable patterns are more likely to be influenced by substantive bias than categorical patterns, leading higher likelihood of sound change.

Participants in the current study failed to explicitly identify the specific vowel contexts of /n~/l/ alternation/non-alternation. No significant difference on the alternation rate was found between vowel contexts (i.e. high front vowels vs. non-high front vowels) across languages (except for VUL). Note that this result did not indicate a failure of learning the alternation, because participants tended to preserve the initial /n/, which was opposite to their L1. The non-learning of specific vowel contexts of alternation may be due to, as mentioned above, the challenging task of revising a L1 rule. Therefore, future research can test a pattern which does not exist in participants' L1. The non-learning of specific vowel context may be also attributed to the distinction between phonetic naturalness vs. phonetic motivation. A pattern is *unnatural*, if it goes against what articulatory effort and perceptual distinctiveness would predict. A pattern is *unmotivated*, if the pattern is not necessarily the opposite to the predictions from articulatory efforts or perceptual distinctiveness, but instead it is neither grounded on phonetic factors, nor violate them (Beguš, 2018). The change from /n/ to /l/ before non-high-front vowels is phonetically *motivated* rather than phonetically *natural*. And the change

from /n/ to /l/ before high front vowels is phonetically *unmotivated* rather than phonetically *unnatural*. The phonetic grounding difference is lower for *motivated* vs. *unmotivated* patterns, in comparison to *natural* vs. *unnatural* patterns. Therefore, the current results may imply that the effect of substantive bias can be activated in learning variable patterns with phonetic motivations, but the effect is not as strong as learning variable patterns with phonetic naturalness. Such a proposal requires future experiment which test variable patterns with phonetic naturalness.

Crucially, this study found that uncertainty makes substantive bias active as shown from the learning of /n/ to /l/ alternation by native speakers of HKC. In line with previous studies on substantive bias by Glewwe (2019) and Do & Havenhill (2021), the current findings suggest that the substantive bias effect is not global, but it is activated under certain circumstances. The current study found that *uncertainty* is one of such contexts that could trigger the effects of substantive bias, suggesting the shape and the distribution of patterns in input could influence the effect of substantive bias.

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