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An Articulatory Study on Consonant Cluster Simplification in L1 Korean and L2 English*

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ABSTRACT

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The present study aims to investigate to what extent and how consonant cluster simplification occurs in L1 Korean and L2 English coda consonant clusters. To this end, four types of coda clusters, including /lp/ and /lk/ were examined with Korean speakers in two ultrasound imaging experiments. Experiment 1 showed that the variability patterns in the production of coda clusters emerged, including three types of variants for /lk/ (e.g., "partial velar," "full velar," and "zero velar" and two types of variants for /lp/ sequences (e.g., /l/-deletion and /p/-deletion). Their realization patterns varied depending on cluster type and individual speakers. "Partial velar" variants, particularly, are indicative of gestural hiding and gestural overlap inducing articulated but inaudible consonant clusters. Experiment 2 demonstrated that no-deletion variants were more dominant than deletion forms, along with hyperarticulation variants for English CC clusters (43% vs. 37% vs 20%). These findings provide support for gradient realizations of /CCC/ clusters in L2 English such as /ptk, ktp, lpt, lkt/, depending on cluster type and L2 speakers. Compared to the production of L1 Korean CCC, "no-deletion" variants were elicited more frequently, showing the exemplars of gestural hiding and gestural overlap.

KEYWORDS
consonant cluster simplification, Korean, English, deletion, gestural overlap, gestural hiding, coda condition, ultrasound imaging technique

1. Introduction

Phonologically strong positions such as onset tend to tolerate more marked structures like consonant clusters across languages, compared to weak positions like coda position. However, many phonological repair strategies are mobilized to avoid more marked structures like complex consonant clusters or to remove phonological contrast in codas (Pigott 1999). For instance, double codas are simplified into singletons by deleting one consonant or phonemic contrasts in word-final coda are neutralized into a coronal in Korean (e.g., /t, t^h, t', s, h/ => [t]) (Lee 2003). Japanese also has some restrictions on allowable coda consonants (Itô 1986). This coda condition stipulates that only a nasal is licensed to coda when followed by a homorganic onset consonant or a coda is allowed as part of geminates. Additionally, voicing neutralization in coda position has been reported to be universal especially word-finally across languages, including German, Dutch, Spanish, Japanese, etc. (Beaton 2016, Braver 2013, Roettger et al. 2014, Warner et al. 2004, Simonet et al, 2008). Although this neutralization has been shown to be phonetically incomplete, voiceless obstruents tend to overshadow voiced counterparts universally. These previous studies seem to endorse the claim that weaker position, i.e., coda induces many phonological operations associated with coda weakening such as deletion, reduction, and neutralization as adaptive strategies to avoid more marked structure, exhibiting the onset-coda asymmetry. This asymmetry has been attributable to the difference in processing prominence between these two prosodic positions in the sense that coda position is less prominent in word recognition than onset position, and as a consequence, the former is more susceptible to weakening at phonemic or phonetic level.

In the same vein, consonant cluster simplification (henceforth, CCS) seems to be in marked contrast with onset maximization principle, which is assumed to be a general syllabification process to reflect the tendency to create the unmarked, core CV syllables (Blevins 1995, Clements and Keyser 1983, Steriade 1982). On the phonological side, CCS has been handled with constraints like *Complex Coda or Lazy (Kirchner 1998). Apart from phonological markedness, it seems plausible that it takes less articulatory effort to produce less number of consonants from the functional or articulatory perspective. Of course, the extent of tolerance of complex segments in onset or coda varies across languages. For instance, such a functional constraint as Lazy plays a crucial role in organizing the lexicon or triggering phonological repair processes in Korean and Japanese among many other languages whereas it does not exercise power in English or Russian.

A great bulk of previous research has been extensively dedicated to providing phonological analyses to the cluster simplification processes, assuming this CCS takes place categorically. Furthermore, some studies have attempted to characterize acoustic properties of coda consonant clusters (henceforth, CCC) in English and to compare Korean speakers' production with English speakers' (Cho 2022). However, the present study aims at revealing the articulatory characteristics of CCS at phonetic-fine level and addresses the question as to whether consonant clusters are categorically simplified, i.e., undergoes deletion under the pressure against complex codas in Korean or whether the trace of the articulatory gesture of the consonant remains through seemingly-deleted segments.

1.1 Consonant cluster simplification in L1 Korean

Maximal syllable structure in Korean is C(G)VC, i.e., singleton onset (and a glide) followed by a nucleus vowel followed by a singleton coda (Kim 2022, 구현옥 2019, 이호영 1996, 이문규 2004). Korean allows 11 types of double codas underlyingly, which are represented in orthography (구현옥 2019) (e.g., /ks,nc,sh,ls,lt^h,lh,lm,lp^h,lk,lp,ps/). However, because of maximal syllable structure, when stems with double codas underlyingly surface in isolation or are combined with a word or suffix beginning with a vowel, the stem-final coda consonant is re-syllabified onto the onset of the following syllable. However, when they are followed by any morphemes or words beginning with a consonant, one of the double codas is deleted. Namely, the underlying complex codas show the alternation between double consonants and singleton consonants in the surface, depending on the phonological context as exemplified in (1).

There are three patterns of stem-final CCS as an effort to adapt to syllable structure according to which consonant surfaces or falls victim to deletion. The first case is that C_1 survives on the surface with the deletion of C_2 in the double consonant clusters C_1C_2, e.g., /ks,nc,ng,ls,lt^h,lh,ps/. The second type is that C_1C_2 is simplified to C_2, e.g., /lm,lp^h/. The last type is shown in clusters such as /lk/ and /lp/ which exhibit a wider range of variation on the surface by deleting either the first or second consonant as seen in (1d) and (1f). Numerous studies on the CCS have shown that the type of alternation is affected by many factors, including dialects, speakers' generation, frequency of phonological contexts, etc. 남경완·오재혁's (2009) study showed that Seoul dialect speakers tend to reduce /lk/ to [l] rather than [k] and simplify /lp/ to [l] over [p]. It was shown that [l] surfaces by 78%, 96% and 99% for /lk/ words, respectively /ilkta/ 'read', /malkta/, 'be clear', /nalkta/ 'be old'. Furthermore, /lp/ clusters in words /palpta/ 'step', /nəlpta/ 'be broad', /c'alpta/ 'be short' are simplified to [l] by 54%, 68% and 72% respectively. Kwon et al.'s (2023) corpus study suggested that the variability patterns for Korean /lp/ and /lk/ sequences differ depending on the cluter type, showing that /l/-retaining variants are more common for /lp/ than for /lk/ sequences.

(1)	a. /ks/ [k]	/neks/	[nek]	'soul'	/neks+i/	[nek.si]	'soul+nom.'
		/moks/	[mok]	'share'	/moks+i/	[mok.si]	'share+nom.'
	b. /nc/ [n]	/anc+ta/	[an.t'a]	'sit+dec.'	/anc+a/	[an.ca]	'sit+result.'
		/ənc+ko/	[ən.k'o]	'lay+cons'	/anc+ə/	[an.cə]	'lay+result'
	c. /nh/ [n]	/manh+nay/	[man.nay]	'many+dec.'	/manh+i/	[ma.ni]	'a lot'
		/k'ɨnh+nɨn/	[k'ɨn.nɨn]	'cutting'	/k'ɨnh+ə/	[k'ɨn.ə]	'cut+result'
	d. /lk/ [k]~[l]	/talk/	[tak]~[tal]	'chicken'	/talk+i/	[tal.ki]	'chicken+nom.'
		/hɨlk/	[hɨk]~[hɨl]	'earth'	/hɨlk+i/	[hɨl.ki]	'earth+nom.'
		/malk+ko/	[mal.k'o]~[ma.k'o]	'clear+cons'	/malka/	[mal.ka]	'clear+dec. '
	e. /lm/ [m]	/salm/	[sam]	'life'	/salm+i/	[sal.mi]	'life+nom.'
		/cəlm+ko/	[cəm.k'o]	'young+conse..'	/cəlm+ə/	[cəl.mə]	'young+dec.'
	f. /lp/ [l]~[p]	/jətəlp/	[jə.təl]	'eight'	/jətlp +i/	[jətəl.pi]	'eight+nom.'
		/nəlp+ko/	[nəl.k'o]~[nəp.k'o]	'broad+cons'	/nəlp+i /	[nəl.pi]	'breadth'
	g. /ls/ [l]	/ols/	[ol]	'price'	/ols+i/	[ol.si]	'price+nom.'
		/mulkols/	[mul.kol]	'drain'	/mulkols+i/	[mul.kol.si]	'drain+nom.'
	h. /lt^h/ [l]	/halt^h+ko/	[hal.k'o]	'lick+consec.'	/ halt^h+a /	[hal.t^{h}a]	'lick+result.'
		/hult^h+ko/	[hul.k'o]	'skim+consec.'	/ hult^h+ə/	[hul.t^{h}ə]	'skim+result.'
	i. /lp^h/ [p^h]	/ɨlp^h+ko/	[ɨp^h.k'o]	'recite+consec.'	/ɨlp^h+ə/	[/ɨl.p^{h}ə]	'recite+result.'
	j. /lh/ [l]	/t'ulh+ko/	[t'ul.k'o]	'pierce+consec.'	/t'ulh+ə/	[t'u.lə]	'pierce+result.'
		/silh+so/	[sil.s'o]	'dislike+dec.'	/silh+ə/	[si.lə]	'dislike+dec.'
	k. /ps/ [p]	/kaps/	[kap]	'price'	/kaps+i/	[kap.si]	'price+nom.'
		/əps+ko/	[əp+k'o]	'have no+consec.'	/əps+i/	[əp.si]	'without'

One of the most controversial phonological issues is which consonant is the winner in this surface survival competition (문양수 2001, 이진호 1997, 전종호 1998, Kim 1973, 2011, Oh 1993). One proposal is that regardless of whether C_1 or C_2, more sonorous consonant is retained while less sonorous one undergoes deletion, following sonority scale suggested by Hogg and McCully (1987) and Clements (1990) (이진호 1997). This account holds true for many cases of simplification of the clusters such as /nc,nh,ls,lt^h,lh/ because these clusters are simplified to /n,n,l,l,l/, respectively. However, many other cases are not still resolved by this account, including /ks, ps, lm, lp/ because these are reduced to less sonorant consonant. (Note that less sonorant member of onset cluster survives on the surface in English, Polish and Russian (Gnanadesikan 1995, Gierut 1999, Pater and Barlow 2003).

Another account is provided in the principle of Close Articulation (Kim 1973, 2011). According to Kim, this principle stipulates the tendency to narrow the articulatory aperture for consonants, and he claims that this principle is conducive to accounting for Korean CCS. To be specific, he suggests that the consonant with lower aperture is retained in the simplification process. This account might be appropriate to explain the simplification of the clusters such as /ps, lm, lp^h/ because bilabials are comparatively lower in aperture and they are faithfully preserved in the surface. However, this approach has many potential drawbacks. One is that it is not clear how to quantify the aperture of the consonants unlike vowels and another flaw is that it is not easy to determine the target of deletion when the clusters have similar degree of aperture such as /nc,nh,ls,lt^h,lh/.

In addition, 문양수 (2001) proposed that the consonant with higher degree of consonantal strength is retained in the simplification process and a constraint, i.e., Parse-peripherality is responsible for this preservation. He specified the consonantal strength of consonants with different places of articulation in the order of velar >> labial >> coronal. Consonantal strength is defined as the degree in which segments are resistant to assimilation processes. This way gives a plausible account for the simplification of clusters /ks, ps, lm, lp^h/ but is not sufficient to explain many other cases, including clusters /nc,nh,ls,lt^h,lh/.

Despite numerous interesting proposals, single approach alone failed to provide a comprehensive solution to all the data of the simplification processes. Furthermore, in some dialects of North Gyeongsang, North Jeolla, and North Chungcheong, when noun stems ending with double codas are followed by a vowel initial suffix, C_2 is not re-syllabified into the neighboring syllable but instead, only C_1 or C_2 survives in the isolation forms in the surface unlike the pattern of standard Korean. These forms are widely attested in many dialects (Cho 2002, Han 1992, Park 1993). Cho (2002) points out that these are examples of perfect paradigm uniformity because morphologically related words share the same base forms regardless of phonological context. He suggests that these variants in derived forms should be handled by output-output correspondence constraint such as OO-Dep(seg) banning insertion of any segments in the derived forms.

(2) Dialectal variations (Cho 2002, Han 1992, Park 1993)

/kaps/	[kap]	/kaps-i/	[kabi]	*[kapsi]	‘price+nom.’
/hɨlk/	[hɨk]	/hɨlk-i/	[hɨgi]	*[hɨlgi]	‘soil+nom.’
/salm/	[sam]	/salm-i/	[sami]	*[salmi]	‘life+nom.’

In summary, previous studies on Korean CCS have been dedicated to addressing two issues: which consonant of double codas survives in the surface in the reduction process and what is a formal phonological mechanism responsible for the simplification. To resolve these issues, many phonetic, phonological features, principles and constraints have been proposed, including aperture, gravity, sonority, and base-identity constraints.

Notwithstanding such numerous suggestions and some discrepancies in their phonological analyses, there is one consensus that no single proposal is sufficient to give a comprehensive account for these two controversial debates. However, there is a common assumption underlying these phonological approaches; It is the case that CCS occurs categorically in Korean despite minor phonological variations in their alternation patterns across regional or age-related dialects.

1.2 Consonant deletion or gestural hiding in L2 English

CCS in English has been well documented and known to occur either obligatorily or optionally, in particular in coda position (Browman and Goldstein 1992, Côte 2000, Guy 1980, Kang and Oh 2004, Steriade 2000). For instance, coda deletion, a case of CCS has been attributed to phonotactic restrictions or constraint interactions (e.g., “si[g]n, paradi[g]m, colum[n], lon[g], etc.”) as exemplified in (3a). In addition to this categorical deletion at lexical, phonological level, the proponents of articulatory phonology suggested an idea of a gestural “hiding” to explain the seemingly consonant deletion occurring across word boundary in connected speech as in (3b) (Browman and Goldstein 1992, 1995). For example, their X-ray studies showed that the gesture of the word-final alveolar /t/, i.e., the raising of the tongue tip or blade arises in the C_1C_2##C_3 clusters (e.g., “perfe<u>ct</u> <u>m</u>emory”) even in the fluent speech as well as in isolation forms although the C_2 [t] is not audible. This phenomenon was referred to as “gestural hiding” and was interpreted to mean that the gestural overlap occurs in the timing dimension between the alveolar closure gesture of C_2 [t] and the velaric closure gesture of C_1 [k] or the labial closure gesture of C_3 [m] due to the faster speech rate, inducing the acoustical hiding (i.e., *inaudibility*) of the intervening C_2 [t]. This interpretation poses an interesting challenge to traditional phonological analysis in that CCS in this context seems to be perceptual illusion but is not an actual deletion from the perspective of the articulator movement.

(3) Consonant cluster simplification (CCS) in English (Kang and Oh 2004)

a. Obligatory CCS within words

[gn]-[n]	signature-sign, resignation-resign
[mn]-[m]	columnar-column, hymnal-hymn
[gm]-[m]	paradigmatic-paradigm, phlegmatic-phlegm
[ŋg]-[ŋ]	longer-long, younger-young
[mb]-[m]	bombard-bomb, dumbo-dumb

b. Optional CCS across word boundary (Browman and Goldstein 1992)

[kt#m]~[km]	perfect memory	[ld#v]~[lv]	old version
[st#w]~[sw]	last week	[st#k]~[sk]	pest control
[pt#w]~[pw]	slept well	[ft#s]~[fs]	soft smile
[st#p]~[sp]	fast paced	[zd#s]~[zs]	closed store

Recent decades of L2 studies showed that L2 production is influenced by speech perception, or (mis)mapping of L2 sound categories onto L1 equivalent categories. Speech Learning Model (SLM) proposed by Flege (1995, 2002) claims that speech perception is executed on the basis of acoustic signals and L2 speakers’ production errors are induced by their incorrect perception of acoustic properties of L2 sounds. On the other hand, Perceptual Assimilation Model (PAM) suggested by Best and other colleagues posits that L2 sounds are perceived and mapped onto L1 sounds on the basis of gestural (dis)similarities along with the assumption of the link between perception and production (Best 1994, Best and Tyler 2007, Best et al. 2001).

Given this background, the present study is mainly concerned with how Korean L2 learners of English articulate English consonant clusters across word boundary seen in (3b) with respect to the presence/absence of the gestures of target for simplification. Hence, if Best and others' PAM works, the gestural deletion of the consonant in L1 Korean might be applied to L2 English context based on the articulatory, gestural configuration similarities. Under PAM, the gestural coordination among consonant clusters in L2 English can be perceptually mapped or assimilated to L1 Korean consonant sequences as this L1-L2 mapping shows the gestural similarities like velaric closure. For example, sequences like /lkt/ in English "milk tea" can be assimilated to the identical consonant sequences /lkt/ in Korean /malkta/ "be clean". If this is the case, it is expected that CCS might take place in L2 English resulting from the assimilation of gestural coordination evident in L1 Korean. However, it is conceivable that CCS in L1 Korean does not transfer to the articulation of consonant clusters in L2 English if the assumption of PAM does not hold true for the consonant sequences with respect to gestural coordination patterns among the consonants.

1.3 The present study

Given the descriptive and theoretical background in previous studies, the goal of the present preliminary study is to investigate whether Korean CCS genuinely takes place categorically at phonemic level or gradiently occurs at phonetic level from the articulatory perspective. This attempt might seem to challenge the long-standing phonological assumption associated with the simplification process. The proponents of articulatory phonology have claimed that the deletion rules which were traditionally considered purely removal of segments seem to be acoustically deletion rules but do not induce articulatory deletion of segments (Browman and Goldstein 1992, 1995, Byrd 1995). As previously mentioned, X-ray studies have shown that in the fluent speech, word-final coronal /t/ in /kt#m/ of "perfect memory" is not deleted, but the tongue blade is raised toward the alveolar ridge and makes full constriction although the coronal is not audible. This finding led to the suggestion that closure gesture of /t/ is completely overlapped by the closure phase of the preceding velar /k/ in the intergestural timing dimension, which makes /t/ inaudible. From the perspective of articulatory phonology, the alveolar segment is not deleted but its primary gesture, the closure of tongue blade against the alveolar ridge is still present. Namely, the seemingly-deletion could be labeled as a case of perceptual illusion or gestural hiding.

In the similar vein, the current study aims at investigating whether Korean consonant clusters are simplified by deleting one consonant as predicted by the categorical rule-based account. To testify to the application of the simplification, we selected two types of coda clusters, i.e., /lk/ and /lp/ out of eleven in (1). As previously described, when noun stems ending with /lk,lp/ occur in isolation or are followed by a consonant-initial suffix, one of the two consonants is known to undergo deletion. For this reason, these clusters exhibit two variants, i.e., [l]~[k], [l]~[p] depending on dialects or age-groups. In this study, ultrasound imaging technique was used to directly see the presence/absence of the gesture of C_1 or C_2 in /C_1C_2+C_3/ sequences. By investigating whether the tongue dorsum is raised toward the soft palate for /k/ in /lkt/ clusters in words /malkta/ "be clear+dec." and comparing the tongue dorsum position of /k/ in /malkta/ with that of /l/ in /malta/, we would judge if the C_2 /k/ is squarely deleted and thus CCS takes place. In case the identical cluster /lk/ is simplified to [k], its tongue configuration would be compared with the tongue configurations of /k/ and /l/ of /makta/ and /malta/ to check if the tongue blade gesture of C_1 /l/ is still present. This articulatory study would reveal the nature of Korean CCS which was assumed to be categorical deletion. If we observe the articulatory traces of the tongue configurations of both C_1 and C_2 in /CC/ clusters, this rule should be redefined as perceptually illusory simplification due to gestural overlap between C_1 and C_2, not as the deletion or actual simplification rule. Conversely, if no trace of articulatory gestures of C_1 or C_2, it might corroborate the traditional, phonological definition of the simplification rule.

The second goal of this study is to examine whether the production of CCS in L2 English is affected by the application mode of CCS in L1 Korean. Under the prediction of PAM, the gestural coordination in L2 consonantal sequences is perceptually assimilated to that in L1 and is likely to be reflected in L2 production. Thus, this study aims at investigating whether the articulation of L1 Korean consonant clusters transfers to the production of L2 English consonant sequences. To do this, the articulation of English consonant clusters such as /lk#t/ and /lp#t/ is under investigation and compared with the similar sequences /...lk+t…/ and /…lp+t…/ in Korean. For example, if CCS occurs with the deletion of /k/ in the identical /lkt/ sequences in L2 English as well as L1 Korean, it would be indicative of mapping the deletion in L1 onto L2. If it arises only in L1 Korean, such transfer would not play a crucial role in L2 production.

2. Production Experiment 1: Consonant Cluster Simplification in L1 Korean

2.1 Participants

Six Korean native speakers participated in the ultrasound imaging experiment. At the time of experiment, they were majoring in English at Daegu University in Korea. Four were female and two male. They were aged 21-25 years (mean: 22.8, SD: 1.7). All participants were paid monetary compensation. Average period of learning English at formal education institute was 14.5 years, ranging from 13 to 18 years. They were studying English as a foreign language on average for 2.6 hours on a daily basis, ranging from 0 to 4 hours (SD: 1.9). They had experience of staying in the English-speaking country on average for 0.8 year, ranging from 0 to 1 year. Five subjects had been in English-speaking country for a certain period. Their self-evaluation of English proficiency was on average 4.8 out of 10 point scale, ranging from 4 to 7 (SD: 1.1).

2.2 Stimuli

To see the production of Korean coda consonant clusters, we chose two types of double codas, i.e., /lk/ and /lp/ out of eleven double coda types. Then, three adjectival stems ending with /lk/ coda and three other verb stems ending with /lp/ coda were randomly selected: {malk- "clear", nɨlk- "old", ilk- "read"} vs. {nəlp- "broad", palp- "tread", t'əlp- "bitter"}. To create the phonological environment where CCS may potentially arise, declarative verb suffix {-ta} and consecutive suffix {-ko} were attached to the six stems as exemplified in (4). Thus, 12 real words were created as experimental stimuli (2 coda types × 3 verb stems × 2 verb suffixes). Since one of the double codas is assumed to be deleted if the simplification process occurs, we investigated whether C_1 or C_2 is still pronounced, leaving the trace of their articulatory gestures, i.e., tongue blade for /l/ or tongue dorsum for /k/.

To examine whether C_1 or C_2 of the double codas is purely deleted, we created two control stimuli for each experimental token, i.e., verb or adjectival stem with double codas followed by a consonant-initial suffix by removing only one coda consonant from the double coda stems. For example, /l/ coda stem and /k/ coda stem were created from /lk/ coda stems and each was attached with the suffix as seen in /makta/ and /malta/. Likewise, /p/ coda stem and /l/ coda stem were created from /lp/ double coda stems and each control stem was also attached with a consonant-initial suffix {-ta} or {-ko}.

Hence, in total, 36 stimuli were used for the production materials (12 experimental stimuli with double codas and 24 control stimuli with singleton codas). These 36 tokens were also embedded in a carrier sentence "ikkesɨn _______ eyyo" in Korean orthography, meaning "This is ________." Six participants were asked to read each stimuli embedded in this carrier sentence as fast and naturally as they could to elicit the surface forms where the consonant cluster simplification is likely to be applied.

(4) Materials for cluster simplification in Korean

Coda/Onset	/t/-initial suffix '-ta'			/k/-initial suffix '-ko'		
C_1+C_2	/lk+t/, /lp+t/	/k+t/, /p+t/	/l+t/	/lk+k/, /lp+k/	/k+k/, /p+k/	/l+k/
/lk/	malkta nɨlkta ilkta	makta nɨkta ikta	malta nɨlta ilta	malkko nɨlkko ilkko	makko nɨkko ikko	malko nɨlko ilko
/lp/	nəlpta palpta t'əlpta	nəpta papta t'əpta	nəlta palta t'əlta	nəlpko palpko t'əlpko	nəpko papko t'əpko	nəlko palko t'əlta

2.3 Procedures

The ultrasound imaging experiment was performed with Korean native speakers to extract the entire tongue body. Ultrasound is known to be conducive for imaging tongue tip, blade or dorsum raising (Ahn 2018, Gick et al. 2006). The ultrasound imaging task was conducted in a quiet phonetics room at Daegu University in Korea. Recordings of articulatory and acoustic stimuli were conducted, and both data were obtained simultaneously using the Articulate Assistant Advanced (AAA) software. Each participant was seated before a computer that installed AAA software. The software was connected to an EchoB ultrasound machine. The machine had a 5 to 10 MHz convex-curved transducer, which took 82 frames per second across a 92° field of view. The transducer was connected to a microphone and fixed to the chin within the headset.

The subjects were instructed to read a list of stimuli embedded in the carrier sentence to a microphone fixed within the headset. The list of stimuli was written down in Korean or English orthography on several sheets of paper, and it contained three repetitions of the same tokens. The order of the stimuli was randomized; accordingly, the participants were asked to read it at a normal speaking rate. The AAA software recorded midsagittal images of the tongue along with acoustic data of the stimuli. The auditory signal from the microphone and the ultrasound visual signals from the ultrasound machine were synchronized using a SyncBrightUp unit (Articulate Instruments Ltd. 2010). The depth was set to 80 mm with a 5 to 10 MHz transducer.

After recording ultrasound images as well as audio data, midsagittal images of the alveolars, labials and velars from Korean and English stimuli were extracted. By scanning the spectrogram and waveforms visually presented on the AAA, the midpoint of the stop closure was selected, and the frame of the closure was extracted. In the beginning phase of the stop closure, the tongue blade or tip does not reach the gestural peak—in particular, the complete closure and at its end point—so the tongue tip, blade or dorsum is more likely to be abducted from the alveolar ridge or velum or more susceptible to strong anticipatory coarticulation with the following vowel. For this reason, the midpoint seems to appropriately represent the gestural peak of each consonant.

To quantify the tongue configuration, the extracted images were overlaid with the tongue contours by drawing the tongue body lines via the function of "Edit Splines" in AAA. Then, the tongue contours were again extracted in a series of x-y coordinates. These x-y coordinates were exported to the Excel files using AAA.

The adjusted tongue contours were subjected to a smoothing spline analysis of variance (henceforth, SSANOVA) for the statistical analyses (Davidson 2006, Gu 2002, 2014). An SSANOVA was used to test the significant differences between two or three tongue contours obtained from one speaker. Based on the (x-y) coordinate plots of the average tongue contours, the contour sets are calculated as significantly different when the confidence intervals (95%) from the set of contours do not overlap. This non-overlap of the tongue contours was evaluated as significantly different ($p < .05$).

2.4 Results

2.4.1 For the clusters /-lk+t/ and /-lk+k/

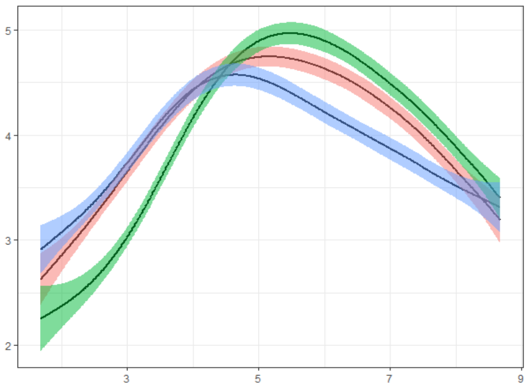
To look into the application mode of CCS from the articulatory perspective, the tongue configuration at the mid time point between C_1 /l/ and C_3 /t,k/ was compared with that of syllable-final /t/ or /k/ in CC sequences /…kt…/ or /…lt…/. To check out whether the medial /k/ is deleted, the highest point in tongue body line which is assumed to make constriction against the velum was designated as the point of interest. Results of ultrasound imaging obtained from six Korean speakers exhibited three types of variants with respect to CCS: (1) Incomplete simplification, (2) C_1 /l/-deletion, and (3) C_2 /k/-deletion. Incomplete simplification variants are labeled as "partial velar" and refer to the case where the highest point of tongue dorsum of /k/ in consonant cluster /…lkt…/ is positioned in the mid-point between the identical velar placed in non-simplification sequence /…kt…/ and the lateral /l/ in /…lt…/ context. /l/-deletion variants represent the case where the tongue position of the medial target velar is not significantly different from that of the velar in the /…kt…/ sequence, named as "full velar". /k/-deletion form is labeled as "zero velar", being defined as the variant where the highest point of the medial position in CCC is aligned with that of the lateral /l/ placed in non-simplification context /…lt…/.

Table 1 shows the mean rates (%) of three types of variants realized in a CCS context. Overall, CCS arose across all six speakers though the range of variants differed to some extent across speakers. As described in traditional phonological literature, two variants, i.e., /l/-deletion and /k/-deletion forms were produced among four speakers (K1, K3, K5, K6). Three speakers (K1, K2, K4) realized "partial velar" variants to some significant extent. Speakers collapsed, /l/-deletion variants were dominant at 47%, and /k/-deletion forms also emerged at 26%, confirming the alternation between two realizations in a CCS context. Of interest is the finding that incomplete deletion variants, i.e., "partial velar" forms were also quite common, amounting to 26%.

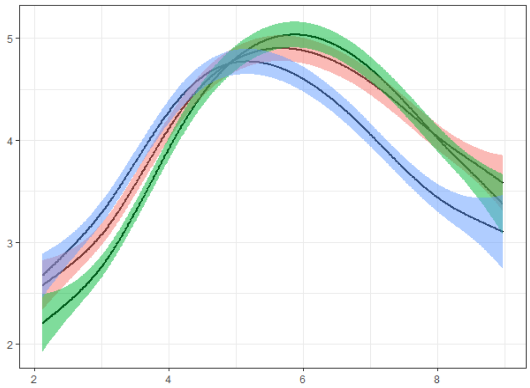
Table 1. Mean Rates (%) of Variants of Target Velars in a CCS Context

Variants	Subjects						
	K1	K2	K3	K4	K5	K6	Total
Partial velar (=incomplete deletion)	33	50	0	66	0	0	26
Full velar (=/l/-deletion)	33	0	75	33	83	66	47
Zero velar (=/k/-deletion)	33	50	25	0	16	33	26

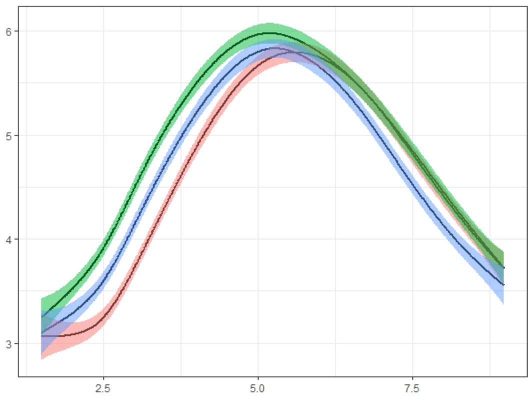
Our findings indicate that the application of Korean CCS is gradient rather than categorical unlike the purely phonological description. Korean speakers realized the consonant clusters in three types of variants which contained a partial velar, full velar or zero-velar. Figure 1 represents tongue body configurations of the portion corresponding to the medial segment C_2 /k/ placed in a CCS context, i.e., /…lkt…/ or /..lkk…/, of a velar /k/ in a non-CCS context and of a lateral /l/ in a non-CCS context. The x-axis represents the frontness dimension where the leftmost shows the tongue root and the right most points to the tongue tip. The y-axis shows the relative tongue body height represented in pixels where the upper part is relatively high. Fig. 1(a) shows an example of a partial (or *incomplete*) application of CCS. The highest point, i.e., constriction point at the soft palate (pink curve) in /k/-portion in /…lkt…/ sequences lies in-between that of /k/ in /…kt…/ sequences (green curve) and that of /l/ in /…lt…/ sequences (blue curve). This suggests that the tongue dorsum did not fully contact the soft palate when it comes to the production of /k/ in a CCS context, albeit moved toward the constriction point. This might be called an exemplar of target undershoot or incomplete CCS. It seems that this configuration induces perceptual illusion where /k/ sounds like deleted aurally but is actually articulated though not fully, conceivably due to the gestural overlap between C_1 and C_3 in the $C_1C_2C_3$. Fig. 1(b) illustrates a case of the categorical application of CCS with C_1 /l/-deletion because the tongue body contour for the /k/ portion placed in a CCS context (pink curve) completely overlaps with that of /k/ in a non-CCS context (green curve). Figure 1(c) shows an example of C_2 /k/-deletion variant of which the tongue contour along with the constriction area (pink curve) overlaps with that of a lateral /l/ in a non-CCS context (blue curve) but does not with that of a velar /k/ in a non-CCS context (green curve). This is indicative of a complete deletion of a velaric constriction gesture of a middle /k/ in CCC clusters.



(a) Partial velar (K1, K2, K5)



(b) Full velar (K1, K3, K5, K6)



(c) Zero velar (K1, K2, K3, K5, K6)

Figure 1. **Tongue contours of the portion of the medial /k/ in sequences /..lk+t…/ or /…lk+k…/ i.e., a CCC context (pink curve), of the velar /k/ in sequences /…kt…/ (green curve) and of the lateral /l/ in sequences /...lt…/ (blue curve)**

Our articulatory findings are significant in revealing that half of Korean speakers who participated in this experiment do not fully simplify the consonant clusters (CCC) by deleting the medial velar consonant as opposed to the expectation of the categorical application of CCS. Furthermore, the results demonstrate that the articulatory strategies to resolve the consonant clusters vary across individual Korean speakers with respect to the range of surface realizations or the type of preferred phonological behaviors. K1 realized the CCC sequences as three variants on the articulation side whereas the other five speakers adopted two phonological repair modes, i.e., /k/-

deletion and /l/-deletion. Additionally, the preferred variants also displayed inter-speaker variation. For instance, K4 favored incomplete deletion over /l/-deletion while /l/-deletion was preferred to /k/-deletion by K3, K5, and K6. K1 and K2 produced incomplete deletion as frequently as /l/-deletion or /k/-deletion.

Of interest is the finding that the rates of the application modes of CCS varied depending on CCC cluster type as well. Table 2 shows mean rates of three types of variants for the medial velar /k/ in /CCC/ sequences in a different CCS context. When the verbal or adjectival stems ending with /lk/ are followed by the declarative ending /ta/, the /k/ is realized as “partial velar” or “full velar” at 44%. Complete /k/-deletion occurs only at 12%. However, when /lkk/ sequences are derived from the concatenation of /ko/, quite a divergent pattern of variants emerged as seen below. “Full velar” variants were dominant at 50%, /k/-deletion forms were quite common at 39% and “partial velar” variants were least frequent at 11%. This finding of divergent variation patterns cannot be captured by the purely phonological description whether it is rule-based or constraint-based. It suggests that the application of CCS regarding the /lk/ sequences seem to be gradient rather than categorical and that to some extent, CCS might be a case of perceptual illusion and not arise from the articulatory side.

Table 2. Mean Rates (%) of Variants of Target Velars in a CCS Context by CCC Type

	CCC Types		
Variants	/...lk+t.../ (e.g., ‘malkta’)	/...lk+k.../ (e.g., ‘malkko’)	Total
Partial velar (=incomplete deletion)	44	11	26
Full velar (=/l/-deletion)	44	50	47
Zero velar (=/k/-deletion)	12	39	26

2.4.2 For the clusters /-lp+t/ and /-lp+k/

We looked into the application mode of CCS when the /CCC/ clusters such as /lpt/ and /lpk/ are created by the combination of adjectival or verbal stems and a declarative ending ‘-ta’ or a connective ending ‘-ko’. The results of ultrasound imaging are classified into two variants which undergo CCS, i.e., /p/-deletion realized as /lt/ or /lk/ and /l/-deletion forms produced as /pt/ or /pk/. To judge whether /p/-deletion or /l/-deletion is applied, the mid-point of CCC sequences which corresponds to the underlying /p/ was extracted from recorded ultrasound images and compared with the tongue configurations of /p/ in /pt/ sequences and of /l/ in /lt/ sequences.

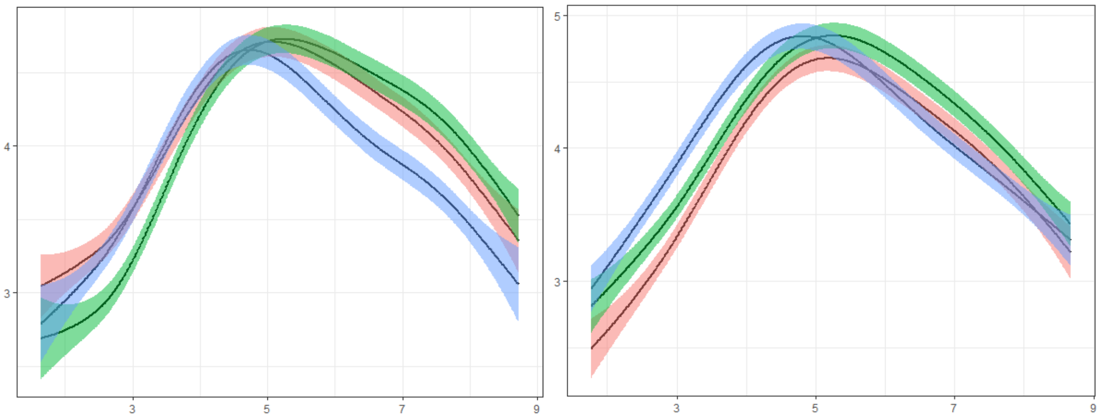
The results showed that CCS applied categorically and subjects realized /lpt/ and /lpk/ sequences as two variants, i.e., /p/-deletion and /l/-deletion forms. Table 3 shows mean rates of two variants elicited from the production of /lpt, lpk/ sequences, i.e., embedded in a CCS context. As seen below, /p/-deletion variants were dominant over /l/-deletion forms for all subjects. This finding is significant in the sense that two variants resulting from CCS exhibit the different likelihood of occurrences.

Table 3. Mean Rates (%) of Variants of CCC Sequences in a CCS Context

	Subjects						
Variants	K1	K2	K3	K4	K5	K6	Total
/p/-deletion	80	80	50	80	100	80	78
/l/-deletion)	20	20	50	20	0	20	22

Figure 2 represents SSANOVA of tongue contour plots of the production of the medial consonant in /lpt/ or /lpk/ placed in a CCS context (pink curve), of the /p/ in CC sequence /pt/ contained in a non-CCS context (green) and of the /l/ in CC sequences /lt/ embedded in a non-CCS context (blue curve). As illustrated, Fig. 2(a) depicts /l/-deletion variants where the tongue front region of the target for CCS is overlapped with that of /p/ in /pt/

sequences but does not overlap with that of /l/ in /lt/ sequences. This indicates that /lpt/ sequences are realized as /pt/ due to /l/-deletion, i.e., the application of CCS. Fig. 2(b) represents a sample of tongue configuration of the case where the cluster undergoes /p/-deletion as a result of the application of CCS. As illustrated, the tongue front region of the target for CCS (pink curve) mostly overlaps with that of /l/ in a non-CCS context, i.e., /lt/ (blue curve) but does not overlap with that of /p/ in /pt/ sequences (green curve). This comparison suggests that /lpt/ sequences are articulated as /lt/ due to /p/-deletion.



(a) /l/-deletion (b) /p/-deletion

Figure 2. **Tongue contours of the portion of the medial /p/ in sequences /..lp+t…/ or /…lp+k…/ i.e., a CCC context (pink curve), of the labial /p/ in sequences /…pt…/ (green curve) and of the lateral /l/ in sequences /...lt…/ (blue curve)**

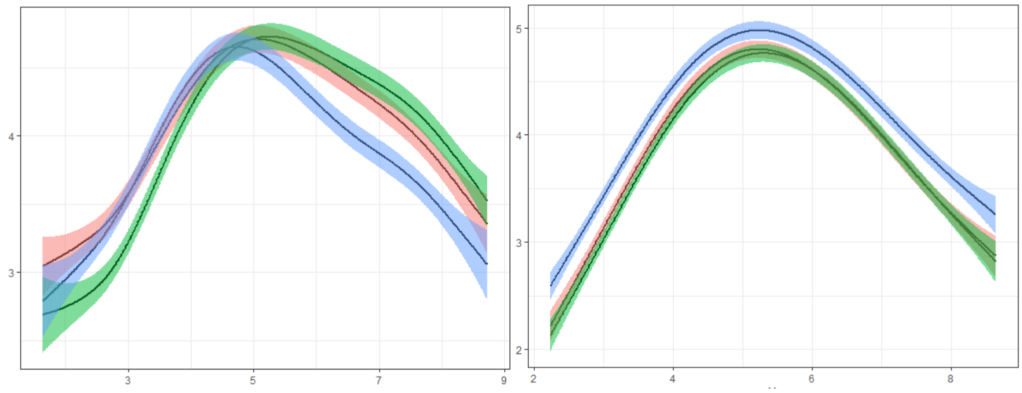
Furthermore, the preference of /p/-deletion variants to /l/-deletion forms was also consistent regardless of whether the CCC type is /lpt/ or /lpk/ as seen in Table 4. Overall, Korean subjects tend to delete /p/ rather than /l/ in the production of /lpt, lpk/ sequences across speakers or CCC cluster type.

Table 4. Mean Rates (%) of Variants of Target Labials in a CCS Context by CCC Type

	CCC Types	
Variants	/...lp+t.../ (e.g., ‘nelpta’)	/...lp+k.../ (e.g., ‘nelpko’)
/p/-deletion	63	64
/l/-deletion)	37	36

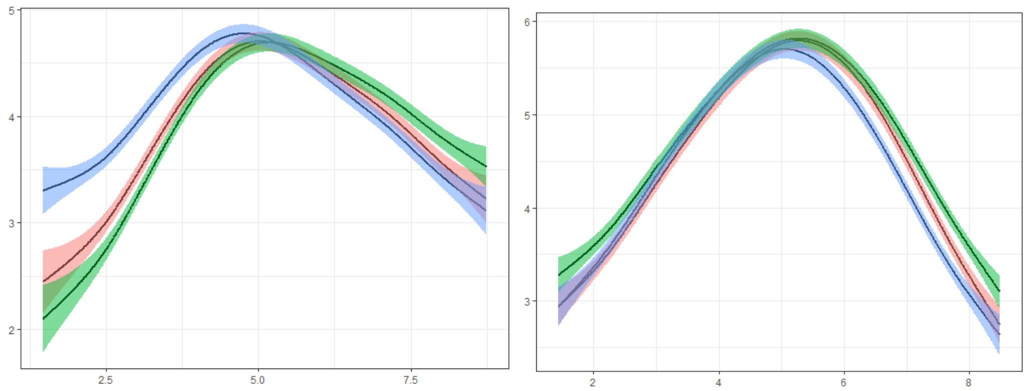
Although CCS seems to be applied categorically with reference to the sequences /lpt/ and /lpk/, it is also found that the resultant variants from the application of CCS exhibit variability within the reduced /p/ or /l/ category at phonetic-fine level. Figure 3 illustrates two types of /l/-deletion variants created from /lpt/ or /lpk/ sequences. Two variant outcomes from K1 and K2 in Fig. 3 show that /l/ is categorically deleted due to the reduction of CCC sequences because the tongue front region of the portion in a CCS context (pink curve) overlaps with that of /p/ in a non-CCS context (green) but does not overlap with that of /l/ in a non-CCS environment (blue curve). However, scrutiny into both the variants reveals that tongue front is articulated further front for the reduced variant than for the /l/ in a non-CCS context (Fig. 3(a)). Conversely, Fig. 3(b) shows that the resultant variant elicited from CCS is articulated further back than the /l/ in a non-CCS context. Likewise, Figure 4 also exemplifies the sub-phonemic variation of /p/-deletion forms at the articulatory level. Both the variants in Fig. 4(a) and 4(b) show the categorical

/p/-deletion. However, the forms derived from a CCS context (pink curve) differ in the extent how much their tongue fronts are farther away from the tongue front of /l/ in a non-CCS context.



(a) /l/-deletion variant A ('ttelpta' from K1) (b) /l/-deletion variant B ('ttelpta' from K2)

Figure 3. Variation of /l/-deletion



(a) /p/-deletion variant A ("nelpta" from K1) (b) /p/-deletion variant B ("palko" from K6)

Figure 4. Variation of /p/-deletion

3. Production Experiment 2: L2 English Consonant Clusters

3.1 Participants

Four Korean native speakers participated in the ultrasound imaging experiment. All of them were the same subjects who participated in the production of Korean consonant clusters in the current research. They were majoring in English at Daegu University in Korea. Two were female and two male. Their ages ranged from 21 to 24 years (mean: 22.7, SD: 1.7). Average period of learning English at formal education institutes was 14.5 years, ranging from 13 to 18 years. They were studying English as a foreign language on average for 3 hours on a daily basis, ranging from 0 to 5 hours (SD: 1.9). They had experience of staying in the English-speaking country on average for 0.8 year, ranging from 0 to 1 year. Only one subject had been in English-speaking country for one year. Their self-evaluation of English proficiency was on average 5 out of 10-point scale (SD: 1).

3.2 Stimuli and Procedure

To examine whether/how CCS occurs when it comes to the production of /CCC/ sequences in L2 English, two groups of two-word sequences were randomly created by combining two English words. The first group of stimuli were employed as test group to see the realization patterns of CCC clusters as seen in (5). All the stimuli consisted of four types of CC clusters such as /lk,lp,pt,kt/ in word-final coda and three consonants /p,t,k/ in word-initial onset. Thus, four types of /CCC/ sequences were created across word boundaries: /lk+t/, /lp+t/, /pt+k/, /kt+p/. Three tokens consisting of two words were created for each type of /CCC/ cluster. The first word in the two-word sequences contained a vowel /ɪ,ʌ,ɛ,e,æ,ɑ/ before the /CC/ coda word-finally and the second words were monosyllabic, beginning with a consonant followed by a vowel /i,ɪ,ɛ,ʌ,æ,ɔ/. A total of twelve tokens were prepared for test stimuli.

The second group of stimuli were created by combining two words to be used for a control group. To create a non-CCS context, the first words in the sequences ended with the identical consonants in the test group stimuli, such as /lk,lp,pt,kt/ and the second words were fixed as three words “ant, app, arm” beginning with a vowel /æ, a/ to control the coarticulatory effect of the vowel on the preceding word-final consonant. As in the test group, for each type of CC cluster type, three two-word sequence tokens were created. The articulation of C_2 in /$C_1C_2C_3$/ sequences, i.e., /p,t,k/ was compared with the production of the identical consonant C_2 in /C_1C_2/ clusters across word boundaries (e.g., *sil<u>k</u> tea* vs. *sil<u>k</u> ant*). Thus, a total of twelve two-word sequences were elicited for a control group.

In total, combining all target test and control tokens, 24 two-word sequences of stimuli were prepared for the production targets. Each token was uttered within a carrier frame, “This is _______” in English. The order of the reading tokens was randomized and all the tokens were produced three times. Hence, 288 tokens were obtained for ultrasound imaging technique and analyses (=24 sequences x 4 participants x 3 repetitions).

The procedures of conducting ultrasound imaging experiment, obtaining and analyzing data were identical to that employed in Experiment 1.

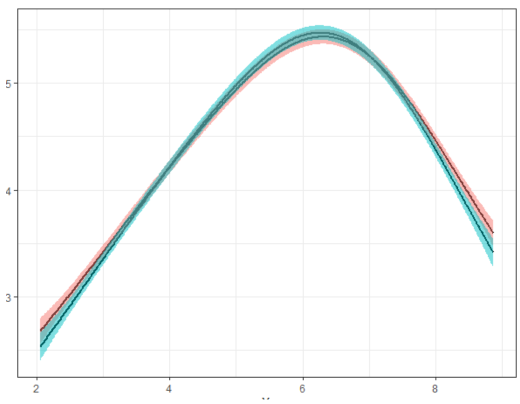
(5) Materials for cluster reduction (Test group) and non-reduction (Control group) in English

Coda/Onset	Test group: C_2 /p,t,k/ Reduction	Control group: C_2 /p,t,k/ non-reduction
/lk+t/	silk tea milk tea bulk tea	silk ant milk ant bulk ant
/lp+t/	help ten gulp ton scalp tan	help ant gulp ant scalp ant
/pt+k/	apt key adopt kid abrupt call	apt app adopt app abrupt app
/kt+p/	perfect pet compact pack respect pet	perfect arm compact arm respect arm

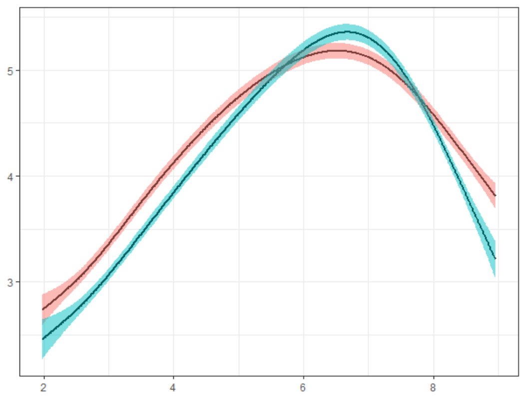
3.3 Results

We examined whether CCS in English occurs in the $C_1C_2C_3$ sequences across word boundary such as /pt#k/,

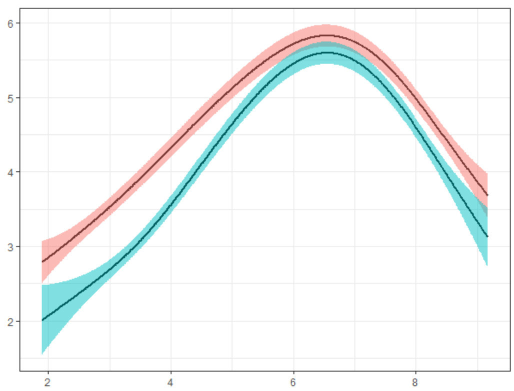
/kt#k/, /lp#t/, /lk#t/ in the Korean L2 English speakers' articulation. Ultrasound imaging data were classified into three types of articulation: (i) No-deletion of word-final consonants C_2 /p,t,k/, (ii) Deletion of word-final consonants, and (iii) Hyperarticulation of word-final consonants. The type of no-deletion was defined as the case where the tongue configurations of the portion corresponding the word-final /p,t,k/ substantially overlap with those of the identical consonants followed by a word-initial vowel (Fig. 5(a)). This articulation can be labeled as perceptual illusion where the intervening consonant is not audible but the main articulator (i.e., tongue tip or back) still moves towards the target along the palate. Deletion variants are the case where the tongue contours of the C_2 /p,t,k/ do not overlap with those of the identical consonants placed in a non-CCS context, i.e., followed by a vowel (e.g., *apt key* vs. *apt app*). This is a typical case of the application of CCS as depicted in Fig. 5(b). Hyperarticulation refers to a case where the tongue front region of the alveolar /t/ in a CCS context is articulated further front than that of the /t/ in a non-CCS environment or the tongue back of the velar /k/ in a CCS context is produced further higher than that of the /k/ in a non-CCS context (Fig. 5(c)).



(a) No-deletion (=No-CCS from K1)



(b) Deletion (=CCS from K1)



(c) Hyperarticulation (from K1)

Figure 5. SSANOVA of tongue contours of the word-final consonants (/p,t,k/) placed in a CCS context and in a non-CCS context. (Pink curves represent the tongue contours of the consonant flanking two consonants in a CCS context and blue curves refer to the tongue contours of the identical consonants placed in a non-CCS context)

With this criteria of judgment, Table 5 shows the mean rates of the three articulatory variants of CCS sequences obtained from four Korean L2 speakers. As illustrated, no-deletion variants are most frequent, constituting 43% and deletion forms are quite common at 37%. Hyperarticulation variants are least common at 20%. If Hyperarticulation is considered as a special case of no-deletion variants, canonical variants amount to 63%. The emergence of these three variant types was also observed in the Korean speakers' production of /…stp…/ or /…stk…/ in L2 English (e.g., no-/t/ deletion, /t/-deletion, hyperarticulation of /t/, "must pad", "must call", Yun and Sung 2022). Furthermore, the distribution patterns of variants exhibited inter-speaker variation. Two speakers (K1, K3) applied CCS more frequently than they realized canonical forms. Conversely, no-deletion variants, i.e., "gestural hiding" cases were more common than deletion forms for K4, and K2 produced no-deletion variants as frequently as deletion forms.

Table 5. Mean Rates (%) of Variants of CCC Sequences in a CCS Context in English

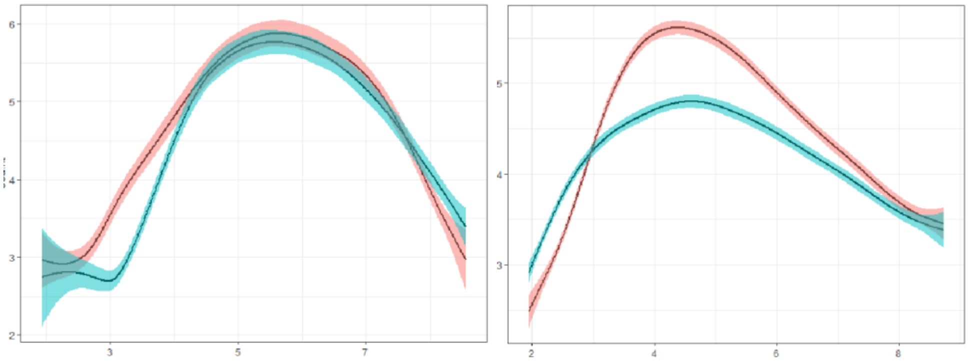
	Subjects				
Variants	K1	K2	K3	K4	Total
No-deletion	27	42	33	73	43
Deletion (/t, p, k/)	55	42	42	9	37
Hyperarticulation	18	16	25	18	20

Of interest is the fact that the types of variants of CCC or the likelihood of CCS varied depending on CCC cluster types as seen in Table 6. Table 6 shows the mean rates of variants of CCC sequences embedded in a CCS context by CCC types. For the two sequences /pt#k/ and /lp#t/, deletion variants were produced most frequently, meaning that Korean subjects reduced CCC by deleting word-final /t,p/. These sequences were less likely to be realized as canonical forms. In contrast, the other two sequences /kt#p/ and /lk#t/ exhibited the opposite articulation pattern. To be specific, CCS did not arise at all for /kt#p/ sequence and was applied less commonly for /lk#t/ sequence. This tendency indicates that word-final /t,k/ in a CCS context have less susceptibility to CCS but rather are articulated by raising the tongue tip for /t/ and the tongue dorsum for /k/. These exemplify the case of "a gestural hiding".

Table 6. Mean Rates (%) of Variants of CCC Sequences in a CCS Context by CCC Type

	CCC Types				
Variants	/pt#k/ ("apt key")	/kt#p/ ("perfect pet")	/lp#t/ ("help ten")	/lk#t/ ("milk tea")	Total
No-deletion	9	50	33	82	43
Deletion (/t, p, k/)	63	0	67	18	37
Hyperarticulation	27	50	0	0	20

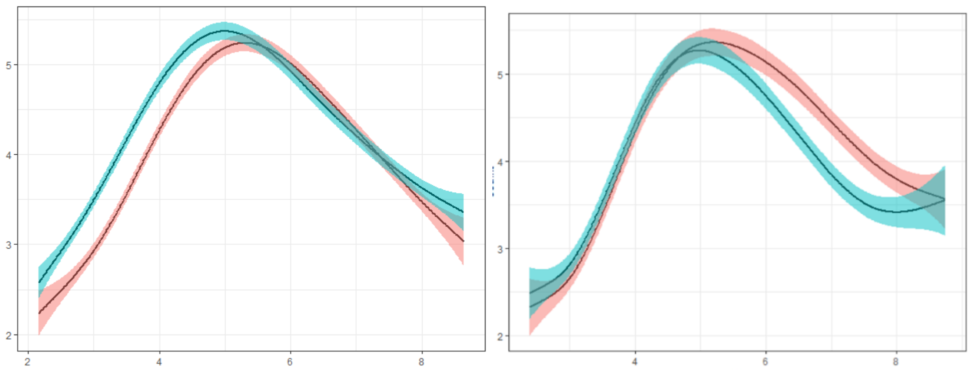
Figure 6 shows an example SSANOVA of tongue contours of no-deletion variants and deletion variants. Fig. 6(a) is labeled as the case of no-deletion variants where the tongue contour of the portion /t/ in /ptk/ sequence (pink curve) significantly overlaps with that of that of /t/ in a non-CCS context (blue curve) (e.g., *abrupt call* vs. *abrupt app*). Fig. 6(b) can be identified as a deletion variant because the tongue configuration of the portion of C_2 (pink curve) in /pt#k/ of "abrupt call" refers to [k] in the sense that the tongue dorsum is raised toward the velar, indicative of /t/ deletion, compared to the tongue contour of /t/ in /pt/ sequence of "abrupt app" (blue curve). Articulation of /pt#k/ sequences favored CCS by the deletion of /t/ over a gestural hiding, i.e., no-deletion forms. This finding suggests that the elision of so-called word-final /t/ in CC sequences followed by another consonant is not obligatory but rather optional.



(a) No deletion (in /pt#k/ from K4) (b) Deletion (/pt#k/ from K3)

Figure 6. **SSANOVA of tongue contours of the word-final /t/ in /pt#k/ sequences i.e., in a CCS context (pink curves) and in /pt#V/ in a non-CCS context (blue curves)**

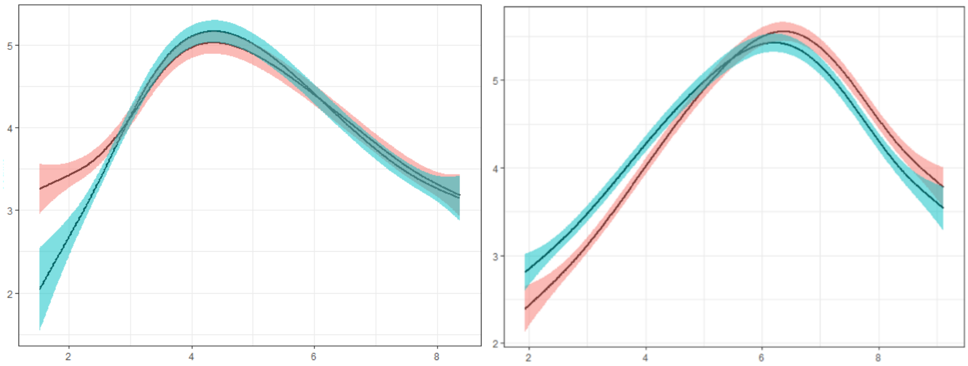
The /kt#p/ sequences exhibited quite different production patterns, compared with the /pt#k/ sequences as shown in Table 6. This shows that the identical word-final /t/ is realized in a divergent fashion depending on the CCC type it is embedded in. Fig. 7(a) shows a no-deletion variant where the front region of the tongue of /t/ portion in a /ktp/ cluster (pink curve) (e.g., "perfect pet") overlaps with that of /t/ in /kt#V/ sequences (blue curve) ("perfect arm"). CCS does not occur, preserving the word-final /t/. Fig. 7(b) illustrates a case of hyperarticulation of /t/ where the target /t/ placed in a CCS context (e.g., "compact pack") is articulated further front than that in a non-CCS context (e.g., "compact arm"). Such a /t/ does not elide but seems to undergo gestural overshoot by raising the tongue tip or blade toward the alveolar. In marked contrast with /ptk/ sequences, /ktp/ sequences did not allow CCS at all, but exhibited hyperarticulation or a gestural hiding by transposing the tongue toward the alveolar.



(a) No deletion (in /kt#p/ from K2) (b) Hyperarticulation (/kt#p/ from K2)

Figure 7. **SSANOVA of tongue contours of the word-final /t/ in /kt#k/ sequences i.e., in a CCS context (pink curves) and in /kt#V/ in a non-CCS context (blue curves)**

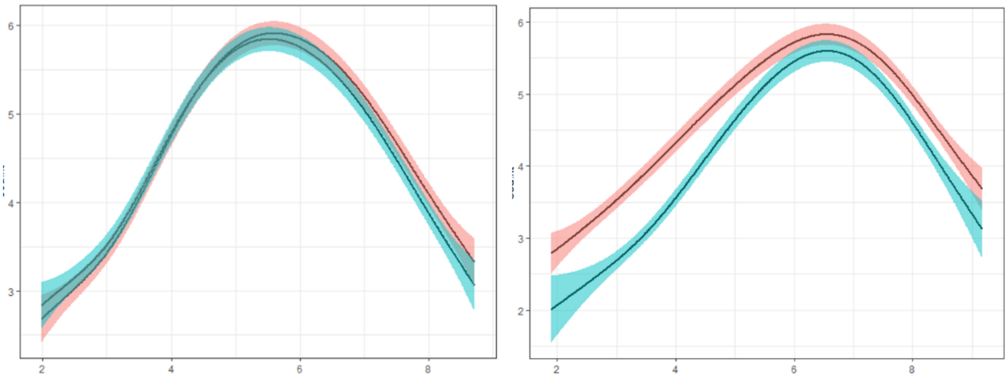
The sequences of /lp#t/ were realized as two variants, i.e., no-deletion and deletion variants as depicted in Figure 8. Deletion forms emerged almost double the times of occurrences of canonical, no-deletion variants (67% vs. 33%). This indicates that CCS is more likely to occur when the medial word-final target is /p/ by deleting it. Figure 8(a) shows an example of no /p/-deletion variants (e.g., "scalp tan" vs. "scalp ant") whereas /p/-deletion forms are illustrated in Fig. 8(b). In Fig. 8(b), the tongue front part of the medial consonant is further front than that of /p/ couched in a non-CCs context, suggesting that the former resembles one of the flanking alveolars such as [l] or [t].



(a) No deletion (in /lp#t/ from K2) (b) Deletion (/lp#t/ from K1)

Figure 8. **SSANOVA of tongue contours of the word-medial segment in /lp#t/ sequences i.e., in a CCS context (pink curves) and in /lp#V/ in a non-CCS context (blue curves)**

Like /lp#t/ sequences, /lk#t/ sequences elicited two types of variants, i.e., no-deletion and deletion variants. However, /lk#t/ sequences exhibited the opposite pattern of distribution of variants. Canonical forms, i.e., no-deletion variants were dominant over deletion forms (82% vs. 18%). That is, a great majority of tokens did not undergo CCS with the deletion of /k/. Fig. 9(a) depicts a sample of no-deletion of /k/ where the tongue contour of /k/ in a /lk#t/ sequence (pink curve) completely overlaps with that of /k/ in a /lk#V/ sequence (blue curve). This overlapping serves the clue to the judgment that the tongue dorsum of /k/ lying in a CCS context raises toward the velum in the same degree as the /k/ placed in a non-CCS context. It is suggested that compared to the realization of /t/ in a CCS context, /k/ is more likely to be the target for a gestural hiding from the comparatively higher rates of the nonapplication of CCS. Fig. 9(b) exemplifies a case of /k/-deletion where the tongue front region of the word-final segmental portion in a /lk#t/ sequence is further front than that in a /lk#V/ sequence, indicating that its tongue position is different from /k/ in a non-CCS context.



(a) No deletion (in /lk#t/ from K2) (b) Deletion (/lk#t/ from K2)

Figure 9. **SSANOVA of tongue contours of the word-medial segment in /lk#t/ sequences i.e., in a CCS context (pink curves) and in /lk#V/ in a non-CCS context (blue curves)**

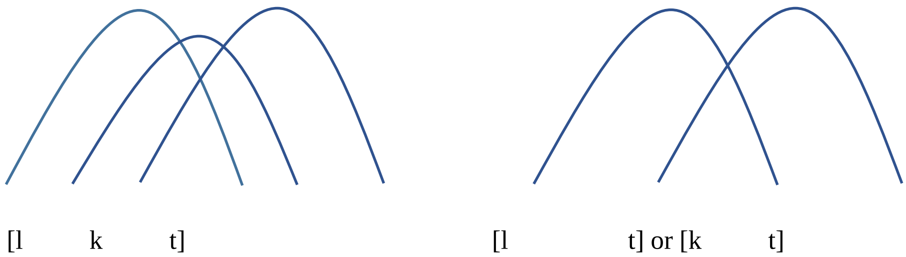
4. General Discussion

In the present study, two ultrasound imaging experiments were carried out to investigate the application mode of CCS in L2 English as well as in L1 Korean. In ultrasound experiment 1, we examined whether CCS occurs with the deletion of the medial consonants placed in two types of CCC in L1 Korean, including /lk+t, lk+p/. Ultrasound experiment 2 was conducted to assess the application mode of CCS with four types of CCC such as /pt#k, kt#p, lp#t, lk#t/ in L2 English.

The articulatory study yielded several novel findings. First, the application of Korean CCS is gradient rather than categorical with reference to certain types of CCC unlike the prediction of traditional phonological rules (Ellis and Hardcastle 2002, Ernestus et al. 2006, Gow 2003). For example, /lkt/ sequences are realized as three types of variants with respect to the pronunciation of the medial /k/. They can be labelled as "partial velar (=incomplete deletion)", "full velar (=/l/-deletion)", or "zero velar (=/k/-deletion)", following the labelling of Wright and Kerswill (1989) and Gaskell (2003). Previous studies have documented solely two categorical variants, i.e., "/l/-deletion," or "/k/-deletion," but this study found that some medial /k/ is articulated with lesser raising of the tongue dorsum toward the velum than the identical /k/ placed in a non-CCS context (e.g., "mal**k**ta" vs. "ma**k**ta"). As seen in Figure 1(a), the highest point of tongue dorsum for /k/ in a CCS context is placed between that of /k/ in a non-CCS context and that of /l/. It seems that the gesture of the tongue dorsum raising undergoes undershooting toward the velum. This variant also can be categorized as a case of "a gestural hiding" in the sense that the sound is acoustically inaudible probably due to the gestural overlap among the flanking alveolars like /l/ or /t/, but the main articulator still moves toward the target along the palate (Browman and Goldstein 1995). Another explanation is that this variant is a type of gestural undershoot frequently accompanied in reduced speech (Ernestus and Warner 2011). Alternative account is that lexical items containing /lk/ ending might have more robust abstract representation for these CC clusters than those with /lp/ clusters, facilitating the gestural realization (or *preservation*) of CC sequences in the surface and inducing a gradient fashion in the production.

Phonetic gradience or categorical deletion in /CCC/ sequences can be captured by employing the temporal organization of gestural relation grammar proposed by Byrd (1995), Gafos (2002) and Davidson (2006). Figure 10(a) shows the gestural relations of the /CCC/ sequence of /..lkt../ for the "partial velar" variant where the gesture of medial /k/ is not articulatorily elided but still raised toward the velum to the point lower than the constriction point of /k/ in isolation. The aforementioned "partial velar" variants are interpreted to stem from the overlap of gestures of surrounding consonants /l/ and /t/, whereby the closure gesture of [k] is overshadowed between the closure gestures of [l] and [t] and consequently [k] is not audible although the tongue dorsum of [k] moves toward the velum articulatory as evident in the present ultrasound experiment. This finding and interpretation are formally delineated in the gestural coordination schema in Fig. 10(a). The middle curve (the gesture for [k]) is substantially overlapped with the leftmost curve (the gesture for [l]) and the rightmost curve (the gesture for [t]). In addition, unlike the [l] and [t], the highest point of [k] does not reach the peak constriction against the velum, indicative of "target undershoot". Figure 10(b) shows the gestural orchestration representation for /k/- or /l/-deletion variants where the gestural curve for one consonant is not marked primarily due to the actual deletion of its gesture. As a consequence, this coordination is phonetically implemented, leading to the phonetic representation for [malta] or [makta]. Note that the left curve represents the gesture for [l] or [k] and the right curve refers to that for [t].

Moreover, this study is also significant in revealing the relative occurrences of each variant (see Table 2). "Partial velar" and "full velar" variants emerge more frequently than "zero velar" forms (44% vs. 12%). Nonetheless, it still remains unclear whether CCS is gradiently applied for all CCC clusters in Korean. Further studies might benefit from investigating a wider range of CCC types in Korean. At any case, unlike the gradation fashion in CCS evident in a /lkt/ sequence, /lpt/ sequences show only two types of categorical variation in their production, i.e., /p/-deletion or /l/-deletion (See Table 4). Thus, considering the limited amount of articulatory findings in the present preliminary study, it is plausible that the gradedness in Korean CCS is contingent on the specific CCC cluster types. Additionally, the likelihood of CCS and the rates of each variant can vary depending on individual speakers (Table 1 and 3). For some speakers (K2, K4), "partial velar" variants were dominant for a /lkt/ sequence whereas others favored "full velar," or "zero velar" variants (K3, K5, K6). However, as for a /lpt/ sequence, a majority of speakers preferred /p/-deletion variants to /l/-deletion forms.



(a) Gestural overlap & target undershoot (b) Gestural overlap

Figure 10. Schema for a gestural hiding temporal relations in /CCC/ in [malkta] (a) and for deletion variant [malta] or [makta] (b)

Second, the present data show that the distribution of the variants for /CCC/ sequences can differ depending upon the type of suffixal ending attached to the adjectival or verbal stems in Korean. This finding has not been reported in previous studies on Korean CCS. This might be intriguing in the sense that the target consonant for reduction can be determined to some extent by the suffixal type. For example, when the stem ending with /lk/ is attached to the declarative suffix ending /ta/, "partial velar," or "full velar" (i.e., /l/-deletion) variants are more common than "zero velar" (i.e., /k/-deletion) forms. However, when a connective ending /-ko/ is attached, the /lk/ sequence is realized as "full velar" variant most frequently. In /lpt/ and /lpk/ sequences, however, this preferential selection pattern does not occur, which is not clear yet.

Findings concerning the application mode of CCS in L2 English give interesting implications. As in Table 7, different types of consonant sequences displayed the different likelihood of variant types between L1 Korean and L2 English. First, /k/ in the /lkt/ sequences was retained more frequently in L2 English (e.g., /silk tea/) than in L1 Korean (e.g., /malkta/ "be clean"). This suggests that CCS has greater likelihood of application for /lkt/ sequences in L1 Korean than in L2 English (56% vs. 18%). It is implied that the applicablity of CCS in L1 Korean is not likely to transfer to L2 English as much as expected. What accounts might be offered for this asymmetry in the likelihood of the application of CCS? One possible account lies in the difference in boundary strength between $C_1C_2$and C_3 and Korean speakers might sensitively resort to this difference. The words used for the production of Korean stimuli contain morpheme boundary between the stems ending with CC and the suffix starting with C (e.g., /malk + ta/ "clean+suffix"). However, the /CC#C/ sequences in English contain word boundary. Thus, the identical /CCC/ sequences within the words in Korean might have more robust sequential strength in their lexical representations than those across the words in English. This might have induced more gestural overlap in the temporal dimension and led to higher likelihood of the application of CCS by deleting the middle consonant in /CCC/ sequences. Alternative scenario is that Korean speakers are equipped with the internal knowledge regarding the difference in the phonotactics of Korean and English. Specifically, since they are aware that Korean does not allow a /CC/ sequence in coda but complex /CCC/ sequences are permissible in English, it might be the case that they tend to preserve /CCC/ sequences in English more frequently than in Korean.

Table 7. Mean Rates (%) of Variants of CCC Sequences in a CCS Context by Language

Variants	/…lkt…/		/…lpt…/	
	Kor	Eng	Kor	Eng
No-deletion	44	82	0	33
Deletion (/p, k/)	56	18	100	67

The preference of /l/-retaining variants for /lp/ sequences to those for /lk/ sequences found in the present study is consistent with the recent Korean corpus study by Kwon et al. (2023). Our finding shows that /lp/ codas in Korean were realized as /l/-variants at 63% whereas /l/-retaining variants occurred at 53% with /lk/ sequences. Kim and Kang (2021) also showed that C_1-preservation variants in /C_1C_2/ coda clusters in Korean is affected by speakers' age as well, coupled with the finding that younger Korean speakers prefer C_1-retaining variants to C_2-preserving forms in /C_1C_2/ coda sequences. However, this asymmetry in the variability pattern for the production of Korean /lpt/ and /lkt/ sequences did not emerge in or transfer to the production of the identical CCC sequences in English as reported in this study. Korean L2 speakers' strong tendency to preserve both C_1 and C_2 in English /lk(t)/ or /lp(t)) sequences suggests that the gestural hiding is more common in L2 English than in L1 Korean, albeit its extent varies.

Whereas the present study examined the variation patterns for CC sequences when they are followed by a consonant-initial suffix, Kim (2022) investigated how eleven types of coda clusters in Korean are realized when they are attached to a vowel-initial suffix. Kim's production study showed that clusters sharing [±sonorant] features such as /ps, ks, lm/ prefer no-deletion variants whereas those which do not, such as /lp, lk, ls/ favor CCS by deleting one consonant. Of course, these two studies probed into CCS in a different context (i.e., before C-initial suffix vs. before V-initial suffix). The present study, however, showed a different realization pattern between /lp/ and /lk/ variants, which makes this study significant.

Given PAM's claim that L2 sounds are perceptually mapped onto L1 sounds with reference to their gestural (dis)similarity between the two, the finding in this study does not seem to be in congruence with Best and her colleagues' prediction (Best and Tyler 2007). It means that the sequences of consonantal gestures in L2, e.g., the tongue blade raising followed by tongue dorsum raising in /lk/ sequences in English are not perceptually assimilated to the identical sequences in L1 Korean. One account for such a failure might be that gestural assimilation between L2 and L1 sequences is overridden by other factors such as the differences in phonotactics between L2 and L1. In this study, Korean speakers do not adapt complex L2 English coda clusters to L1 Korean counterpart, but rather seem to respect their own phonotactics and reflect them in their articulation.

5. Conclusion

Two ultrasound imaging experiments were performed to examine the application mode of CCS in L1 Korean and L2 English. First, Experiment 1 demonstrated that the variability patterns for /CCC/ sequences in Korean vary depending on cluster type and individual speakers. Production of /lkt/ or /lkk/ sequences yielded three types of variants such as "partial velar," "full velar," and "zero velar" whereas /lpt/ or /lpk/ clusters were realized as two types of variants such as /p/-deletion and /l/-deletion. These results suggest that Korean CCS is applied in gradient fashion rather than categorically as expected in the traditional phonological analysis. In particular, /CCC/ sequences including /lk/ were pronounced as "partial velar" variants at 26%, i.e., the case of a gestural hiding where the middle consonant /k/ is articulated with the movement of tongue dorsum toward the velum, albeit not audible due to gestural overlap and gestural undershoot. Second, Experiment 2 provides support for a range of variants of /CCC/ clusters in L2 English such as /ptk, ktk, lpt, lkt/, depending on cluster type and individual speakers. Compared to the production of L1 Korean CCC, "no-deletion" variants were elicited more frequently, showings the exemplars of gestural hiding and gestural overlap.

A possible limitation of the present study is that only two types of CC clusters (e.g., /lk/ and /lp/) in both Korean and English were compared for the application mode of CCS. Moreover, these two clusters are the ones known to have two alternations, i.e., C_1-deletion or C_2-deletion. If a wider range of clusters in Korean and English are tested, the articulation data might yield more interesting variants for different types of CCC sequences. Furthermore, L2 speakers of different proficiencies might produce divergent variant forms for each cluster.

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Examples in: English
Applicable Languages: English
Applicable Level: Tertiary

