Co-articulation between consonant and vowel in Taiwanese

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1. Introduction. This study investigates the co-articulation between the consonant and vowel in Taiwanese bisyllabic words that contain the sequences of [V**.**CV] and [VC**.**V], where the intervocalic C may be the onset of the following syllable, or the coda of the preceding syllable. It determines (*i*) the degree of consonant-vowel and vowel-consonant co-articulation during the four types of sequences, [**.**CV], [VC**.**], [C**.**V], and [V**.**C], by examining the changes in tongue position with respect to the different consonant and vowel types in the sequences and (*ii*) the difference in the degree of co-articulation between the tautosyllabic sequences, [**.**CV] and [VC**.**], and the heterosyllabic ones, [C**.**V] and [V**.**C].

2. Method. Speech samples of 46 meaningful Taiwanese bisyllabic words were elicited from three male adult speakers in their early 20s who were born into and grew up in Taiwanese-speaking families in Taiwan. The test bisyllabic words contain the [V**.**CV] and [VC**.**V] sequences, where C = [p t k] and V = [i a u]. Ten repetitions of each test bisyllabic word were digitally recorded of the speakers. The NDI Wave was used to collect synchronized audio signals and articulatory actions at three different points on the tongue (henceforth, tongue points), which are tongue blade, anterodorsum, and posterodorsum. To determine the degree of consonant-vowel and vowel-consonant co-articulation, Euclidean distance (henceforth, ED) was computed (as performed in the other co-articulatory studies, e.g., [1]) at the three tongue points (*i*) between the positions at the vowel onset and vowel mid-point during the [**.**CV] and [C**.**V] sequences and (*ii*) between the positions at the vowel mid-point and vowel offset during the [VC**.**] and [V**.**C] sequences. A large or small ED is taken to indicate a corresponding large or small degree of co-articulation between the neighboring segments.

3. Results. The average ED data across all the three tongue points for the four types of test sequences, [**.**CV], [VC**.**], [C**.**V], and [V**.**C], for three male Taiwanese speakers (M1, M2, M3) are presented in Table 1. A summary result is given as follows.

3.1. Tautosyllabic [.CV] sequences. (*i*) For [**.**pV], the ED is small (0.81-3.62 mm), regardless of the vowel type. The small ED suggests a minimal carryover effect of [p] on the articulation of the following vowel. (*ii*) For [**.**tV], there is an increase in the ED relative to the ED for [**.**pV]. The increase in ED is significant when V = [a] (10.42-12.88 mm) or [u] (9.67-13.18 mm), suggesting the antagonism between the articulatory gestures associated with the alveolar [t] and the following low vowel [a] or high back vowel [u]. (*iii*) For [**.**kV], the ED is small when V = [i] (0.77-1.20 mm) and large when V = [a] (6.05-11.26 mm), relative to the ED when V = [u] (2.16-5.97 mm). The data (*a*) indicate that [k] is palatalized before [i] and (*b*) suggest that there is a large carryover co-articulation effect of [k] on [a]. (*iv*) Overall, the orders of decreasing degree of co-articulation, as indicated in the average ED across the three tongue points for the [**.**CV] sequences for each of the three speakers (M1/M2/M3), are (*a*) when C = [t] (9.21/9.27/8.22 mm) > when C = [k] (3.32/6.14/4.41 mm) > when C = [p] (2.11/1.68/2.31 mm), and (*b*) when V = [a] (7.34/8.96/7.55 mm) > V = [u] (5.94/6.34/4.61 mm) > V = [i] (1.36/1.78/2.77 mm).

3.2. Tautosyllabic [VC.] sequences. (*i*) Compared with the ED for [**.**pV] (0.81-3.62 mm), there is an increase in the ED for [Vp**.**] (2.45-6.53 mm), suggesting the anticipatory co-articulation effect of [p] on the preceding vowel is larger than the carryover co-articulation effect of [p] on the following vowel. (*ii*) The ED is much large for [Vt**.**] (8.34-14.48 mm) and [Vk**.**] (6.21-9.57 mm), except for a single case of [it**.**] (2.22-4.11 mm), further suggesting a large degree of vowel-consonant co-articulation during the [VC**.**] sequences. The data appear to support the phonological structuring of the syllable, where the syllable-final consonant (the coda) and the preceding vowel (the syllable nucleus) are the constituent units of the rhyme. (*iii*) Overall, the

orders of decreasing degree of co-articulation, as indicated in the average ED across the three tongue points for the [VC**.**] sequences for each of the three speakers (M1/M2/M3), are (*a*) when C = [t] (10.04/8.98/7.53 mm) or [k] (7.29/9.12/7.67 mm) > when C = [p] (5.25/3.86/2.74 mm), and (*b*) when V = [u] (13.43/11.21/10.15 mm) or [a] (9.53/8.08/6.64 mm) > when V = [i] (4.40/5.82/4.45 mm). Note that in Taiwanese the vowel [u] in the [VC**.**] sequences can only be followed by [t], but not [p] or [k].

3.3. Heterosyllabic [C.V] sequences. (*i*) Regardless of the consonant or vowel type the ED for the [C**.**V] sequences is small (not exceeding 3.60 mm) for all the three speakers. (*ii*) Compared with the ED for the [**.**CV] sequences, the ED is much smaller for [t**.**V] (0.50-2.89 mm) and [k**.**V] (0.60-2.72 mm) than for [**.**tV] (2.10-13.18 mm) and [**.**kV] (0.77-11.26 mm), due to the absence of alveolar or velar articulation at the onset of the following vowel in [t**.**V] and [k**.**V]. (*iii*) Note that in the [C**.**V] sequences, the burst release of the oral closure of the preceding coda plosive is followed by a short pause before V in the [C**.**V] sequences. The data suggest re-syllabification does not take place across the syllable boundary in the [C**.**V] sequences, resulting in a small degree of between-segment co-articulation in the [C**.**V] sequences.

3.4. Heterosyllabic [V.C] sequences. (*i*) Differing from the [C**.**V] sequences, the cross syllable boundary co-articulation effect occurs in the [V**.**C] sequences, as evidenced by an increase in the ED for the [V**.**C] sequences (2.05-23.55 mm) relative to the ED for the [C**.**V] sequences (0.50-3.59 mm). (*ii*) The ED is particularly large for [a**.**C] (5.94-23.40 mm), due likely to the articulatory antagonism between the oral closure for the following plosive consonant and the mouth opening during the preceding vowel [a]. (*iii*) The ED is also large for [u**.**C] when C = [t] (16.00-23.55 mm) or [k] (5.99-9.08 mm). (*iv*) The ED is significantly larger for the [V**.**C] sequences, [a**.**p], [a**.**t], [a**.**k], [u**.**t] and [i**.**t], than for the [VC**.**] sequences, [ap**.**], [at**.**], [ak**.**], [ut**.**] and [it**.**]. The data suggest that (*a*) C in the [V**.**C] sequences is ambisyllabic, i.e., functioning simultaneously as the coda of the preceding syllable and the onset of the following syllable, and (*b*) the syllable boundary does not block the vowel-consonant co-articulation, in contrast to the consonant-vowel co-articulation in the [C**.**V] sequences. (*v*) Overall, the orders of decreasing degree of co-articulation, as indicated in the average ED across the three tongue points for the [V**.**C] sequences for each of the three speakers (M1/M2/M3), are (*a*) when C = [t] (17.14/16.70/13.71 mm) > when C = [k] (9.67/10.52/10.23 mm) > when C = [p] (6.70/3.72/3.28 mm), and (*b*) when V = [a] (18.04/16.23/13.00 mm) > V = [u] (11.79/11.10/7.94 mm) > V = [i] (3.68/3.62/6.28 mm).

[.CV]	M1	M2	M3	**[VC.]**	M1	M2	M3	**[C.V]**	M1	M2	M3	**[V.C]**	M1	M2	M3
[**.**pi]	1.21	1.47	2.60	[ip**.**]	3.97	4.29	3.03	[p**.**i]	0.69	1.07	1.93	[i**.**p]	3.49	2.85	2.05
[**.**pa]	3.62	2.74	2.31	[ap**.**]	6.53	3.42	2.45	[p**.**a]	2.79	3.59	1.12	[a**.**p]	12.23	6.61	5.94
[**.**pu]	1.51	0.81	2.01	*	*	*	*	[p**.**u]	0.68	1.88	0.71	[u**.**p]	4.37	1.70	1.85
[**.**ti]	2.10	2.67	4.58	[it**.**]	2.22	3.59	4.11	[t**.**i]	1.11	0.71	1.55	[i**.**t]	4.82	4.18	5.93
[**.**ta]	12.34	12.88	10.42	[at**.**]	14.48	12.13	8.34	[t**.**a]	0.87	2.68	0.69	[a**.**t]	23.04	23.40	19.20
[**.**tu]	13.18	12.25	9.67	[ut**.**]	13.43	11.21	10.15	[t**.**u]	2.89	2.88	0.50	[u**.**t]	23.55	22.53	16.00
[**.**ki]	0.77	1.20	1.14	[ik**.**]	7.00	9.57	6.21	[k**.**i]	0.60	0.66	1.21	[i**.**k]	2.72	3.82	10.85
[**.**ka]	6.05	11.26	9.93	[ak**.**]	7.59	8.68	9.13	[k**.**a]	2.72	2.35	1.05	[a**.**k]	18.85	18.66	13.86
[**.**ku]	3.14	5.97	2.16	*	*	*	*	[k**.**u]	1.70	1.32	1.15	[u**.**k]	7.44	9.08	5.99

Table 1: Average ED (in mm) across the three tongue points (*i*) between the vowel onset and vowel mid-point for the [**.**CV] and [C**.**V] sequences and (*ii*) between the vowel mid-point and vowel offset for the [VC**.**] and [V**.**C] sequences for three male Taiwanese speakers (M1, M2, M3); * = non-occurring.

4. Conclusion. The articulatory data on the ED at three tongue points during the sequences of [**.**CV], [**.**VC], [C**.**V], and [V**.**C] in Taiwanese bisyllabic words reveal that the degree of co-articulation varies with the consonant type, vowel type, segment position in the syllable, and presence/absence of the syllable boundary in the consonant-vowel or vowel-consonant sequences.

5. Reference. [1] Recasens, D., Espinosa A. (2009). An articulatory investigation of lingual coarticulatory resistance and aggressiveness for consonants and vowels in Catalan. *JASA* 125(4), 2288-2298.

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