Language-specific realizations of syllable structure and vowel-to-vowel coarticulation[a]

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This paper investigates the effects of syllable structure on vowel-to-vowel (V-to-V) coarticulation using Thai and English data. Languages differ in syllable complexity and their realizations of syllable structure. It was hypothesized that languages with complex syllable structure (English) would allow more V-to-V coarticulation than languages with simple syllable structure (Thai). Onset and coda consonants are different acoustically, articulatorily, typologically and perceptually. Onsets are generally 'stronger' and more stable than codas because they are longer, louder, and involve tighter articulatory constrictions. It was hypothesized that closed syllables (that end in a consonant C, i.e., VC#V) would allow more V-to-V coarticulation than open syllables (V#CV). /C_1V_1#C_2V_2/ and /$C_1V_1C_2$#V_2t/ sequences were recorded from six native speakers in Thai and six in English. First and second formant frequencies were measured. Results show that English allows more V-to-V coarticulation than Thai regardless of the intervocalic duration and vowel quality difference, but open and closed syllables only affect V-to-V coarticulation minimally. In addition to syllable structure, other possible factors contributing to the language difference in V-to-V coarticulation are discussed. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3466859]

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I. INTRODUCTION

Öhman's (1966) seminal work on vowel-to-vowel (V-to-V) coarticulation had a cross-linguistic perspective. He found that Russian showed the weakest V-to-V coarticulation compared with Swedish and American English. He proposed that the presence of secondary articulation (palatalization) in Russian reduced the tongue's freedom to coarticulate. However, Choi and Keating (1991) found that secondary articulation did not by itself block V-to-V coarticulation, but the languages they examined did exhibit different degrees of coarticulation. Besides Öhman (1966), Manuel (1987, 1990) suggested that vowel phoneme density affects how much V-to-V coarticulation is allowed in a language. Languages with a sparse vowel space would allow more V-to-V coarticulation than languages with a crowded vowel space. She found that Sotho (with seven vowels) exhibited less V-to-V coarticulation than Ndebele and Shona (both with five vowels). She argued that since V-to-V coarticulation affects vowel contrasts, extreme coarticulation would blur or even obliterate phonemic contrast, which would be detrimental to perception.

However, contrary to Manuel's hypothesis, Choi and Keating (1991) and Beddor *et al.* (2002) demonstrated that American English, a language with a crowded vowel space, allowed more V-to-V coarticulation than languages with a sparser vowel space. Han (2007) also found that phonemic vowel contrast did not contribute to the V-to-V coarticulatory patterns in Korean (eight vowels) and Japanese (five vowels). Mok (2006) argued that the reason why Manuel's hypothesis fails to predict the coarticulatory patterns in these languages is because it is based on three implicit assumptions which should be reconsidered: first, the notion of phoneme can adequately account for the phonological and phonetic vowel variations in a language; second, coarticulation is detrimental to perception; and third, languages fully utilize the available phonetic vowel space and vowels are maximally dispersed within this space. Mok showed that Cantonese (eight vowels) and Beijing Mandarin (five vowels) did not differ in degree of V-to-V coarticulation despite having different phonemic vowel density. Vowel quality in these two languages depends heavily on segmental context within the syllable, i.e., syllable structure. For example, the mid vowel phoneme in Mandarin can be realized as [ɤ] (in open syllable), [e] (before coda /j/) or [o] (before coda /w/). The five vowel phonemes in Mandarin involve many different allophonic vowel qualities. The complicated relationships between vowel phonemes and allophonic vowel qualities in the two languages indicate that phonemic analysis focusing on paradigmatic contrasts alone is inadequate to account for the V-to-V coarticulatory patterns in a language.

The results of the above studies suggest that another line of investigation not based on paradigmatic phonemic contrasts is needed to account for language differences in V-to-V coarticulation. Choi and Keating (1991), Beddor *et al.* (2002) and Han (2007) only suggested that some factors other than inventory size may be responsible for their results, without

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clearly discussing what those factors might be. Mok's investigation of the Cantonese and Mandarin vowel systems illustrate that vowel quality can be affected by syntagmatic relationships pertaining to syllable structure. Syllable structure complexity of a language may be a factor influencing language-specific V-to-V coarticulation because it differs greatly among languages. Many important typological differences are also related to syllable structure, e.g., phonotactics, tone and rhythm. V-to-V coarticulation essentially reflects syntagmatic relationships between vowels across a syllable boundary. The complexity of the boundary and the coordination of the boundary with the vowels may affect the coordination between vowels across the boundary. More vowel variation may result from the gestural coordination involved in articulating complex syllable structure. However, the effects of syllable structure on V-to-V coarticulation remain poorly understood. Most studies of V-to-V coarticulation only dealt with one syllable type, i.e., CV (e.g., Recasens, 1987; Manuel, 1990; Magen, 1997; Cho, 2004), and only very few studies investigated language differences in V-to-V coarticulation. It is thus necessary to extend the investigation of V-to-V coarticulation to different syllable types, and to compare languages in which syllable structure has different realizations.

There is independent evidence in the literature supporting the importance of syllable structure on language-specific V-to-V coarticulation. Shona, an African tone language with a very simple syllable structure (mainly CV), exhibits less V-to-V coarticulation than American English, despite having only five vowel phonemes (Beddor *et al.*, 2002). In addition, Ma *et al.* (2008) compared anticipatory coarticulation in VCV sequences in Mandarin and French using EMMA data. Mandarin, a tone language with only five vowel phonemes, also has a very simple syllable structure with no onset clusters and only /n/ and /ŋ/ as coda consonants. Resyllabification is not allowed. Syllables are well delineated with clear juncture (Xu, 1986). Ma *et al.* (2008) found that Mandarin allowed less anticipatory V-to-V coarticulation than French. They attributed the language difference in coarticulation to the different syllable structures in the two languages. These independent results show that syllable structure complexity and its realization can affect degree of V-to-V coarticulation and thus warrant more investigations comparing V-to-V coarticulation patterns in languages with different syllable structure complexity. In this study, Thai, an Asian tone language with a simple syllable structure, is compared with English, a language with a complex syllable structure, in order to explore the effects of language-specific realizations of syllable structure on V-to-V coarticulation.

Thai has a simple syllable structure: $(C_1)(C_2)V_1(V_2)(C_3)$, where elements in brackets are optional (Abramson, 1962). C_2 can be /l, r, w/ only. There are only eleven onset clusters, /pr, pl, p^hr, p^hl, tr, kr, kl, k^hr, k^hl, kw, k^hw/, but clusters with /l/ and /r/ are often pronounced in conversation as a single consonant omitting the liquid, e.g., /plaa/ 'fish' is usually pronounced as /paa/ (Iwasaki and Ingkaphirom, 2005). The two remaining onset clusters /kw, k^hw/ can be regarded as labialized velar consonants /k^w, k^{hw}/ (Henderson, 1949). Therefore, the onset is often realized as a single consonant. C_3 can be /p, t, k, m, n, ŋ/ and possibly an extra [ʔ]. All final stops in Thai are unreleased with no audible explosion and no aspiration. They cannot be linked to the following vowels partly because they are unreleased, and partly because Thai syllable boundaries are well defined by intersyllabic juncture. Final stops are accompanied by a simultaneous glottal stop, and syllables with an initial vowel are produced with a short unphonated state of the glottis forming a zero onset to the vowel (Harris, 2001).

Another important phonological feature that contributes to the discrete nature of the syllable in Thai is the use of lexical tones because the domain of lexical tone is the whole syllable (Abramson, 1962). No resyllabification of final consonants is allowed, as all parts of the syllable carry the lexical tone. In addition, Thai is an isolating language in which there is no inflectional morpheme to code grammatical information like tense or gender. The majority of morphemes are free morphemes which can stand alone as individual words. There is a tendency for native words to be monosyllabic, although there are also a fair number of polysyllabic words in modern Thai. This monomorphemic tendency presumably also contributes to the salience of the syllable in Thai phonology.

Unlike Thai, English has a complex syllable structure allowing a large number of consonants and consonant clusters in both onset and coda: (C)(C)(C)V(C)(C)(C)(C) (Giegerich, 1992). English onsets can have up to three segments, e.g., *spring* /spr/, and codas can have up to four segments, e.g., *sixths* /ks*θ*s/. Coda stops in English can be fully released (in careful or formal style), unreleased (in colloquial style) or released with different degrees of aspiration. In fluent speech, when coda consonants are followed by vowel-initial words, they often abut the following vowel, giving the impression that they are resyllabified to the following syllable. Such impression is enhanced by the elimination of important juncture cues like a glottal stop so the final consonant is released onto the following vowel, especially at fast rate (De Jong, 2001).

Locating syllable boundaries in English is not as straightforward as in Thai. English has irregular syllable structure and often unclear syllable boundaries (Cutler *et al.*, 1986). The syllabification of intervocalic consonants (particularly word-internal) in English has been a controversial issue. Intervocalic consonants before unstressed vowels in English have been analyzed as the coda of the first syllable (Hoard, 1971), the onset of the second syllable (Selkirk, 1982) or being ambisyllabic (Kahn, 1976). There exist many psycholinguistic and phonetic studies of this phenomenon. They showed that syllabification of intervocalic consonants depends on several factors, e.g., the maximum onset principle (put as many consonants as possible into the onset), the sonority contour of a syllable (the level of sonority rises from the onset to the nucleus, and falls from the nucleus to the coda), stress placement, vowel length, phonotactic legality of the sequences, phonetic identity of the consonants, morphological structure of the words, and even spelling (e.g., Davidsen-Nielsen, 1974; Fallows, 1981; Boucher, 1988; Treiman and Danis, 1988; Redford and Randall, 2005). These principles vary in importance and may result in different syllabification of the same sequence.

The above brief comparison shows that Thai has a much simpler syllable structure and more unambiguous syllable boundaries with discrete juncture than English. Syllabification of some intervocalic consonants in English is particularly debatable. Coda consonants in English are often linked to or released onto the following vowels, which is unacceptable in Thai. Given these differences in syllable structure and its realization in the two languages, it is not surprising to find numerous studies in the literature on English syllabification but hardly any on Thai.

A study of nasal coarticulation in Thai and English can provide extra insight into the nature of coarticulation in Thai. Beddor and Krakow (1999) investigated native English and native Thai listeners' perception of oral and nasalized vowels in different contexts. According to them, on average 80% of a vowel before a nasal consonant was nasalized in American English, but only around 45% or smaller in Thai. They found that Thai listeners were less likely than English listeners to attribute nasality of the vowel in NVN to the coarticulatory context, consistent with the lesser extent of coarticulatory nasalization exhibited by Thai speakers' production. The smaller extent of nasal coarticulation in Thai suggests that coarticulatory organization in Thai, and possibly languages phonologically similar to Thai, may be fundamentally different from that in English. Thai may not be as 'coarticulating' as English in many respects.

The above discussion suggests that there is an unexplored relationship between syllable structure complexity and coarticulatory patterns. If syllable structure complexity can affect language-specific V-to-V coarticulation, as several studies have shown, it is hypothesized that Thai, a tone language with simple syllable structure and unambiguous boundaries, will allow less V-to-V coarticulation than English, a language with complex syllable structure and variable realizations of its structure.

Besides syllable structure complexity, different parts of the syllable may also affect V-to-V coarticulation. There are many studies showing that syllable onset and coda are different acoustically, articulatorily, typologically and perceptually. Acoustically, many studies showed that onset consonants are longer and less variable than coda consonants (e.g., Haggard, 1973a, 1973b; Anderson and Port, 1994). They also have higher amplitude than coda consonants (Redford and Diehl, 1999). CV transitions are generally more informative about the stop consonant identity than VC transitions (Pickett *et al.*, 1995). Onset consonants exhibit a stronger cohesion with the vowels than coda consonants as defined by locus equations (Sussman *et al.*, 1997).

Many articulatory studies also show that syllable onset and coda consonants coordinate differently with the vowels, and onset gestures are more distinct and stable than those for coda consonants (e.g., Macchi, 1988; Sproat and Fujimura, 1993; Browman and Goldstein, 1995; Byrd, 1996; Krakow, 1999). Browman and Goldstein (1988) suggested that the center of onset consonant sequence tightly coordinates with the following vowel gestures, but it is the left edge of the coda consonant sequence that most tightly coordinates with the preceding vowel gestures. Syllable affiliation of the consonant clusters in VC_nV sequence can affect the gestural coordination between the consonants and the second vowel (Browman and Goldstein, 1995; Byrd, 1995). Krakow (1999) thoroughly reviewed the large literature on nasal, lateral and stop articulations and syllable structure in American English. She concluded that onset position is stronger than coda position because it is associated with tighter articulatory constrictions which involve greater articulatory effort and less variability. Her conclusion is echoed by Gick *et al.*'s (2006) and Kochetov's (2006) studies on different languages. There is a clear relationship between articulatory gestures and syllable position cross-linguistically.

The acoustic and articulatory differences between onset and coda consonants are echoed by the typological difference between CV and VC syllables in the world's languages. CV is the only and the most frequent syllable type that occurs in all languages. Some languages do not allow syllables without an onset (VC), e.g., Arabic, while structures with no coda (CV) are very common. Some languages prohibit codas altogether, e.g., Hawaiian. Many languages also allow many more consonants in the onset than in the coda positions (Greenberg, 1978; Maddieson, 1984). Coda consonants are more susceptible to loss than onset consonants in language change. Perceptually, onset consonants are more distinguishable than coda consonants in noise (Redford and Diehl, 1999). VC syllables are perceived as CV syllables under certain conditions, even though they can still be distinct acoustically (De Jong, 2001), which shows a tendency toward a CV organization in perception. Samuel (1989) found a robust selective adaptation effect specific to syllable positions. He suggested that the perceptual system was sensitive to syllable structure.

The above studies point to the conclusion that onsets and codas are different, and that the syllable is an important unit in both production and perception. The acoustic and articulatory studies show that, in general, coda consonants are more sensitive to change and coarticulatory effects than onset consonants. Since onsets are shown to be more stable and to have a tighter coordination with vowels, and codas to be weaker and more variable, it is conceivable that with the same segmental sequence (VCV), closed syllables (VC#V) would allow more V-to-V coarticulation than open syllables (V#CV) in general as codas are more transparent to coarticulation. However, the effects of syllable structure on V-to-V coarticulation are still unclear. Modarresi *et al.* (2004) examined how syllable affiliation affects V-to-V coarticulation. They compared nonsense sequences /CV#CV/ with /tVC#Vt/ in American English using several intervocalic consonants. They found that in general, closed syllables had slightly more overall coarticulation than open syllables. They explained the results by the different temporal intervals between open and closed syllables in their data, because they measured F2 frequencies at two temporal locations for carryover coarticulation: measuring at the stop burst for closed syllables but at the onset of second vowel for open syllables.

TABLE I. Experimental materials for open versus closed syllables in Thai (upper panel) and English (lower panel).

Intervocalic consonant	Open syllables		Closed syllables	
		Thai materials		
/p/	[ta¹.pa¹]	[ta¹.pi¹]	[hap².at²]	[hap².it⁴]
	'Eye, throw'	'Eye, year'	'Carry, might'	'Carry, a nickname'
	[ti¹.pa¹]	[ti¹.pi¹]	[hip².at²]	[hip².it⁴]
	'Hit, throw'	'Hit, year'	'Trunk, might'	'Trunk, a nickname'
/t/	[ta¹.ta¹]	[ta¹.ti¹]	[hat².at²]	[hat².it⁴]
	'Eye, eye'	'Eye, hit'	'Beach, might'	'Beach, a nickname'
	[ti¹.ta¹]	[ti¹.ti¹]	[sit³.at²]	[sit³.it⁴]
	'Hit, eye'	'Hit, hit'	'Pale, might'	'Pale, a nickname'
		English materials		
/p/	[tʰɑ.pʰɑ]	[tʰɑ.pʰi]	[hɑp.ɑt]	[hɑp.it]
	Tar Pa	Tar Pea	Harp Art	Harp Eat
	[tʰi.pʰɑ]	[tʰi.pʰi]	[hip.ɑt]	[hip.it]
	Tea Pa	Tea Pea	Heap Art	Heap Eat
/t/	[tʰɑ.tʰɑ]	[tʰɑ.tʰi]	[hɑt.ɑt]	[hɑt.it]
	Tar Tar	Tar Tea	Heart Art	Heart Eat
	[tʰi.tʰɑ]	[tʰi.tʰi]	[hit.ɑt]	[hit. it]
	Tea Tar	Tea Tea	Heat Art	Heat Eat

The superscripts show the tones in Thai: 1=mid tone (32), 2=low tone (21), 3=high tone (51), 4=rising tone (45), 5=falling tone (213).

Therefore, it is still unclear how different syllable structures can affect V-to-V coarticulation in fluent speech without the temporal confound.

In summary, two specific hypotheses regarding syllable structure and V-to-V coarticulation are tested in this study. The main hypothesis is whether English, with complex syllable structure and variable realizations of it structure, allows more V-to-V coarticulation than Thai. A secondary hypothesis is whether closed syllables (coda) allow more V-to-V coarticulation than open syllables (onset) in general. Since codas are realized differently in Thai and English, if ambisyllabicity can affect V-to-V coarticulation, then syllable structure should have different effects in Thai (with no ambisyllabic consonants) and English (as some intervocalic consonants may be ambisyllabic).

II. METHOD

A. Subjects

Six native speakers of Bangkok Thai (three male three female) and six native speakers of Southern British English (two male four female) were recorded. All speakers were graduate students at the University of Cambridge and had no history of speech or hearing impairment. They were in their twenties or earlier thirties. They were paid to participate in the experiments.

B. Materials

Monosyllabic real words in the two languages were used to form the target sequences, but the resultant combinations were nonsense sequences. Two vowels (/i a/ in Thai, /i ɑ/ in English) and two intervocalic consonants (/p t/) were used for the materials in the form of $/C_1V_1\#C_2V_2/$ (for open syllables) and $/C_1V_1C_2\#V_2t/$ (for closed syllables). The first consonants were /t/, /s/ or /h/ for forming real words in the language being tested. Table I shows the materials in both languages. The two consonants /p t/ are unaspirated as onset and unreleased as coda in Thai, but vice versa in English.

The target sequences were embedded in carrier phrases listed below to elicit contrastive stress. The target sequences were always placed in the second half of the carrier phrase. Both the first and the second words in the critical sequences can be the target syllable, depending on the direction of coarticulation: the first syllable is the target for investigating anticipatory coarticulation and the second syllable for investigating carryover coarticulation. For example, in 'Not a Tape Art, it's a Harp Art again', the sequence 'Harp Art' is the one used. Contrastive stress falls on 'Harp' which is not analyzed, while 'Art' is the one used for investigating carryover coarticulation. Anticipatory coarticulation on the syllable 'Harp' is elicited by using 'Not a Harp Work, it's a Harp Art again', with contrastive stress falling on 'Art'. The target syllables never bear contrastive stress to allow more V-to-V coarticulation. Fillers were also included in the materials. Five repetitions of the materials were intended but seven repetitions were collected from the speakers. Since most of the tokens were produced acceptably, the data were averaged over at least five and no more than seven tokens.

Carrier phrases:
Thai: /mai³ tɕai³ ______, pʰut³ ______ dai³ mai⁵/
(Gloss: 'Not _______, can you say ______?')
English: Not a ________, it's a _________ again

C. Procedures

All speakers were recorded in a sound-treated room at the phonetics laboratory at the University of Cambridge. Before the actual recording, they practiced by reading a randomized list of the materials several times. All speakers were

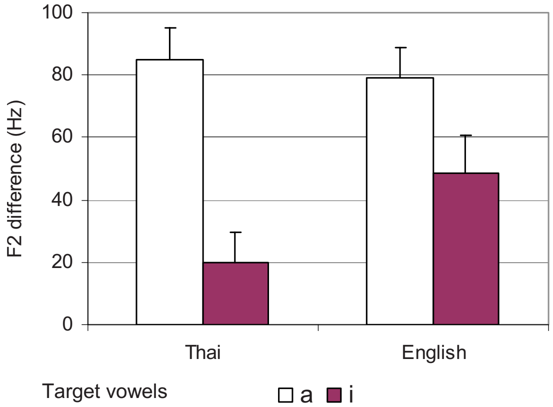


FIG. 1. (Color online) F2 difference in anticipatory coarticulation for Target /a/ (/ɑ/) and Target /i/ in Thai and English.

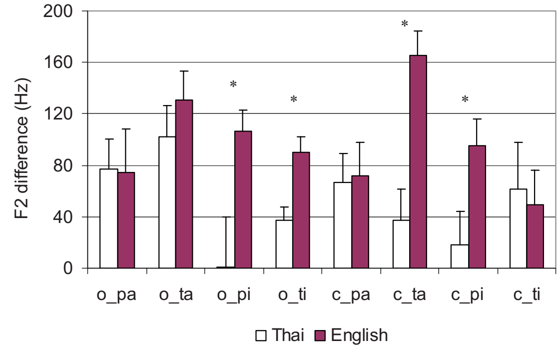


FIG. 2. (Color online) F2 difference in carryover coarticulation for Thai and English under different target vowels, stops and syllable forms. '*' = $p < 0.05$; 'o' = second vowel in /CV#CV/ (open syllable); 'c' = second vowel in /CVC#Vt/ (closed syllable); 'p' or 't' = intervocalic stops; 'a' or 'i' = target vowels (/ɑ/ in English).

instructed to read the materials with a normal speaking rate. The Thai materials were presented to the Thai speakers in Thai script. The speech was recorded using a MKH 40 P48 microphone and a Symetrix SX 202 amplifier as input to a DTC-60ES DAT recorder at 44.1 kHz sampling rate. The speech signal was later downsampled to 16 kHz using Xwaves.

D. Acoustic measurements

The acoustic waveforms were segmented by using the beginning and ending of periodic vocalic voicing to define onset and offset of the target vowels. Hanning windows of length 25 ms were placed so one started at the onset and the other ended at the offset. DFT and LPC spectra (18 pole, autocorrelation method) were computed for each windowed signal. Wideband spectrograms were also generated. The frequencies of the first two formants (F1 and F2) were measured from the LPC spectra, supplemented by wide band spectrograms and DFT spectra. Measurements of F1 and F2 were only made at the offset of the first syllables without contrastive stress (for anticipatory coarticulation) and onset of the second syllables without contrastive stress (for carryover coarticulation). Since the two intervocalic consonants /p t/ are aspirated both as onset and coda in English, in order to avoid the temporal confound in Modarresi *et al.* (2004), F1 and F2 frequencies of the second vowel were measured at the beginning of periodicity of the vowel for both open and closed syllables. The intervocalic duration between the two measuring points was also measured.

Differences in F1 and F2 frequencies (Hz) between symmetric (e.g., /hapa/) and asymmetric (e.g., /hapi/) pairs are used as the measure of coarticulation. F1 difference scores were calculated by subtracting the F1 of the target vowels with an /i/ context from the F1 of the target vowels with an /a/ context (/a/-/i/); F2 difference scores were calculated by subtracting the F2 of the target vowels with an /a/ context from the F2 of the target vowels with an /i/ context (/i/-/a/). This resulted in mostly positive difference scores which were used for statistical analysis. The F1 and F2 difference scores were submitted to four 4-way repeated measures ANOVAs (2 formants × 2 directions): Language (Thai vs English) × Target vowel (/i a/, in Thai, /i ɑ/ in English) × Stop (/p, t/) × Syllable Form (open, closed). When a significant interaction was found, post hoc two-tailed t-tests were conducted to compare simple main effects of the factors involved, as there are only two levels for each factor. Details of the statistical design for intervocalic duration are given in Section III C.

III. RESULTS

Two main questions are asked: whether English allows more V-to-V coarticulation than Thai, and whether closed syllables allow more V-to-V coarticulation than open syllables. The following section is organized according to these two questions.

A. Language

There is no significant main effect of Language or interaction with Language in F1 for either anticipatory and carryover coarticulation. Mean difference scores for the Language main effects in F1 are: Thai: 16 Hz vs English: 10 Hz (anticipatory); Thai: 7 Hz vs English: 7 Hz (carryover). In F2, the Language main effect shows that English (98 Hz) allows more carryover V-to-V coarticulation than Thai (50 Hz) in general [$F(1,10)=12.592$, $p=0.005$]. Anticipatory coarticulation shows the same pattern (Thai: 53 Hz vs English: 64 Hz), but it is not significant.

Language also interacts with other factors in F2. For anticipatory coarticulation, the Language × Target interaction is significant [$F(1,10)=8.462$, $p=0.016$] (see Fig. 1). Post hoc t-tests show that English allows more V-to-V coarticulation than Thai with Target /i/ [$t(10)=-1.835, p=0.048$]. Target /a/ allows more coarticulation than Target /i/ in both languages (Thai [$t(5)=7.565, p=0.001$]; English [$t(5)=3.771, p=0.013$]).

A high-order interaction of Language × Target × Stop × Syllable Form in F2 is significant in the carryover direction [$F(1,10)=14.150, p=0.004$] (Fig. 2). English generally allows more coarticulation than Thai. Post hoc independent two-tailed t-tests confirm that English allows significantly more V-to-V coarticulation than Thai under four conditions (marked with an '*' in Fig. 2): /V#pi/ (o_pi), /V#ti/ (o_ti), /Vt#a/ (c_ta) and /Vp#i/ (c_pi) (o_pi: [$t(10)=-2.490, p$

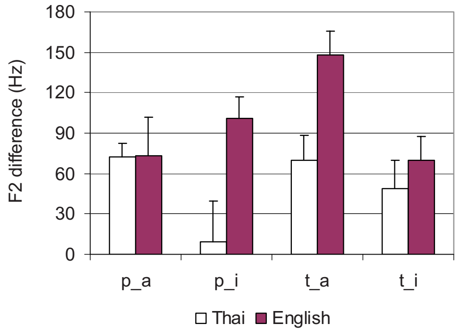


FIG. 3. (Color online) F2 difference in carryover coarticulation for Thai and English under different Target vowels and Stops. 'p' or 't' = intervocalic stops; 'a' or 'i' = target vowels (/ɑ/ in English)

$=0.032$], o_ti: [$t(10)=-3.414$, $p=0.007$], c_ta: [$t(10)=-4.129$, $p=0.002$], c_pi: [$t(10)=-2.315$, $p=0.043$]). Target /i/ shows greater Language differences than Target /a/. Thai never allows significantly more V-to-V coarticulation than English.

Two lower-order interactions in the carryover direction also show more V-to-V coarticulation in English than in Thai for F2. The Language × Target × Stop interaction is shown in Fig. 3. Post hoc t-tests confirm that the language difference is significant for Target /i/ with /p/ [$t(10)=-2.722$, $p=0.022$] and Target /a/ with /t/ [$t(10)=-3.072$, $p=0.012$]). Target /i/ with /t/ has the same pattern, but it is not significant. Figure 4 shows the Language × Target × Syllable Form interaction [$F(1,10)=17.675$, $p=0.002$]. Again, English allows more V-to-V coarticulation than Thai in all cases, and the difference is significant for Target /i/ in open syllables [$t(10)=-3.224$, $p=0.009$] and Target /a/ in closed syllables [$t(10)=-2.673$, $p=0.023$].

B. Onset versus Coda

There is no significant Syllable Form main effect in F1 or F2 for either anticipatory or carryover directions. The mean difference scores for the Syllable Form main effects are as follows (open syllables vs closed syllables): anticipatory F1: 9 Hz vs 18 Hz, F2: 56 Hz vs 60 Hz; carryover F1: 13 Hz vs 2 Hz, F2: 77 Hz vs 71 Hz. Syllable Form also does not interact with other factors for anticipatory coarticulation. For carryover coarticulation, the Language × Target × Stop × Syllable Form [$F(1,10)=14.150$, $p=0.004$] is shown in Fig. 2. However, post hoc pair-sampled two tailed t-tests conducted for Thai and English data separately reveal no significant difference for Syllable Form. The Language × Target × Syllable Form interaction [$F(1,10)=17.675$, $p=0.002$] is shown in Fig. 4. Post hoc t-tests show that closed syllables allow more V-to-V coarticulation than open syllables for Target /i/ in Thai (compare the white bars under 'V.Ci' and 'VC.i' in Fig. 4) [$t(5)=-2.690$, $p=0.043$], but the difference is small (only 21 Hz). In fact, Target /a/ shows the opposite pattern, but it is not significant. No significant Syllable Form difference is found in English.

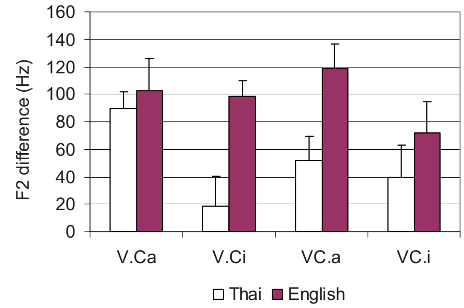


FIG. 4. (Color online) F2 difference in carryover coarticulation of the two Target vowels in two syllable structures in Thai and English.

C. Intervocalic duration

The data show that English allows more V-to-V coarticulation than Thai. Since the intervocalic consonants are realized differently in the two languages, it is necessary to consider, besides the difference in syllable structure, whether other factors have contributed to this pattern. A possible confounding factor is the intervocalic duration, defined above as the duration between the offset of periodicity of the first vowel and the onset of periodicity of the second vowel. Intervocalic duration, however, is not a completely separate factor because it is a concomitant feature of how syllable structure is realized. The intervocalic durations were submitted to two separate 5-way repeated measures ANOVAs with the factors Target vowel (/a i/) × Stop (/p t/) × Syllable Form (open, closed) × Context vowel (/a i/) × Language (Thai, English), one for anticipatory direction and one for carryover direction. Again, post hoc two tailed t-tests were conducted for comparing simple main effects when a significant interaction was found.

1. Anticipatory context

There is no significant main effect for Language or Syllable Form: Language (Thai: 138 ms vs English: 114 ms); Syllable Form (open: 132 ms vs closed: 121 ms). The Language × Stop interaction is significant [$F(1,10)=5.279$, $p=0.044$]. Post hoc two-tailed t-tests show that Thai has a longer intervocalic duration than English when the consonant is /p/ (Thai: 142 ms vs English: 115 ms) [$t(7.276)=2.361$, $p=0.049$], but the difference is not significant when the consonant is /t/ (Thai: 135 ms vs English: 114 ms) [$t(6.597)=1.608$, $p=0.139$]. The Syllable Form × Language interaction is also significant [$F(1,10)=12.157$, $p=0.006$]. The intervocalic duration is also longer in Thai than in English for closed syllables (Thai: 145 ms vs English: 98 ms) [$t(6.091)=2.577$, $p=0.041$], but not for open syllables (Thai: 132 ms vs English: 131 ms) [$t(10)=0.146$, $p=0.887$]. However, Section III A shows that English allows more anticipatory V-to-V coarticulation than Thai when the Target vowel is /i/, irrespective of the intervocalic consonants and syllable structure. Unlike the intervocalic duration, there is no Language difference in V-to-V coarticulation in the Language × Stop and Language × Syllable Form interactions. Therefore, the longer intervocalic duration in Thai found in these two interactions cannot explain the Language difference in anticipatory V-to-V coarticulation.

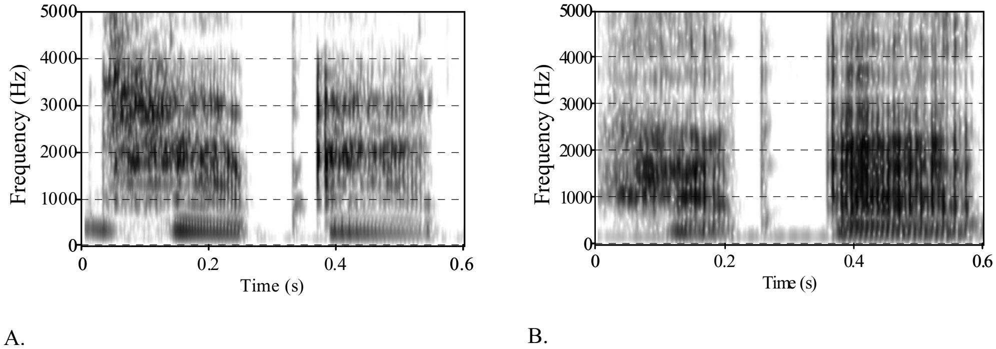


FIG. 5. Closed syllables with a weak burst produced by two Thai speakers. A) /hap#at/ produced by a female Thai speaker. B) /hat#at/ produced by a male Thai speaker.

Phonologically, syllable-final stops are not released in Thai, but in practice, sometimes a weak burst can be detected in speech. Figure 5 shows two such cases. Without such a burst it is difficult to determine the exact duration of the final stop closure. The short silent intervals between the stop release and the onset of the second vowel are likely to be glottal stops. Cases like these suggest that final unreleased stops are often accompanied by a glottal stop (Harris, 2001). This also shows the discrete nature of the syllable in Thai, because the burst with no strong aspiration, even if it is present, cannot abut the following vowel. Cases like the utterances shown in Fig. 5 are possible in English, but much less common in fluent speech. If that is the case, then it may not be surprising why the intervocalic duration in closed syllables can be longer in Thai than in English.

Another comparison in the Language × Syllable Form interaction is that, in English, the intervocalic duration of open syllables is longer than that of closed syllables (131 ms vs 98 ms) [$t(5)=10.983, p<0.001$]. Figure 6 shows two sequences with an intervocalic /p/ produced by the same female English speaker, one as onset and one as coda. The closure duration for /p/ is quite similar in the two forms: 56 ms as onset and 65 ms as coda. The more obvious difference is the aspiration duration. It is 69 ms for onset /p/ while it is only 34 ms for coda /p/. The durational difference seen here suggests that onset and coda stops in English, although they can become similar under some circumstances, are nevertheless still distinct in terms of duration, at least at a normal speaking rate.

2. Carryover context

There is no significant main effect for Language or Syllable Form: Language (Thai: 123 ms vs English: 118 ms); Syllable Form (open: 120 ms vs closed: 120 ms). The Language × Stop × Context interaction [$F(1,10),=9.523$, $p=0.012$] and two lower-order interactions Language × Stop [$F(1,10)=13.515$, $p=0.004$] and Language × Context [$F(1,10)=5.516$, $p=0.041$] are significant. Table II shows the mean intervocalic duration and standard deviations for the Language × Stop × Context interaction. However, post hoc independent two-tailed t-tests show that there is no significant Language difference in all these interactions.

A language difference is found in the Language × Syllable Form × Target interaction [($F(1,10)=11.903$, $p=0.006$] (see Fig. 7). Contrary to the duration patterns in the anticipatory condition, English instead has a longer intervocalic duration than Thai for Target /a/ (/ɑ/ in English) in open syllables ('V.Ca') [$t(10)=-2.246$, $p=0.048$]. The longer intervocalic duration of 'V.Ca' in English than in Thai corresponds to the 'V.Ca' in Fig. 4, which shows no significant difference in V-to-V coarticulation between Thai and English. What is more important is that the intervocalic duration in 'V.Ci' and 'VC.a' in Fig. 7 is not significantly different for Thai and English, but there is more V-to-V coarticulation in English than Thai under the same conditions (see 'V.Ci' and 'VC.a' in Fig. 4). These results clearly show that the difference of V-to-V coarticulation observed in Thai and English is not confounded by the intervocalic duration.

3. Summary

The intervocalic duration is longer in Thai than in English in the anticipatory condition (when the consonant is /p/ or in closed syllables), but the two languages do not differ in V-to-V coarticulation under those conditions. English allows

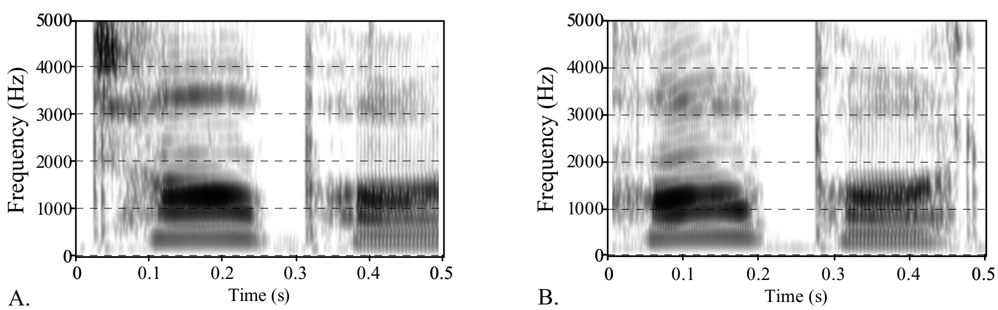


FIG. 6. Open and closed syllables with intervocalic /p/ produced by a female English speaker. A) /tɑ#pɑ/. B) /hɑp#ɑt/.

TABLE II. Mean intervocalic duration (ms) and standard deviations for the Language × Stop × Context interaction.

	Thai		English	
Context	/p/	/t/	/p/	/t/
/a/	118 (18.9)	117 (19)	116 (13.6)	114 (13.9)
/i/	130 (20.6)	125 (21.9)	115 (10.6)	124 (13.4)

more anticipatory V-to-V coarticulation than Thai when the target vowel is /i/, but with no difference in their intervocalic duration. English consistently allows more carryover V-to-V coarticulation than Thai, while there is no consistent intervocalic durational difference between the two languages in the carryover condition. English allows more V-to-V coarticulation than Thai even when there is no significant difference between their intervocalic duration. Thus, we can safely conclude that the different V-to-V coarticulatory patterns found in Thai and English are not due to the difference in intervocalic duration.

D. Vowel quality

In addition to intervocalic duration, differences in vowel quality between the two languages may contribute to the different degrees of V-to-V coarticulation reported above. In order to explore this possibility, F1 and F2 frequency data (not the difference scores) of the target vowels (/i a/ in Thai, /i ɑ/ in English) collapsed across the two intervocalic consonants and the two context vowels were compared using independent samples t-tests. The mean F1 and F2 data for each language can be found in Fig. 8. Both F1 and F2 of /i/ are not significantly different between the two languages. In the anticipatory condition [Fig. 8(A)], F2 of English /ɑ/ is significantly lower than Thai /a/ [$t(10)=3.3385$, $p=0.007$]. In the carryover condition [Fig. 8(B)], both F1 and F2 of English /ɑ/ are significantly lower than Thai /a/ (F1: [$t(10)=2.301$, $p=0.044$]; F2: [$t(10)=2.485$, $p=0.032$]). Nevertheless, the difference in vowel quality (/a/ vs /ɑ/) cannot satisfactorily account for the V-to-V coarticulatory patterns in the two languages. First of all, there is no Language difference in V-to-V coarticulation in F1 despite F1 of English /ɑ/ being lower than Thai /a/ in carryover condition. Second, more Language differences in V-to-V coarticulation are found with the target vowel /i/, but the two languages do not differ in either F1 or F2 of /i/. Therefore, the expected difference in F2 between /a/ and /ɑ/ should not be a major factor contributing to the different coarticulatory patterns of the two languages.

IV. DISCUSSION

The results show that English allows significantly more anticipatory and carryover V-to-V coarticulation than Thai in F2, and the language difference is greater in the carryover direction. Carryover coarticulation exceeds anticipatory coarticulation in both Thai (Mok, 2006) and English (Fowler, 1981; Huffman, 1986; Beddor *et al.*, 2002). This may explain why the language difference is more evident in carryover than anticipatory coarticulation. No language difference is

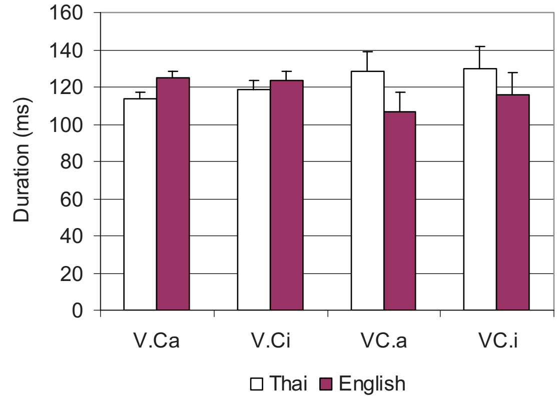
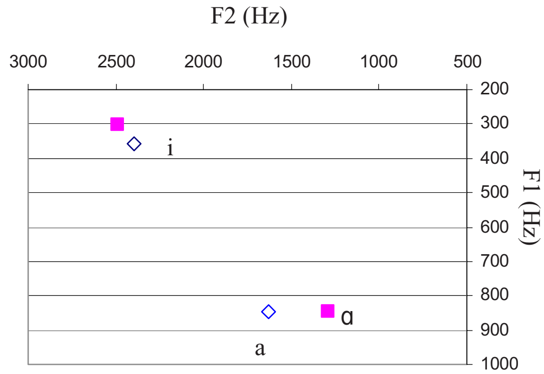


FIG. 7. (Color online) Intervocalic duration in Thai and English for the two target vowels in open and closed syllables.

found in F1. It may be because F2 is more sensitive to coarticulatory variation, as shown in many previous studies in coarticulation. It may also be because the two languages do not differ much in jaw coarticulation (Recasens and Pallarès, 2000). In any case, Thai never allows more V-to-V coarticulation than English. The language difference in coarticulation is not influenced by the intervocalic duration or the vowel quality difference between the two languages. Closed syllables allow slightly more V-to-V coarticulation than open syllables for Target /i/ in Thai, but the effect is quite small. There is no consistent pattern of syllable structure effect on V-to-V coarticulation in English.

The Thai and English comparison supports the notion that syllable structure of a language and its realizations affect degree of V-to-V coarticulation. Languages with simple syllable structure and unambiguous boundary may allow less V-to-V coarticulation than languages with complex syllable structure and variable realizations of its structure. It is possible that when a language has a complex syllable structure, the functional load on the vowel is smaller than a language with simple syllable structure because more cues are carried by the consonants, so more vowel variation is allowed. By the same token, since there are fewer components in simple syllable structure, it is conceivable that vowel quality may allow less variation. Also, a complex structure places more demand on the coordination of articulatory gestures than a simple structure, which in turn can increase the degree of coarticulation. This idea seems worth pursuing with more languages that differ in syllable structure complexity and realizations.

Syllable structures of a language relate to other typological differences. For example, languages exhibit different rhythmic patterns. Stress-timed languages often have more complex syllable structure and also allow more vowel reduction and variation than syllable-timed languages (Roach, 1982; Dauer, 1983). Smith (1995) found different V-to-V coordination patterns for Italian (syllable-timed) and Japanese (mora-timed). The influence of speech rhythm on V-to-V coarticulation seems worth investigating, as more reliable measures have been developed in recent years for categorizing languages into rhythmic groups (Ramus *et al.*, 1999; Grabe and Low, 2002). We can compare typical stress-timed languages (e.g., English) with typical syllable-timed



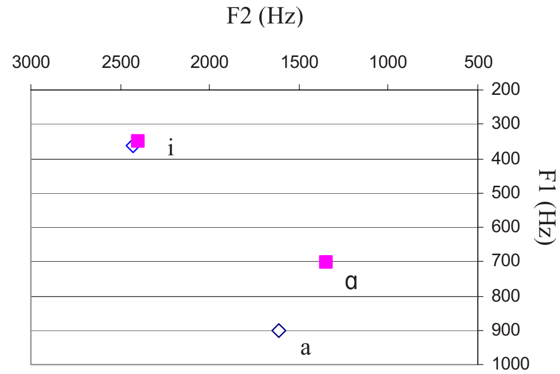


FIG. 8. (Color online) Formant frequencies of the two target vowels in Thai (empty diamond) and English (filled squares) in A) anticipatory condition and B) carryover condition.

languages (e.g., Spanish). It is possible that a stress-timed language, with complex syllable structure and frequent vowel reduction, will allow more V-to-V coarticulation than a syllable-timed language.

Although the idea of syllable structure complexity is promising, the materials used in the experiment have simple structure (CV and CVC) because more complex structure is not allowed in Thai. It is possible that the Thai and English difference in V-to-V coarticulation may be caused by other differences between the two languages. For example, Thai, together with Shona (Beddor *et al.*, 2002) and Mandarin (Ma *et al.*, 2008) mentioned in the Introduction, have simple syllable structure and demonstrate little V-to-V coarticulation. They are also tone languages. The use of lexical tones is a salient feature. Since the domain of lexical tones is the whole syllable, it probably contributes to the discreteness of the syllable in these languages. Impressionistically, Thai and Mandarin speech sounds more staccato than speech in other languages that also have simple syllable structure but with no lexical tones, e.g., French or Spanish. The use of lexical tone, however, is not totally independent of syllable structure, since there exists a significant negative correlation between the complexity of syllable structure and the complexity of tone systems. Languages with complex syllable structure are less likely to be tonal, and vice versa (Maddieson, 2007). Such a correlation highlights the role of syllable structure complexity in shaping the characteristics of different languages. This further strengthens the hypothesis that syllable structure complexity can affect language differences, including coarticulation. Nevertheless, it is impossible to separate the sole effect of syllable structure in the present data. In order to further investigate this, it is necessary to compare languages that differ in syllable structure but are more similar in other aspects. Comparing languages like Spanish and French with languages like English and German would be a possible choice.

Two more factors need to be considered before we can attribute the language difference in V-to-V coarticulation found in this study to syllable structure complexity. The first one is vowel quality. The Results section shows that there is no language difference in V-to-V coarticulation where there is a difference in vowel quality (F1 of Thai /a/ and English /ɑ/ in the carryover condition), while English /i/ allows significantly more V-to-V coarticulation than Thai /i/ in F2 with no language difference in vowel quality. Therefore, vowel quality difference cannot explain the language difference in V-to-V coarticulation. Another factor is speech rate. Although it is intuitively appealing to hypothesize that a faster speaking rate could induce more V-to-V coarticulation, there are surprisingly few studies on this topic. Hertrich and Ackermann (1995) compared normal, slow and slower speaking rates in German, and found that anticipatory V-to-V coarticulation did not depend on speech rate, but carryover coarticulation did reduce at a slower speech rate. Mok (2006) compared normal and fast speech rates in Cantonese and Mandarin. She found that V-to-V coarticulation in the two languages was not affected by speech rate when the rate difference was about 20%. In fact, many studies demonstrated that vowel undershoot (and hence more coarticulation) only occurs with a large durational difference (around 40%–60%), probably when the speakers are close to their maximum speed of articulation (e.g., Gay, 1978; Fourakis, 1991; Van Son and Pols, 1992; Moon and Lindblom, 1994). In the present study, English allows more V-to-V coarticulation than Thai in both anticipatory and carryover directions with the same speech rate. Also, both groups of subjects produced the utterances with a normal speech rate. Even if there was a difference between the two languages, the magnitude is unlikely to be around 40%–60%. It is reasonable to assume that speech rate does not affect the language difference in V-to-V coarticulation. Therefore, we can conclude that the language difference has something to do with their syllable structure, or at least characteristics related to their syllable structure. The results suggest that we are on the right track, although more studies are needed to confirm and refine our conclusion.

Finally, the present results only give minimal support to the second hypothesis that closed syllables would allow more V-to-V coarticulation than open syllables. Closed syllables allow slightly more V-to-V coarticulation than open syllables for Target /i/ in Thai, but there is no consistent pattern of syllable structure effect in English. One possibility is that ambisyllabicity may have affected the English results. However, there is no consensus on the existence or definition of ambisyllabicity (e.g., see review in Fallows, 1981; Treiman and Danis, 1988; Trammell, 1992). The durational data in Section III C 1 also show that there is a significant difference between the duration of the intervocalic consonant as an onset and as a coda, with onset having a longer duration than coda. This corresponds very well with the findings of canonical onset and coda duration discussed in the Introduction. This shows that the speakers were treating the intervocalic consonant differently as onset and as coda, i.e., they are not ambisyllabic. The minimal effect in Thai with unambiguous syllable boundaries also casts doubt on the ambisyllabic explanation for the English data.

Given the vast literature on the various differences between onset and coda, it is still worthwhile to explore further whether and how onset and coda can affect V-to-V coarticulation, despite the indecisive results here. If further study still finds no difference between onset and coda on V-to-V coarticulation, the results would be compatible with Öhman's (1966) original model of V-to-V coarticulation. He proposed that vowels form a continuous diphthongal movement with consonants superimposed onto this continuous carrier. He suggested that the tongue can be regarded as separate and relatively independent articulatory systems sharing some muscles. Although Öhman's study was about consonant types (palatalized vs plain) but not syllable structure, an extension of his hierarchical model predicts that onset and coda consonants would not affect V-to-V coarticulation differently because consonants and vowels are not regarded as a linear sequence of successive gestures. The separate motor control for consonants and vowels suggests that they do not interact with each other depending on syllable structure. Rather, the superimposed consonants only distort the dominant continuous vowel trajectory momentarily, so whether the consonant is an onset or coda should not make any difference.

There are many studies on V-to-V coarticulation, but only a few of them compared language differences, and they mainly focus on vowel inventory density. Previous studies have shown that inventory density cannot satisfactorily account for language differences. This study investigates the issue from a new perspective. It offers a more comprehensive account of the language differences in V-to-V coarticulation because syllable structure is closely related to other typological differences between languages. This approach enables us to consider various aspects of language differences as a unified whole. There are still many unknown factors in why languages differ in V-to-V coarticulation, and the effects of syllable structure complexity need further investigation. The results of this study point out some new directions that are worth pursuing.

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