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# Investigating Taiwan Southern Min subsyllabic structure using maximum entropy models and wordlikeness judgments

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To resolve the issue of Taiwan Southern Min syllabic structure, we first investigated the probabilistic co-occurrence of segments using maximum entropy models to simulate phonotactic learning processes. The algorithm constructed the constraint-based grammars that fitted the gradient phonotactic patterns of the input by yielding the numeric weights of the learned constraints. In addition to the baseline defined by the feature matrices, the constraints were augmented with the subsyllabic tier to express the hierarchical relationship of segments. For a comparison with the modeling consequences under different subsyllabic hypotheses, we further conducted a wordlikeness judgment experiment on nonsense syllables on a continuous scale. It was revealed that the body-coda model distinguished systematic gaps, accidental gaps, and attested syllables over a continuum of violation scores and obtained a significant correlation between violation scores and wordlikeness judgments. This study thus has provided evidence supporting Taiwan Southern Min as having body-coda structure that not only enhanced the phonotactic learning but also confirmed native speakers' phonotactic intuitions.

## 1. Introduction

Subsyllabic structure across languages has been proposed as the flat model, the onset-rhyme model, or the body-coda model (e.g., Clements & Keyser, 1983; Davis, 1989; Fudge, 1969, 1987; Godlsmith, 1990; Hayes, 1989; Hyman, 1985; Kahn, 1976; Kiparsky, 1979; Levin, 1985; McCarthy & Prince, 1990; Selkirk, 1982; Treiman, 1988). As shown in Figure 1 (a), the flat model claims that segmental nodes are concatenated sequentially, without the branching structure within a syllable. Figure 1 (b) shows the onset-rhyme model that posits an intermediate rhyme node under which a vowel and a postvocalic consonant are associated closely. Figure 1 (c) exhibits the body-coda model in which a prevocalic consonant and a vowel comprise an intermediate body level. As in Figure 1 (d), lastly, within a syllabic structure, a prevocalic consonant and a postvocalic consonant constitute a discontinuous subpart before joining with a vowel.

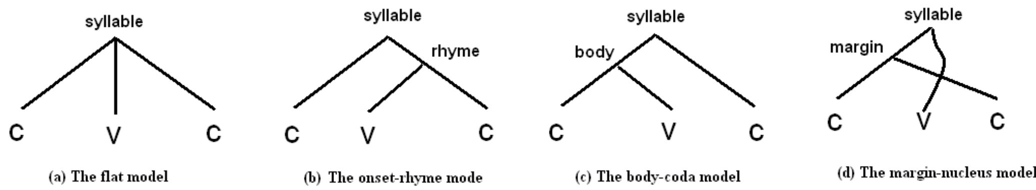


Figure 1. Four types of subsyllabic structure

Subsyllabic structure across languages has been presented along multiple threads of evidence: (1) stress or tone assignment based on syllable weight of the rhyme (e.g., Blevins, 1995; van der Hulst & Ritter, 1999) (2) co-occurrence restrictions (e.g., Fudge, 1987; Treiman, 1988) (3) spontaneous or experimentally elicited speech errors (e.g., Fowler, 1987; Mackay, 1972; Shattuck-Hufnagel, 1983) (4) naturally occurring or experimentally contrived word games (e.g., Fudge, 1987; Hockett, 1973; Pierrehumbert & Nair, 1995; Treiman,1983) (5) other experimental techniques such as word-blending, unit substitution, sound similarity judgment, concept formation, unit reduplication, and nonce-word recall (e.g., Derwing, 2007; Wang, 1995; Yoon & Derwing, 2001).

In the pursuit of syllabic constituency in languages, the rhyme-coda model has been most widely accepted across languages (e.g., Blevins, 1995; der Hulst & Ritter, 1999; Fudge, 1969, 1987; Goldsmith, 1990; Kiparsky, 1979; Levins, 1985; Selkirk, 1982; Treiman, 1988). Crucially, a rhyme as the constituent that carries syllable weight can affect the distribution of primary stresses or contour tones in a language, leaving the prevocalic consonant not involving in the prosodic assignment. Citing evidence from English distributional constraints, speech errors, and word games, Fudge (1987) further contended that rhyme as a universal phonological unit.

Alternatively, in the moraic theory a mora is a hypothetic unit governing the metric weight or length, with a light syllable having a single mora and a heavy syllable having two morae (e.g., Hyman, 1985). Within a syllable, the prevocalic consonant and the nucleus converge under a moraic node, whereas the postvocalic consonant is placed under the other moraic node. This moraic theory expects a similar subsyllabic structure as the body-coda model in Figure 1 (c).

In the other version of the moraic theory (e.g., Hayes, 1989), the prevocalic consonant directly links with the syllabic node, yet the nucleus and the postvocalic consonant associated with two separate moraic nodes under a syllabic node. This moraic theory espoused the property of no intermediate branching node between the syllable and the segments, as show in Fig. 1 (a). Similar proposals were also found in the ternary branching model (e.g., Davis, 1989) and the flat model (Kahn, 1976). Unlike the other three models, however, the margin-nucleus model lacks theoretic modeling and direct evidence from languages (but cf. Fudge, 1973, 1987), even though it is logically plausible.

Following this research line, the study pursues the question as to Taiwan Southern Min subsyllabic structure. Which subsyllabic structure does Taiwan Southern Min syllables contain? Taiwan Southern Min lacks evidence of the rhyme as the locus of syllable weight (Cheng & Tseng, 1997). Taiwan Southern Min syllables have long been proposed as having the onset-rhyme construction (Bao, 1990; Cheng & Cheng, 1977; Chung, 1996); for instance, Bao adopted evidence of *Fanquie*, originally used to specify the pronunciation of a novel character in terms of two known ones in traditional Chinese philological literature, to conclude onset-rhyme structure in Taiwan Southern Min. By contrast, the contestation that Taiwan Southern Min syllables are moraically represented has been provided by other linguists (e.g., Chung, 1999; Cheng, 2002). Adopting experimental evidence (e.g., the body-sharing novel compounds were more easily memorized than the rhyme-sharing novel compounds), Derwing and his colleague (Derwing, 2007; Wang & Derwing, 1993) supported the body-coda construction as well.

Given the above contradictory evidence, the question regarding Taiwan Southern Min subsyllabic structure has not been fully settled down. In this article, we attempted to resolve the issue by computing the strength of coherence between adjacent segments within a syllable. Particularly, we attempted to simulate Taiwan Southern Min phonotactic learning based on the four subsyllabic hypotheses using maximum entropy models of phonotactic learning. For a reexamination of the modeling results, we also conducted a wordlikeness judgment experiment following the maximum entropy models of phonotactic learning. The working hypothesis adopted here is that proper subsyllabic structure not only fosters the phonotactic learning (i.e., making learning viable and efficient) but also corresponds with native speakers' phonotactic intuitions.

This article will be organized as follows. In the second section will be to present further literature review of Taiwan Southern Min subsyllabic structure. The third section will be to delicately introduce maximum entropy models of phonotactic learning on four types of subsyllabic hypotheses in Taiwan Southern Min. The fourth section will be to describe a wordlikeness judgment experiment and examine both of modeling and experimental results. In the last section will arrive at the conclusion on Taiwan Southern Min subsyllabic structure.

## 2. Some other issues on Taiwan Southern Min syllable structure

Traditionally, Taiwan Southern Min, like most of other Chinese languages (e.g., Mandarin), has no more than four segments in a syllable; see Table 1 (a)-(l). The maximum syllable structure can be CGVG or CGVX (Cheng & Cheng, 1977; Chung, 1996). Within a syllable, the onset consonant (C) is called as an *initial* whereas the rest elements of a syllable constitute a *final*. Within the *final* are a prevocalic glide (G), a nucleus vowel (V), and a postvocalic glide (G) or a postvocalic obstruent (X) that all construct a *rhyme* as well. Notwithstanding arguably a prevocalic glide may form a consonant cluster or a coarticulatory component with a preceding consonant (Bao, 1990;

Duanmu, 1990), this study would adopt the widely accepted view that a prevocalic glide belongs to part of a nucleus vowel. Although there are also debates as to the status of a postvocalic glide or obstruent (Chung, 1996; Lin, 1989), but this study would tentatively determine a postvocalic glide as subordinate to a nucleus vowel, but a postvocalic obstruent as independent from a nucleus vowel. In the maximum entropy modeling, this study would thus schematize Taiwan Southern Min syllable structure as C-V-C, in which C- is a pre-glide consonant, V is an integral part that comprises maximum three segments (i.e., a prenuclear glide, a nucleus vowel and a postnuclear glide), and -C is a postvocalic obstruent.

A number of syllable types attested in a contemporary Taiwan Southern Min dictionary (Tung, 2001) will bring about a few further considerations of syllable structure. The example (m) in Table 1 that comprises five segments occurs when the postnuclear consonant is a glottal stop. A glottal stop in Taiwan Southern Min has been argued as a segmental or tonal element (e.g., Chung, 1995; Hung, 1994; Li, 1989). Although a glottal stop viewed as a toneme holds a maximum syllable size of four segments, a glottal stop in the following modeling would rather be treated as a distinctive segment in order to technically distinguish such attested syllables as /ka$^{53}$/, /kaʔ$^{53}$/, and /kak$^{53}$/ in Taiwan Southern Min. In addition, the examples (n) and (l) exhibit the syllables containing the segment sequences that involve the nucleic nasal consonants [m] or [ŋ] and the other consonants. Given these, the current maximum entropy models would also be required to acquire syllable structure of maximum five segments as well as consonant clusters consequently.

Table 1. The attested syllable types in Taiwan Southern Min

| | Syllable types | Examples | Glosses |
|---|---|---|---|
| (a) | V | i$^{53}$ | 'chair' |
| (b) | VX | ap$^{53}$ | 'box' |
| (c) | VG | au$^{53}$ | 'press' |
| (d) | GV | io$^{55}$ | 'waist' |
| (e) | GVG | uai$^{55}$ | 'awry' |
| (f) | GVX | ian$^{55}$ | 'smoke' |
| (g) | CV | li$^{33}$ | 'profits' |
| (h) | CGV | sia$^{53}$ | 'write' |
| (i) | CVX | kun$^{55}$ | 'troops' |
| (j) | CVG | tai$^{13}$ | 'bury' |
| (k) | CGVG | ziau$^{21}$ | 'scratch' |
| (l) | CGVX | puan$^{13}$ | 'plate' |
| (m) | CGVGX | ŋiauʔ$^{53}$ | 'squirm' |
| (n) | CX | sŋ$^{55}$ | 'sour' |
| (l) | CXX | ts$^{h}$ŋʔ$^{31}$ | 'blow the nose' |

According to Chung (1996), seven distributional constraints of syllable structure have been proposed in Taiwan Southern Min: (1) the N-Constraint requires diphthongs to have at least one high vowel, e.g., *eo, *ao; (2) the Dissimilatory Constraint prohibits [α back](…)[α back] in a di- or triphthong, e.g., *ie, *uo, *uei, * iou; (3) the Fall Constraint disallows a falling diphthong from preceding a coda, e.g., *aip/m, *ait/n, *aik/ŋ; (4) the Branching-R Constraint bans [+high][+high] in the VC-structure, e.g., *ik, *iŋ, *uk, *uŋ; (5) the Branching-N Constraint prevents a prevocalic *u* from co-occurring with a velar coda, *uak, *uaŋ, *uek, *ueŋ; (6) the Labial Constraint prohibits [+labial](…)[+labial] within the syllable unless the two labials are onset and nucleus, e.g., *um, *op, * iop, *uam; (7) the Nasal Constraint requires that a maximum of one nasal autosegment may occur in a syllable (given that C(G)(V)(G)- and -X are two domains for nasality percolation), e.g., *mãn, * bãn. The first two distributional constraints are carried out within the nucleus, the next four distributional constraints within the rhyme, and the seventh distributional constraint within the body. A raw probability of constraints within certain subsyllabic component probably cannot determine syllable structure of a language (Fudge, 1987). Instead, the interaction with the other constraints and the application scope over the lexicon of a particular constraint will play a promising role of evaluating its effectiveness in influencing syllable structure of a language.

## 3. The application of maximum entropy models in Taiwan Southern Min

Maximum entropy can be traced back to Biblical times and have been widely applied outside the linguistic domains (e.g., natural language processing (NLP) in Berger, Della Pietra, & Della Pietra, 1996). A specific maximum entropy model (Hays & Wilson, 2008) is a stochastic model used to simulate the behaviors of phonotactic learning processes. The learning aims at constructing the constraint-based grammar (Prince & Smolensky, 2004) that best fits the learning data. Technically speaking, the model is meant to calculate the maximum mathematical fitness of the random-sampling inputs in each learning cycle. Given a constraint-seeking algorithm, the last goal of modeling is to make the summation of the violation scores of the weighted constraints minimized for all the attested data.

Some principles approaching such a goal are inherently determined in the modeling: First, the most accurate constraints are prioritized for adopting as the learned phonotactic constraints. The accuracy is defined as the O/E value, that is, the number of violations of the constraint observed in the learning data (O), divided by the number of violations expected from the current grammar (E). Second, if there is a tie of accuracy, generality is the secondary consideration. Shorter constraints (fewer feature matrices) are favored over longer ones (more feature matrices). Simpler constraints (involving fewer feature specifications) are also favored over more complex ones (more feature specifications). Constraints involving more segments are preferred to those with few segments.

### 3.1 Learning data

The learning data as the input were the lexical entries from a contemporary Taiwan Southern Min dictionary (Tung, 2001). The lexical entries were adopted from a variety of spoken resources with a few written texts as a supplement. There were totally 6,893 lexical entries (i.e., monosyllabic morphemes or characters) listed in the dictionary. For assessing syllable type frequency, all of the corresponding morphemes or characters were summed up. Segments involved were encoded as the machine-readable symbols in terms of the SPE-style feature specifications. Maximum entropy models subsequently can yield the feature-defined constraints by internalizing the learning data.

### 3.2 Setting parameters

Maximum entropy models must proceed after the parameters were set in advance. These values were used to extract more effective constraints but block less useful constraints. The maximum O/E value for constraints was 0.3 and the accuracy schedule was at [.001, .01, .1]. The maximum number of constraints to discover was unlimited in that the model could acquire as many constraints as possible. The maximum gram size of constraints was 4 (defined by the number of feature matrices), based on the observation that the majority of Taiwan Southern Min syllables were no longer than four segments, and the model eventually converged as the maximal gram size was only three. In terms of the constraint definitions, a complementation operator ^ was used to address the logical implication between a segment sequence, that is, as *if a particular segment has a feature matrix, then any preceding or following segment must have another feature matrix*. According to Hayes & Wilson (2008), the use of a complementation operator improved the performance of the modeling as well as the interpretation of the learned grammars.

Crucially, four types of projections were considered to distinguish the four hypotheses of Taiwan Southern Min syllable structure. A projection worked like inserting a boundary at the projected domain edges that enhanced the cohesiveness of segments within the projected domain but blocked segments outside the projected domain. Analogically, a projection worked like constructing hierarchical structure as well. The Flat model was the default baseline in which no internal branching structure within a syllable is posited. For the syllable /#pan#/, syllable tier was marked as (i.e., [±boundary]) to anchor the syllabic boundaries (i.e., #), corresponding with the segmental features in the segment tier. In addition to the syllable tier and segment tier, the Body model was projected with the intermediate tier in which an onset and a nucleus were more closely combined. The body tier was marked as subsyllabic boundaries (i.e., [±body]) corresponding with the segment sequence /#pan#/. The Rhyme model was used to demonstrate the intermediate branching node under which a nucleus and a coda converged. The rhyme tier was marked as the subsyllabic boundaries (i.e., [±rime]) to specify the segment sequence /#pan#/ in the segment tier. Finally, the margin tier was marked as the subsyllabic boundaries (i.e., [±margin]) corresponding with the segment sequence /#pan#/ as hypothesized in the Margin model. Contrasting a sequential order by default, the Margin model was used to address a novel assumption in which a prevocalic consonant and a postvocalic consonant were groped before joining a nucleus.

### 3.3 Evaluation

The testing data consisted of all the toneless combinations of onsets (p, $p^h$, b, m, t, $t^h$, l, n, k, $k^h$, g, ŋ, h, ts, $ts^h$, s, z), nuclei (a, ã, ai, ãĩ, au, ãũ, e, ẽ, i, ĩ, ia, ĩã, iau, ĩãũ, io, iɔ, ĩõ, iu, ĩũ, o, õ, ɔ, u, ua, ũã, uai, ũãĩ, ue, ũẽ, ui, ũĩ), and codas (p, t, k, m, n, ŋ, ʔ) in Taiwan Southern Min. There were totally possible 4,608 syllable types. Of all the syllable types, 836 were attested in the dictionary.

The testing data was then input to the learned grammars to generate the violation score for each syllable. The violation score of a syllable $x$, denoted h($x$), is

$$h(x) = \sum_{i=1}^{N} w_i C_i(x),$$

where
$w_i$ is the weight of the $_i$th constraint,
$C_i(x)$ is the number of times that $x$ violates the $_i$th constraint, and
$\sum_{i=1}^{N}$ denotes summation over all constraints ($C_1$, $C_2$,…, $C_N$).

The transformation from the violation score to the value representing degree of wellformedness of a syllable can be conducted by calculating the maxent value of $x$, denoted P*($x$).

$$P^*(x) = \exp(-h(x))$$

The violation score is negated, and $e$ (the base of the natural logarithm) is raised to the result. The probability of $x$ in the modeling is calculated by determining its share in the total maxent values of all possible syllables in Ω, a quantity designed as $Z$. In effect, the probability makes a lot of sense for determining an optimal constraint by comparing its contribution to the model with other competing constraints in the modeling.

$$P(x) = P^*(x) / Z$$

$$\text{where } Z = \sum_{y \in \Omega} P^*(y)$$

The evaluation can begin with whether any of the four models can predict categorical lexical status of Taiwan Southern Min. Attested syllables were supposed to obtain 0 violation score as composed to nonsense syllables. As exhibited in Table 2(a), the Body model and the Rhyme model were more capable of assigning attested syllables

0 violation score[1] (i.e., nearly 100%) and assigned nonsense syllables non-zero violation scores, whereas the other two models were to a larger degree away from the accurate lexicality distinction. As for the other three indexes, attested syllables were expected to be significantly distinguishable from nonsense syllables. As shown in Table 2 (b)-(c), average violation scores of nonsense syllables were higher than average violation scores of attested syllables, average maxent values of attested syllables were higher than average maxent values of nonsense syllables, and average probability of attested syllables were higher than average probability of nonsense syllables. In terms of the thee indexes, quantitatively, the difference size between attested syllables and nonsense syllables was larger in the Body and Rhyme models than in the other two models. The comparisons across the four models supports one thing: Only the Body and Rhyme models are able to learn Taiwan Southern Min phonotactic grammar (i.e., distinguishing attested and nonsense syllables). Neither the Flat model nor the Margin model can do phonotactic learning as well as the Body and Rhyme models.

Table 2. Results of the maximum entropy models

(a)

| Accuracy rates | Body | Rhyme | Flat | Margin |
|---|---|---|---|---|
| Attested | 99.88% | 99.88% | 59.14% | 59.14% |
| Nonsense | 78.54% | 83.88% | 89.44% | 85.94% |

(b)

| Average violation scores | Body | Rhyme | Flat | Margin |
|---|---|---|---|---|
| Attested | 0.007 | 0.004 | 1.133 | 1.060 |
| Nonsense | 6.072 | 7.582 | 3.463 | 2.525 |

(c)

| Average maxent values | Body | Rhyme | Flat | Margin |
|---|---|---|---|---|
| Attested | 0.999 | 0.999 | 0.640 | 0.633 |
| Nonsense | 0.219 | 0.163 | 0.161 | 0.210 |

(d)

| Average probability | Body | Rhyme | Flat | Margin |
|---|---|---|---|---|
| Attested | 0.06% | 0.07% | 0.06% | 0.05% |
| Nonsense | 0.01% | 0.01% | 0.01% | 0.02% |

One additional thought regarding the results is that wellformedness of certain nonsense syllables provided evidence for accidental gaps which were considered

[1] The only syllable that the Body and Rhyme models failed to learn is an onomatopoeic morpheme [ŋh] 'the sound of having a bowel movement'.

well-formed but underrepresented in the lexicon. Conversely, a couple of lexical exceptions (e.g., [ŋh]) which were considered ill-formed but overrepresented in the lexicon were found although the size was relatively limited.

Before moving on, we should examine the learned grammars from the Body and Rhyme models. The constraints of both learned grammars are exhibited in Table 3 and Table 4, respectively. Frequencies of constraints between the Body and Rhyme models are almost equal and the learned constraints were almost comparable.

Table 3. The learned constraints in the Body model (24 constraints)

| | Constraints | Tiers | Weights | Examples |
|---|---|---|---|---|
| 1 | *[^-voice][-syl] | Body | 1.192 | tŋ (*dŋ) |
| 2 | *[-syl][^+son,+body] | default | 5.458 | ta, tŋ (*tp) |
| 3 | *[+nasal][-nasal] | Body | 2.438 | *na, * ãu |
| 4 | *[^-nasal,+body][-nasal,+body] | default | 3.778 | ba, au (*ma, *ãu) |
| 5 | *[+approx,-nasal][^+syl,-nasal] | Body | 5.880 | au (*aũ) |
| 6 | *[^+syl,-nasal][+cor] | default | 4.714 | at, an (*ãt, *ãn) |
| 7 | *[-high][^+high] | Body | 5.144 | ai, au (*ae, *ao) |
| 8 | *[+boundary][-body] | default | 2.501 | *[-p |
| 9 | *[+back][^-back] | Body | 4.695 | ui, ua (*uo) |
| 10 | *[-body][-boundary] | default | 5.012 | *-pt |
| 11 | *[-high,-low][-boundary] | Body | 4.073 | *ei, *ou, *ɔa |
| 12 | *[^-nasal,+body][+lab] | default | 4.016 | ap (*ãp) |
| 13 | *[-low,-round][-low,-back] | Body | 4.816 | *ei, *oi, *oe, *ie |
| 14 | *[+back][+lab] | default | 4.725 | *up, *ɔm |
| 15 | *[^+cont,+spread][+lab] | Body | 2.928 | hm (*kʰm) |
| 16 | *[+syl,+nasal][-syl,+son] | default | 1.772 | *ãl, *ãm |
| 17 | *[+voice][^+syl,-nasal] | Body | 4.287 | ba (*bã, *bt) |
| 18 | *[+syl,+nasal][+velar] | default | 4.819 | *õk, ãk |
| 19 | *[-boundary][-syl][-boundary] | Body | 4.852 | *[...C...] |
| 20 | *[-high,-low][+cor] | default | 3.863 | *et, *en, *ot, *on |
| 21 | *[+syl][-boundary][^+high] | Body | 1.371 | iau (*uae, *iuo) |
| 22 | *[-high,-low,-round][^-cont,+glottal] | default | 4.689 | eʔ, oʔ (*ok, *ek) |
| 23 | *[+syl][^+low][-boundary] | Body | 1.670 | iau (*iou, *ieu) |
| 24 | *[+syl][^-high][+son] | default | 4.267 | ian (*uin, *aun) |

Table 4. The learned constraints in the rhyme model (23 constraints)

| | Constraints | Tiers | Weights | Examples |
|---|---|---|---|---|
| 1 | *[^+high][-high] | Rhyme | 5.768 | ia (*ea) |
| 2 | *[-syl][-syl,-nasal] | default | 3.056 | *tk (tŋ) |
| 3 | *[-approx][-boundary] | Rhyme | 2.394 | *t] |
| 4 | *[^-voice,-rime][-rime] | default | 7.495 | tŋ (*dŋ) |
| 5 | *[^+syl,-nasal][+syl,-nasal] | Rhyme | 2.205 | ai (*ãi) |
| 6 | *[^+syl,-nasal][+cor] | default | 4.723 | at, an (*ãt, *ãn) |
| 7 | *[^+syl,+nasal][+syl,+nasal] | Rhyme | 5.695 | ãĩ (*aĩ) |
| 8 | *[+nasal][+approx,-nasal] | default | 5.460 | *na, *ãi |
| 9 | *[^-back][+back] | Rhyme | 5.094 | au, io (*ou, *uo) |
| 10 | *[+nasal,+rime][-syl,+son] | default | 1.689 | *ãm, *ãl |
| 11 | *[-high,-low][+approx] | Rhyme | 3.843 | *eu, *ei, *ou, *oa |
| 12 | *[+nasal][+lab] | default | 2.499 | *ãp, *nm |
| 13 | *[-low,-round][-low,-back] | Rhyme | 4.919 | *ei, *oi, *oe, *ie |
| 14 | *[-cont][+lab] | default | 3.624 | *km (hm) |
| 15 | *[-high,-low,-round][^-cont,+glottal] | Rhyme | 5.781 | eʔ, oʔ (*ek, *ok) |
| 16 | *[+nasal,+rime][+velar] | default | 4.859 | *ãk, ãŋ |
| 17 | *[^-nasal,-back][+lab] | Rhyme | 4.102 | em, ep (*ẽm, *ẽp, *om, *op) |
| 18 | *[+voice][^+syl,-nasal] | default | 4.867 | ga (*gã, *gt) |
| 19 | *[^+high][-boundary][+son] | Rhyme | 1.283 | uan (*aun) |
| 20 | *[-boundary][-syl][^-cont,+glottal] | default | 6.764 | $ts^hŋʔ$ ($*ts^hŋk$) |
| 21 | *[-nasal,-high,+round][^+velar] | Rhyme | 4.769 | ɔk, ɔŋ (*ɔt, *ɔn) |
| 22 | *[+rime][^-high][+son] | default | 2.551 | uai, uen (*uin, *iun) |
| 23 | *[-boundary][+high][^-cont,+glottal] | Rhyme | 5.360 | uiʔ (*uik) |

In Table 3, the Body model learned twenty-four constraints totally. Provided the seven constraints (Chung, 1996), we are able to compare the learned constraints against Chung's proposal: the N-Constraint is represented as constraint (7), the Dissimilatory Constraint as constraint (9, 13), the Fall Constraint as constraint (24), the Labial Constraint as constraint (14), and the Nasal Constraint as constraints (3, 4, 5, 6, 16). In Table 4, twenty-three constraints were learned in the Rhyme model. Analogously, the Rhyme model learned the N-Constraint represented as constraint (1), the Dissimilatory Constraint as constraint (9, 13), the Fall Constraint as constraint (19, 22), the Labial Constraint as constraint (17), and the Nasal Constraint as constraints (5, 7, 8, 10).

The nonoccurrence of the Branching-R Constraint and Branching-N Constraint was expected since the following syllable types (i.e., [tsuaŋ], [uaŋ], [siŋ], [pʰiŋ], [piŋ], [kiŋ], [hiŋ], [tsʰiŋ], [liŋ], [tsiŋ], [biŋ], [tʰiŋ], [sik], [pik], [lik], [kik], [hik], [gik], [tsik], [bik]) were already attested in the Taiwan Southern Min dictionary. Such attested syllables might decrease the effectiveness of the Branching-R Constraint and Branching-N Constraint, therefore causing unsystematic predictions of lexicality of the associated syllable types.

## 4. Testing learned grammars using wordlikeness judgments

As indicated in literature (e.g., Greenberg & Jenkins, 1964; Ohala & Ohala, 1986; Vitevitch, Luce, & Charles-Luce, & Kemmerer, 1997; Wang, 1998; Frisch, Large, & Pisoni, 2000; Treiman, Kessler, Knewasser, Tincoff, & Bowman, 2000; Bailey & Hahn, 2001; Hay, Pierrehumbert, & Beckman, 2003; Hammond, 2004; Myers & Tsay, 2004; Kirby & Yu, 2007), nonsense syllables of a language may exhibit a continuum of wellformedness shown in native speakers' wordlikeness judgments. For nonsense syllables, accident gaps are judged no worse than attested syllables and some systematic gaps are judged no worse than accidental gaps.

The main goal of the present experiment was not to investigate the gradience property of phonotactic grammars elicited from Taiwan Southern Min native speakers, but to examine the predictability of the three maximum entropy models of phonotactic learning. The comparison based on lexical status across the models in previous section could only account for certain categorical phonotactic patterns. In this section will be to report an experiment designed to collect wordlikeness judgments from Taiwan Southern Min native speakers. Both Body model and the Rhyme model were capable of distinguishing attested syllables from nonsense ones but they constructed the constraints assigned with different feature definitions and quantitative weights. The inherent difference between the two models will thus be used to contrast the wordlikeness judgments of native speakers in order to determine Taiwan Southern Min syllable structure.

Nonsense syllables were most crucial to the present experimental study. Not only did they avoid the confounding properties of real words like semantic representations, age of acquisition, imagineability in wordlikeness judgments, but did also the wordlikeness of nonsense syllables serve as a useful counterpart to contrast the violations scores and maxent values generated from the maximal entropy models of phonotactic learning.

### 4.1Methods

#### *4.1.1 Participants*

Seventeen undergraduates (7 males and 10 females) in National Chung Cheng University in Chiayi Taiwan were recruited in the experiment. All of them acquired Taiwan Southern Min as the first native language and were speaking Taiwan Southern Min frequently at home. No hearing or speech disorder was self-reported by the participants.

*4.1.2 Materials*

Because of the realistic consideration of experimentation, we could not use all the gigantic amount of testing data (a total of 4,607 items) in a single experimental task. We shrank down the size of the potential materials, yet still selective, balanced, and representative, following the method in Bailey & Hahn's (2001).

Bailey & Hahn's (2001) criterion was originally used to select the materials with the greatest variety of neighborhood density as well as phoneme transition probability of all the potential materials. All of the testing data were divided into three categories: attested syllables, near-misses, and isolates. Attested syllables were those reported in Tsai (2000). Near-misses were the nonsense syllables that differed from the nearest attested neighbors by exactly one phoneme. Isolates were also the nonsense syllables but differed from the nearest attested neighbors by exactly two phonemes. At the onset of selecting the materials, twenty-two isolates were chosen at random. For each isolate, we then identified all the neighboring near-misses, that is, those that differed from the isolates by one phoneme, as well as differed from the nearest attested syllables by one phoneme. The process resulted into 259 syllable types, including 22 isolates and 237 near-misses. Thanks to the *cba* package (Buchta & Hahsler, 2006) in R, we were able to automate the process of selecting the materials.

In addition to isolates and near-misses, 68 attested syllables were randomly chosen as fillers. The complete set of 307 syllables (plus 20 other syllables for practice) was prepared by a female Taiwan Southern Min native speaker. For all the stimuli, the speaker read them in a falling tone consistently. Since syllables with obstruent codas in Taiwan Southern Min were pronounced with shorter duration and falling pitch contour, the speaker customized the syllables with obstruent codas with “typical” entering tones but the other syllables types with normal falling tones. Fairly speaking, tonotactics (i.e., the constraints of co-occurrence between segments and tones) should be a potential issue and awaits future research. The auditory stimuli prepared by the speaker were simultaneously recorded and digitized in 22k Hz using Praat (Boersma & Weeninks, 2008).

*4.1.3 Procedure*

After the recruitment, participants were seated in a sound-proof booth to perform the task. They were then instructed to put on a pair of headphones and to make wordlikeness judgments to the auditory stimuli by pressing the labeled keys on the keyboard. The numbers on the labels (from 1 to 9 in a continuous scale) denoted the meanings from *very unlike Taiwan Southern Min* to *very like Taiwan Southern Min*, as participants were notified in advance.

Before the real trials began, twenty practice trials whose stimuli were not included in the real trials were used to familiarize participants with the judgments. Each trial initialized with a visual warning of 300 ms, followed by an auditory stimulus from the headphones and a visual cue on the monitor. Without time restriction, participants were able to judge wordlikeness of the auditory stimulus using their Taiwan Southern Min intuitions. The next trial proceeded once the judgment was made. The order of all the trials was randomized with the aid of E-prime (Schneider, Eschman, & Zuccolotto, 2002). The complete experimental procedure took nearly twenty-five minutes.

**4.2 Results**

Prior to analyses, judgment scores of the stimuli were averaged across participants. Judgment scores of real syllables were significantly higher than those of nonsense syllable (average: 5.95 vs. 4.49; $t(324) = -7.567$, $p < .01$ by item; $t(32) = -4.234$, $p < .01$ by participant). Only judgment scores of nonsense syllables would be relevant to the present study. As judgment scores of 259 nonsense syllables served as the predictor, violation scores, maxent values and probability served as the dependent measures in the Spearman correlation analyses. A significant correlation effect between judgment scores and other measures was obtained in the Body model (*rho* = -.15, $S$ = 3766604, $p < .01$), but not in the Rhyme model (*rho* = -.10, $S$ = 3608572, $p > .01$), the Flat model (*rho* < -.01, $S$ = 3270060, $p > .01$) and the Margin model (*rho* = -.09, $S$ = 3593767, $p > .01$)[2]. Table 2 illustrates correlations between judgment scores and violation scores across the four models. The statistics thus supported that the grammars from the Body model better predict Taiwan Southern Min native speakers' intuitions more than those form the other models.

[2] Maxent values and probability were algorithmically derived from violation scores. Three measures thus yielded identical correlation results.

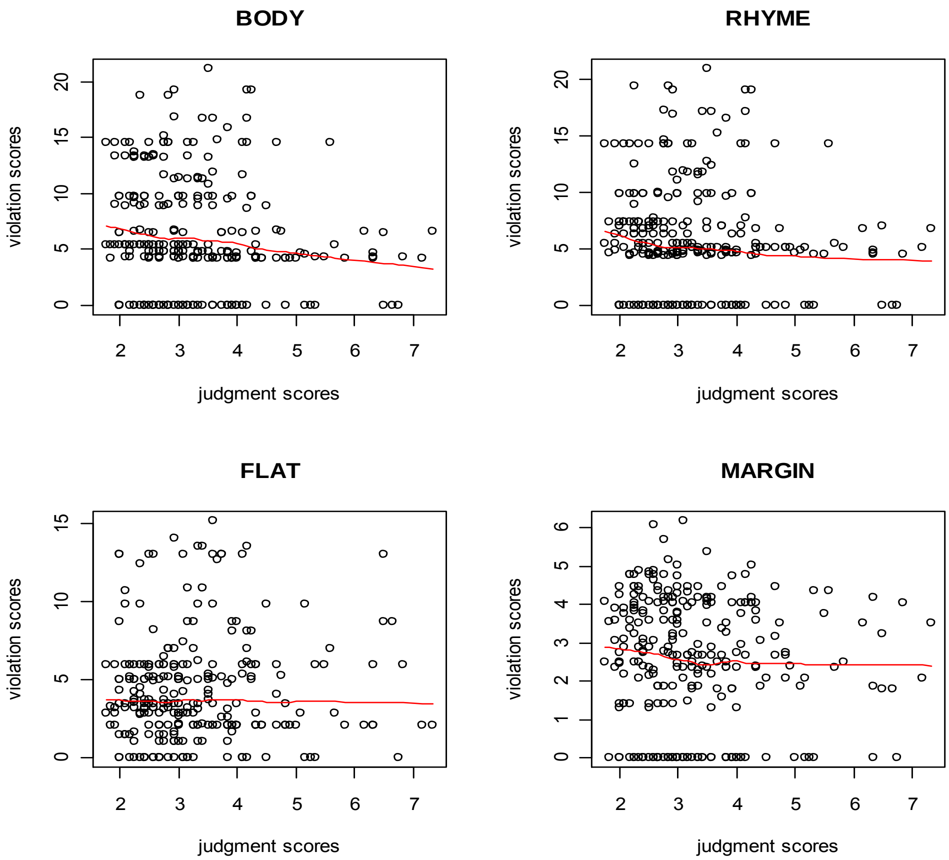


Figure 2. Correlations of judgment scores with violation scores across models

## 5. Conclusion

The issue of subsyllabic structure in Taiwan Southern Min had been unsettled since different sources of evidence came up with contradictory conclusions. The present study attempted to resolve the issue using a novel methodology. By applying maximum entropy models to assess the relative cohesiveness of segments across different subsyllabic domains, we discovered the Body model not only better predicted lexicality of attested and nonsense syllables but also confirmed the continuous wordlikeness judgments that reflected native speakers' phonotactic grammars.

The present results contradicted previous linguistic claims (Bao, 1990; Cheng & Cheng, 1977; Chung, 1996) espousing onset and rhyme as subsyllabic constituents in Taiwan Southern Min, but followed up Derwing and his colleague's (Derwing, 2007; Wang & Derwing, 1993) experimental finding that body-coda structure was processed in Taiwan Southern Min linguistic performance. Moreover, the lesson from which the Flat model and the Margin failed to simulate Taiwan Southern Min phonotactic behaviors was that hierarchical and sequential subsyllabic constituency were the essential linguistic mechanisms in Taiwan Southern Min.

This research line awaits future work on certain issues. First, maximum entropy models would be equivalently suitable for investigating the controversial status of the prevocalic or postvocalic glides. Second, tonotactics would be an issue inviting us to consider the interaction of segments and tones in dealing with syllable structure. Third, an extension of this study to other body-coda languages (e.g., Korean) would help reexamine the present conclusion.

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