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Korean Learners' Production of L1 Korean and L2 English Alveolars: Ultrasound Imaging Evidence of Sub-Phonemic Articulatory Variation*

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ABSTRACT

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The present study aims to investigate the variation in the realization of L1 Korean alveolars and L2 English alveolars at the sub-phonemic level through ultrasound imaging of tongue articulation. Another primary goal is to examine whether transfer from L1 to L2 occurs regarding place of articulation within the phonemic category, i.e., alveolars. To this end, Korean alveolar stops /t, t^h/ and fricative /s/ and English stops /t,d/ and fricative /s/ were elicited from Korean learners of L2 English in an ultrasound experiment. First, results showed that three Korean stops were produced with the tongue tip raising toward the alveolar ridge at the same height, but they exhibited variation regarding the height of the tongue blade gesture at the phonetic-fine gestural level. Second, it was found that three L2 English alveolars were articulated with the tongue tip raising toward the alveolar ridge like L1 Korean alveolars, but the placement pattern of the tongue blade varied depending on individual speakers. Finally, it was demonstrated that Korean stops /t^h, t/ are articulated with the tongue front raising higher, compared to their English counterparts /t, d/, which accounts for the difference in the intraoral pressure and different VOTs between the two languages. Furthermore, the pattern of Korean /s/ and English /s/ showed interspeaker variations in terms of the relative tongue front position. These findings provide support for gradient realizations of L2 English alveolars /t,d,s/ as well as L1 alveolars /t^h,t,s/regarding the gestural movement of the tongue blade, indicative of differential patterns at the sub-phonemic level.

KEYWORDS

alveolar consonants, L2 production, Korean, English, sub-phonemic features, articulatory gestures, ultrasound imaging technique

1. Introduction

Speech sounds are a complex outcome of various physical and acoustic features, produced through the coordinated movement of multiple articulatory structures, including the jaw, lips, tongue, larynx, and others (Ladefoged 2006). The perception or assessment of individual sounds often serves as the basis for their description, remediation, or as an evaluation metric for second language (L2) speech produced by L2 speakers. Moreover, traditional approaches to characterizing speech sounds have primarily focused on the phonemic level. However, an acoustic description based solely on phonemes is inadequate for providing a comprehensive understanding of speech sounds (Ahn 2018). In this regard, recent studies have emphasized the importance of articulatory investigation using ultrasound imaging, which provides direct visual evidence of tongue movement and allows for a more fine-grained analysis of speech beyond the phonemic level.

Given this, this study has three primary objectives in examining the articulatory characteristics of L1 Korean and L2 English alveolars through ultrasound imaging. The first goal is to investigate whether the actual place of articulation for the so-called alveolar sounds in Korean (i.e., /t^h/, /t/, /s/) is consistent along the palate regarding the placement of the tongue tip and blade. The second objective is closely related to the first, namely, whether the alveolars in L2 English involve variable places of articulation among /t/, /d/, and /s/. These two research goals focus on exploring the variability in the place of articulation among phonologically identical alveolars, which are characterized by the featural combination [-labial, -velar] or a single feature [+coronal]. The final goal is to examine the potential transfer of L1 articulatory properties to L2 at the sub-phonemic level, specifically in terms of articulatory gestural movements. If English alveolars are articulated with the tongue tip or blade being raised toward the alveolar ridge as high as Korean alveolars, it is anticipated that negative transfer will occur regarding the point of articulation from L1 to L2.

Despite the ongoing debate, a detailed articulatory examination of Korean so-called alveolar segments remains relatively underexplored, particularly about their L2 English counterparts. Most previous studies have relied on impressionistic or broad articulatory categories, often overlooking the fine-grained gestural variation that may occur within a single phonemic category. This phonological abstraction, while useful for classification, often obscures crucial sub-phonemic differences that may play a significant role in both L1 articulation patterns and L2 acquisition. Given that speech sounds are dynamically constructed through multi-gestural coordination rather than rigid category boundaries, a more nuanced investigation at the sub-phonemic level is warranted.

In this light, the present study offers a novel contribution by focusing on the articulatory realization of L1 Korean and L2 English alveolars, with particular attention to sub-phonemic variability. Drawing upon ultrasound imaging data, this research seeks to reveal how the gestural characteristics, specifically tongue tip and blade movement, may vary systematically within and across languages. Of particular interest is whether articulatory patterns evident in L1 Korean transfer to L2 English, not simply at the phonemic level, but within the phonological space where fine phonetic distinctions are at play. By probing beyond categorical phoneme labels and into the gestural specifics of articulation, this study aims to uncover evidence of subtle, yet potentially systematic, articulatory transfer between L1 and L2.

The theoretical implications are twofold. First, the findings are expected to expand current understanding of the articulatory realization of Korean alveolars, contributing to phonetic typologies and cross-linguistic articulatory research. Second, by bridging theories of L2 speech learning (e.g., Speech Learning Model: SLM and Perceptual Assimilation Model for L2: PAM-L2) [1] with empirical articulatory data, the study contributes to an integrated

[1] SLM**:** A model proposed by Flege (1995) that explains how L2 learners' phonetic categories are formed and modified

view of L2 phonological development—one that considers not only acoustic and perceptual dimensions, but also the underlying articulatory mechanisms. In doing so, the research underscores the importance of articulatory analysis in revealing hidden layers of variation that may influence L2 phonological acquisition, especially in typologically proximate segments such as Korean and English alveolars.

In sum, by targeting the sub-phonemic articulatory detail of Korean and English alveolars, this study fills a crucial gap in the literature, offering empirical insight into the micro-level variation that shapes second language speech and its interaction with native articulatory patterns. The results hold pedagogical relevance as well, by informing pronunciation instruction and error diagnosis based on articulatory evidence, rather than solely auditory impressions or segmental transcription.

2. Theoretical Background

2.1 The Characterization of Korean Alveolars

Traditionally, Korean consonants are classified into labials, alveolars, palatals, velars, or glottals by the criterion of place of articulation (Chang 1996, Goo 2019, Lee 1996). In particular, the classification of Korean stops /t/, /t', t^h/ as either alveolars or dentals, concerning their place of articulation, has been a subject of controversy. Additionally, there have been debates about whether these Korean so-called alveolars are similar to their English counterparts /t/, /d/, and /n/ in terms of place of articulation.

Kim (2004) and Kim et al. (2005) argued that the Korean lax stop /t/ is articulated with apico-dental contact, whereas the tense and aspirated stops /t'/ and /t^h/ involve contact in the apico-laminal region of the tongue, spanning the dental and palato-alveolar areas. Anderson et al.'s (2004) linguogram study indicated that Korean obstruents are primarily produced with laminal contact. Ko's (2013) palatogram study suggested that Korean stops /t/, /t'/, /t^h/ are (denti-)alveolars and are comparable to English coronals in terms of their place of articulation. Furthermore, their linguogram experiment revealed that for Korean alveolars, both the tongue blade and tongue tip are active articulators, whereas in English, the tongue tip is more typically used.

Although less extensively studied, Korean alveolar fricatives such as /s/ have also been reported to be articulated with laminal constriction, in contrast to English /s/, which is typically produced with apical contact (Kim 1999, 2001, Lee 2025). Such articulatory distinctions, while subtle, may have important implications for cross-linguistic influence and L2 speech production, particularly in terms of articulatory transfer from L1 to L2.

Despite these insights, prior research has primarily relied on static articulatory imaging techniques or segmental-level analyses, often overlooking dynamic and gradient articulatory gestures that fall within the same phonemic category. More specifically, sub-phonemic variation—fine-grained differences in articulatory implementation within a phoneme—has received limited empirical attention, even though it may be critical to understanding transfer effects in L2 segmental production.

Accordingly, the present study aims to address these gaps by using ultrasound imaging to examine the articulatory characteristics of Korean alveolars at the sub-phonemic level. In doing so, it seeks to determine whether the articulatory realization of Korean alveolars influences the production of their L2 English counterparts.

through interaction with L1 categories. PAM-L2: An extension of Best's (1995) PAM framework, applied to second language learning, which accounts for how L2 sounds are perceived relative to existing L1 categories and how this perception influences L2 production.

This approach allows for a more nuanced investigation of the phonetic continuity and divergence between L1 and L2, shedding light on the extent to which L1 articulatory habits persist in L2 and the nature of segmental equivalence at the gestural level.

2.2 Articulatory Characteristics of English Alveolars and Their Implications for L2 Acquisition by Korean Learners

Unlike Korean alveolars, the English alveolar stops /t, d/ are known to be made with the contact of the apical part of the tongue with the alveolar region or behind the front teeth (Ladefoged 2006). This means that Korean stops /t^h, t/ are denti-alveolars with the tongue blade as well as the tongue tip, while the English equivalents /t, d/ are mainly alveolars made by the tongue tip (Ko 2013, Ladefoged 2006). This articulatory difference, though subtle, reflects language-specific phonetic norms that may contribute to perceptual and production asymmetries among L2 learners.

Ko (2013) and Ladefoged (2006) both note that the English /t, d/ stops are not only apical but also alveolar in the strict sense of articulatory placement. These sounds are produced with the tongue tip elevated toward the alveolar ridge, often without the involvement of the tongue blade. In articulatory phonetics, such specificity in constriction location and gesture type plays a crucial role in distinguishing segmental inventories across languages, especially when those segments are phonologically equivalent but phonetically divergent. Additionally, Melo, Mota and Berti's (2017) ultrasound study and Cleland and Scobbie (2021) showed that English alveolar stops /t,d/ involve the elevation and anteriorization of the tongue tip toward the alveolar ridge.

Moreover, studies of English fricatives have shown that the alveolar fricative /s/ is predominantly produced with apical contact, often with the tongue tip raised and grooved to create a narrow stream of air directed at the teeth. This sharply contrasts with Korean /s/, which has been reported to involve broader laminal constriction, typically made with a flatter tongue surface and more diffuse airflow (Lee, 2025). As such, while both /s/ sounds are categorized as alveolar fricatives, they exhibit important differences in the shape and coordination of articulatory gestures.

In the context of L2 acquisition, these articulatory differences have potential implications for the process of phonetic transfer. According to models such as the Speech Learning Model (Flege 1995, 2003) and the Perceptual Assimilation Model (Best 1994, 1995), the degree of perceived similarity between L1 and L2 phonemes influences the likelihood of successful phonetic differentiation and category formation. When L1 and L2 segments are perceived as equivalent, learners may default to native articulatory routines, even if such routines do not align with the fine-grained phonetic properties of the L2 target sounds.

Nevertheless, the extent to which learners are sensitive to or capable of acquiring such sub-phonemic distinctions remains underexplored, particularly in articulatory domains. In the case of Korean learners of English, the phonological equivalence between Korean and English alveolars may mask gestural-level differences, potentially leading to persistent L1-based articulatory patterns in L2 production.

Given this, the present study seeks to provide empirical evidence regarding the sub-phonemic articulatory properties of English alveolar segments as produced by Korean L2 speakers. By employing ultrasound imaging to capture fine-grained tongue movement, this study aims to determine whether L2 learners can approximate the native-like apical articulation of English /t, d, s/ or whether they exhibit articulatory transfer from their L1 Korean system. In doing so, the study not only contributes to a better understanding of phonetic variation in L2 production but also addresses theoretical questions concerning the nature of cross-linguistic influence at the sub-phonemic level.

2.3 L2 Sound Acquisition at the Sub-Phonemic Level

Recent decades of L2 studies have shown 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, 2003) claims that speech perception is executed based on acoustic signals and L2 speakers' production errors are incurred by their incorrect perception of the acoustic properties of L2 sounds. On the other hand, Perceptual Assimilation Model (PAM) suggested by Best (1994, 1995) and other colleagues posits that L2 sounds are perceived and mapped onto L1 sounds based on gestural (dis)similarities along with the assumption of the link between perception and production (Best 1994, 1995, Best and Tyler 2007, Best et al. 2001). Under these two models, the larger the perceived distance from L1 to L2 sounds is, the more feasible it is to forge a new phonological category and acquire L2 sounds. Conversely, the less the perceptual similarity between the two, the more difficult it is to form the L2 category in the shared phonological space.

For example, Korean L2 learners showed great difficulty in distinguishing English vowel contrasts (e.g., /æ/-/ɛ/, /ɑ/-/ʌ/, and /ɛ/-/ɪ/), including tense-lax vowels (e.g., /i/-/ɪ/, /u/-/ʊ/). Specifically, English /i/ was wrongly perceived as /ɪ/ at 33%, and the reverse was at 23%, indicative of difficulty of acquisition and production (Flege 1995). The PAM also posits three patterns of perceptual assimilation, (i.e., Two category (TC), Single category (SC), and Category goodness (CG)), and predicts the likelihood of success in distinguishing L2 sounds in the order of TC, CG, and SC (Best 1995, Best and Tyler 2007). TC refers to the case where two L2 sounds are perceptually assimilated to two different L1 categories (e.g., English /t/ => Korean /t^h/; English /d/ => Korean /t/). SC is the type of correspondence between two L2 categories and a single L1 category (e.g., English /ɛ/ => Dutch /ɛ/; English /æ/ => Dutch /ɑ/, Escudero et al., 2012).

To be specific, Park and de Jong's (2008: 709) perception study showed that English /t/ was perceived as Korean aspirated stop /t^h/ at 98%, and English /d/ was perceptually mapped onto Korean lax stop /t/ with 84%. Furthermore, it was shown that English word-initial /s/ was identified as Korean /s'/ by 88% and English /z/ as Korean /ʧ/ with 95% (de Jong and Cho 2012). Under the PAM model, it is speculated that English L2 alveolar pairs /t/-/d/ and /s/-/z/ can be categorized as TC. Accordingly, such equivalence mapping leads us to anticipate that Korean learners might face few challenges in perceiving and producing English alveolars accurately.

However, this prediction within the PAM model may be relevant at the phonemic level. Limited attention has been given to the sub-phonemic articulatory characteristics of second language (L2) alveolar phonemes. To address this gap, the present study aims to determine whether this expectation holds true between L2 and first language (L1) speakers' production at the precise point of articulation.

Best and Tyler's (2007) PAM-L2 posits equivalence between L1 and L2 at phonetic level as well as the phonological level. They assume that speakers develop a common L1-L2 phonetic and phonological system as they acquire L2. Given that, this study explores whether Korean L2 learners implement phonetic attunement with respect to the phonetic fine detail, i.e., delicate place of articulation, when it comes to the production of segments which are classified as identical alveolar categories.

3. Research Questions

In the present study, we address three research questions to reveal the articulatory characteristics of L1 Korean and L2 English alveolars concerning phonetic-fine detail regarding place of articulation, i.e., where the main articulatory gesture is raised along the palate.

1. To what extent do Korean L1 and English L2 alveolar segments differ in their sub-phonemic articulatory realizations, particularly regarding tongue placement along the palate?
2. Does the place of articulation of Korean alveolars influence the target articulatory location of L2 English alveolars in the oral cavity for Korean speakers of L2 English?
3. How do Korean learners of English implement phonetic adjustment in the articulation of L2 alveolars, and what evidence is there of persistent L1-to-L2 articulatory transfer at the level of fine-grained gestural detail?

4. Production Experiment

4.1 Participants

Ten undergraduate students majoring in English at Kyungpook National University participated in this study. All participants were native speakers of Korean with no prior experience studying abroad. Recruitment was conducted through English-related courses offered as part of the participants' degree programs. Before enrollment, the researchers provided a detailed explanation of the study's procedures and the safety of the ultrasound equipment. Participation was entirely voluntary, and students were informed of their right to withdraw at any time without penalty. Those who chose to take part expressed their intent to the researchers and received appropriate compensation for their participation.

This study employed a convenience sampling method, which is commonly used in second language acquisition research (Fred 2005). To mitigate potential limitations associated with convenience sampling, such as the presence of outliers or limited group comparability, a background survey was administered. The survey included items related to participants' self-reported English proficiency, learning experiences, and pronunciation confidence. English proficiency was assessed using two measures: (1) official test scores (e.g., TOEIC, TOEFL), and (2) a self-assessment on a 10-point Likert scale ranging from 1 (low proficiency) to 10 (advanced proficiency). Due to insufficient responses regarding official test scores, the self-assessment scores were used for proficiency classification. Participants who rated themselves between 4 and 7 were categorized as having intermediate English proficiency.

All participants reported over ten years of formal English education through the Korean school system. However, the majority indicated limited opportunities to use English in real-life contexts outside the classroom, particularly in communicative or immersive settings.

4.2 Stimuli

Two sets of stimuli were selected. First, to elicit Korean alveolars, all stimuli consisted of disyllabic 18 words, and each word included one of three target alveolars / t^h, t, s/ word-initially. All tokens had a form of CVCV. To control the coarticulatory effect from its neighboring vowel, the vowel following the word-initial alveolar varied among three vowels /i, a, u/, and the second syllable alternated between /ta/ and /na/. Thus, six tokens started with a lax alveolar /t/, another six stimuli with an aspirated /t^h/, and an alveolar fricative /s/ was included in six tokens, as is exemplified in Table 1. A total of 18 tokens were randomized and embedded in a carrier sentence, "This is ________" in Korean orthography. Each target word was repeated three times. The total number of recorded vowel tokens was 54 (=18 word tokens × 10 subjects × 3 repetitions). It should be noted that Korean tense alveolars, namely /t/ ('ㄸ') and /s/ ('ㅆ'), were not included in the present study. This is because the main objective was to compare the articulatory characteristics of Korean alveolars with their English counterparts, focusing on aspirated and lax stops as well as the fricative /s/, which have direct correspondences in English (/t, d, s/). The tense series lacks such direct L2 equivalents, and including them would have extended the study beyond the intended scope. Similarly, the nasal /n/ was excluded, since its tongue posture and aerodynamic properties differ substantially from oral stops and fricatives, making it less suitable for a direct cross-linguistic comparison within the current experimental design.

Table 1. Korean Stimuli

V1/C1	/t^h/	/t/	/s/
/i/	t^hita, t^hina	tita, tina	sita, sina
/a/	t^hata, t^hana	tata, tana	sata, sana
/u/	t^huta, t^huna	tuta, tuna,	suta, suna

Second, to obtain English alveolars, 18 English words were selected for the production experiment. As illustrated in Table 2, all stimuli were monosyllabic. Since the point of interest in this study is the alveolar, the real word stimuli begin with one of the three English alveolars /t, d, s/ followed by the identical vowels /i, a, u/ as the Korean stimuli. In total, 18 real English words were repeated 3 times for ten subjects. All the English stimuli were embedded in a carrier phrase "This is ___________" and the participants were asked to read the phrases as naturally and fast as they could.

Table 2. English Stimuli

V1/C1	/t/	/d/	/s/
/i/	teem, team	deep, deem	seem, seep
/ɑ/	Tom, top	dop, dob	sop, sob
/u/	too, tool	dude, doom	soup, suit

In sum, 18 stimuli tokens were produced 3 times using ten Korean speakers. Thus, a total of 540 alveolars were obtained (18 tokens × 10 subjects × 3 repetitions).

4.3 Procedures for Data Collection and Analysis

Ultrasound data were obtained to evaluate where the main articulators, i.e., tip or blade of the tongue, are placed along the palate in the oral cavity to elicit Korean and English alveolars by Korean learners of English.

To take the ultrasound recordings, all the participants were invited into a quiet room. To produce midsagittal ultrasound videos, we used a MicrUS EXT-1H ultrasound machine (developed by TELEMED) with Articulate Assistant Advanced (AAA), a software designed to record and analyze speech production data from ultrasound (Articulate Instruments Ltd. 2013). Recordings of articulatory and acoustic stimuli were conducted, and both data were obtained simultaneously using the AAA software. Each participant was seated before a computer running AAA software. The computer was connected to a MicrUS EXT-1H ultrasound machine (Articulate Instruments Ltd., 2013). The machine had a MC4-2R20S-3 64-element 2 to 4 MHz convex-curved transducer, which took 82 frames per second across a 92° field of view. The transducer was fixed to the chin by being attached to the headset.

We used an Articulate Instruments headset (i.e., UltraFit headset) to stabilize the probe, which is required to obtain reliable image data (Spreafico et al. 2018). A microphone was connected with an external Focusrite Scarlette Solo 2nd generation pre-amplifier at the sampling rate of 22,050 Hz. The microphone was physically attached to the headset so that the microphone could be mounted to the transducer and keep a constant distance from the participants' mouths as they recorded the stimuli.

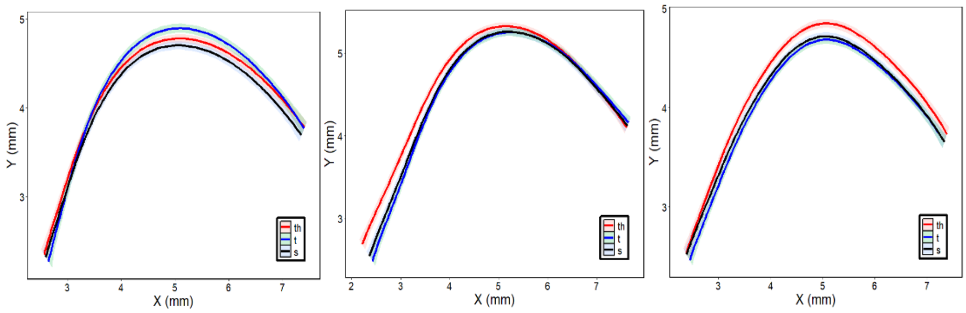
To quantify the analysis of the tongue configuration, the extracted images were overlaid with the tongue contours by drawing the tongue body lines via the function of "Edit Splines" in AAA. Since the tracking method permissible in the current AAA requires manual intervention, we manually traced all midsagittal tongue contours by connecting 36 points along the tongue body line with a mouse on the computer, using the 'Edit Spines' function in AAA (Heyne et al. 2019). Then, the tongue contours were again extracted in a series of 36 (x-y) coordinates. The x axis represents tongue anteriority, and the y-axis refers to tongue height. The tongue splines were exported based on 36 fan lines overlaid on the images by clicking the button 'export' in the window of 'Spline Workspace', resulting in 36 x-y coordinates being exported to the Excel files. The adjusted tongue contours were subjected to a smoothing Spline Analysis of Variance (henceforth, SSANOVA) for the statistical analyses (Davidson 2006, Gu 2002, 2014) because SSANOVA shows the tongue shape for articulation under different conditions and is useful to determine whether or not there are significant differences between the smoothing splines that are the best fits for two data sets being compared.

After that, Cartesian coordinates were converted to polar coordinates of tongue contours with angular coordinate θ and radian coordinate r. After that, tongue contour images were visualized based on transformed polar coordinates, i.e., (θ, r), following a polar SSANOVA model (Heyne et al. 2019, Hussain and Mielke 2021: 6, Mielke 2015, 2861-62). The way to assess significant differences between the two tongue contours in the polar SSANOVA is to check whether the confidence intervals for the two contours overlap. Overlapping means non-significance, and non-overlapping indicates statistical significance between the two SSANOVA tongue curves ($p<.05$).

5. Results

5.1 Sub-Phonemic Variation of Korean Alveolars /t, t^h, s/

We explored whether there is any variability in the movement of tongue front gestures placed in the alveolar region along the palate when it comes to the production of Korean alveolars /t^h, t, s/. To this end, we assessed tongue shape differences, especially in the region of the tongue front, i.e., tongue blade and tip, using SSANOVA comparisons. The results showed that there were no differences in the tongue tip position among the alveolars, indicative of three consonants being characterized by [+alveolar] phonologically. The relative placement of the tongue blade, however, exhibited variation among the three alveolars. Figure 1 shows three types of patterns of the relative location of the tongue blade among /t^h, t, s/. SSANOVA comparisons were made by averaging nine tongue body shapes from each of /t^h/, /t/, and /s/, respectively, contained in the Korean words within a single speaker. Type I represents the comparison where alveolar stops /t^h, t/ are articulated with tongue blade raising higher than alveolar fricative /s/ as seen in Figure 1(a). This pattern shows the typical, canonical tongue shapes for these three alveolars because stops involve contact with the alveolar ridge to build up the oral pressure, whereas fricatives create a narrow air passage without the tongue blade being constricted against the alveolar ridge. Type II refers to a variant case where three alveolars are produced with both the tongue blade and the tongue tip being raised at the identical height along the alveolar ridge. Another peculiar variation type is observed in Type III, where /t^h/ is articulated with both the tongue blade and tip raising higher than /t, s/ (Fig. 1(c)).



(a) Type I (b) Type II (c) Type III

Figure 1. SSANOAV Comparisons of Three Korean Alveolars

(Blue curves refer to the tongue shapes of [t^h], red curves to those of [t], and black curves to those of [s].)

Table 3 shows the distribution of these three patterns among the speakers. As expected, Type I emerged for the greatest number of speakers (i.e., five speakers). It suggests that a majority of speakers articulate alveolar stops by raising the tongue blade higher, compared to their fricative counterparts. Another dominant pattern was Type II, where /t^h, t, s/ are produced with both the tongue blade and tongue tip raising at the same height along the palate. This type was observed for four speakers out of ten. Type III occurred only for one speaker (K2), where /t^h/ was exceptionally produced with a higher tongue blade and tongue tip than /t, s/, which does not align with the production-based expectation.

Table 3. Distribution of Variable Types with Their Characteristics for Korean Alveolars by Speakers

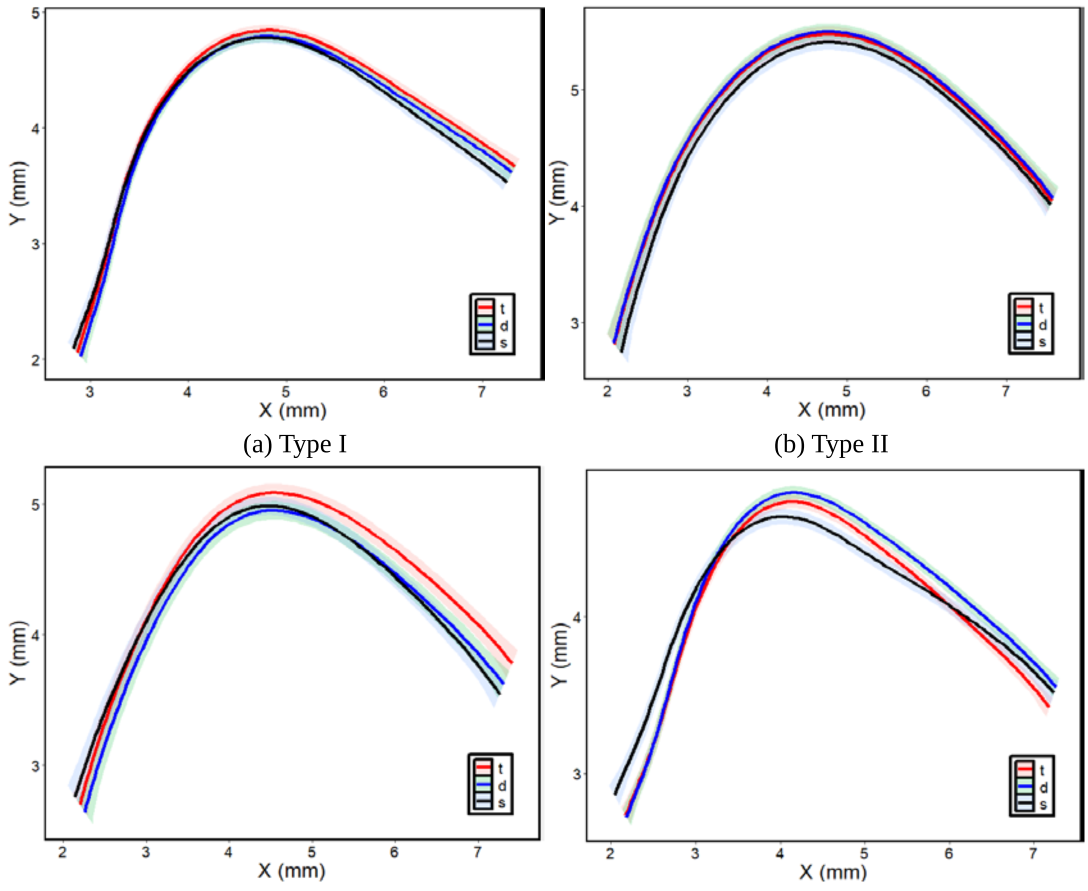
	Type I	Type II	Type III
Tongue tip	alveolar	alveolar	alveolar
Tongue blade	[t^h]≈[t] » [s]	[t^h]≈ [t] ≈ [s]	[t^h]» [t]≈[s]
Speakers	K1, K5, K6, K7, K9	K3, K4, K8, K10	K2

Note: ≈ represents the state where the height of the tongue blade is the same, and » shows the comparison where the tongue blade is positioned higher for one alveolar than for the other.

In summary, all ten Korean speakers maneuvered the tongue tip toward the alveolar ridge to produce both alveolar stops and a fricative as expected. However, their variability was observed for the relative position of the tongue blade. The prevalent pattern was that the tongue blade was raised higher for the stops than for the fricatives, as is conjectured from the articulatory differences between stops and fricatives. Furthermore, two more variants were found, i.e., Type II and III. In these types, the tongue blade was identical between /t/ and /s/ or /t^h/ was produced with the higher raising of the tongue blade, compared to /t, s/.

5.2 Sub-Phonemic Variation of English Alveolars /t, d, s/

One of the goals of this study was to examine how Korean speakers produce L2 English alveolars concerning the place of the tongue blade and tongue tip. In a similar vein to the articulation of L1 Korean alveolars, it was found that the tongue tip was raised exactly toward the alveolar ridge for all English alveolars /t, d, s/. These three alveolars did not differ significantly in the tongue tip targeting the alveolar ridge. Of interest is the finding that, like the case of Korean alveolars, the relative positions of the tongue blade exhibited variability among the alveolars. Figure 2 shows four types of patterns of the relative positions of the three alveolars. Type I is the typical case of production where stops /t, d/ are articulated with both the tongue blade and tip raising higher than a fricative /s/ (Fig. 2(a)). This is naturally expected because stops involve the tongue front making contact with the alveolar ridge along the palate. Another variant pattern is categorized as Type II, where the active articulators, i.e., the tongue blade and the tongue tip, are raised at the same height among the three alveolars as seen in Fig. 2(b). A similar pattern to Type III obtained from Korean alveolars is observed for L2 English alveolars (Fig. 2(c)). Under this variant type, /t/ is produced with the tongue blade raising higher than /d/ or /s/. The last case is not in line with our common way of manner of articulation involving stops and fricatives as illustrated in Fig. (2d). The tongue blade and tip are positioned lower for the stop /t/, for the stop /d/, or the fricative /s/. In brief, although the tongue tip is raised to or makes closure against the alveolar ridge for both the stops and the fricative, the tongue blade position shows variation depending on each alveolar in English. The tongue blade is raised at a higher level for /t,d/ or /s/ or at the same level among all three alveolars in the front region of the oral cavity. These findings indicate that even the production of phonologically identical alveolars defined as [+alveolar] consonants is produced with a variable degree of tongue blade gesture at the sub-phonemic level.



(a) Type I (b) Type II

(c) Type III (d) Type IV

Figure 2. SSANOAV Comparisons of Three L2 English Alveolars

(Blue curves refer to the tongue shapes of [t], red curves to those of [d], and black curves to those of [s].)

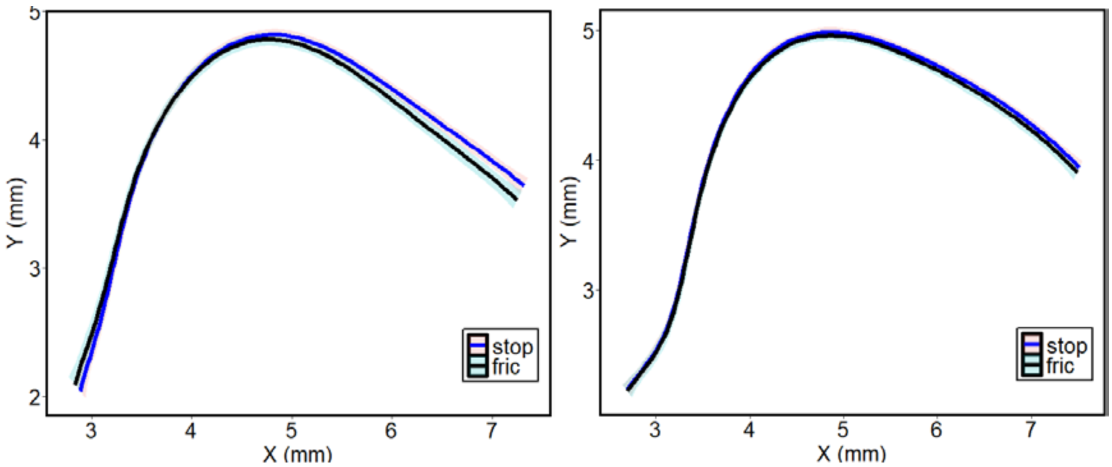
Table 4 shows the occurrences of each type of pattern among the ten Korean L2 speakers. As shown, Type I was observed for three speakers (K1, K2, and K4), Type II for the three other speakers (K3, K7, and K8), and Type III for the three others (K5, K9, and K10). The magnitude of the deviation from the so-called standard Type I is greater for L2 English alveolars than for L1 Korean alveolars.

Table 4. Distribution of Variable Types with Their Characteristics for English Alveolars by Speakers

	Type I	Type II	Type III	Type IV
tongue tip	alveolar	alveolar	alveolar	alveolar
tongue blade	[t]≈[d]»[s]	[t]≈[d]≈[s]	[t]» [d]≈[s]	[d]=[s]»[t]
Speakers	K1, K2, K4	K3, K7, K8	K5, K9, K10	K6

Note: ≈ represents the state where the height of the tongue blade is the same, and » shows the comparison where the tongue blade is positioned higher for one alveolar than for the other.

To see the difference in the gestures of tongue blade and tongue tip between stops /t, d/ and a fricative /s/, the average tongue shapes between [t] and [d] were collapsed, and SSANOVA comparison was made between stops and a fricative. Figure 3 shows two variant types of SSANOVA comparisons of tongue contours between stops and a fricative. Fig. (3a) shows the typical tongue body shapes of the stops and fricatives, with the tongue blade and tip raising higher for [t, d], compared to [s]. This characteristic pattern was produced by five speakers out of ten (K1, K2, K4, K8, and K10). Unlike this type, Fig. (3b) shows a deviant case where alveolar stops and fricatives were produced with the identical level of raising of both the tongue blade and tip. Such an overlapping pattern was identified in five other speakers (K3, K5, K6, K7, and K9).



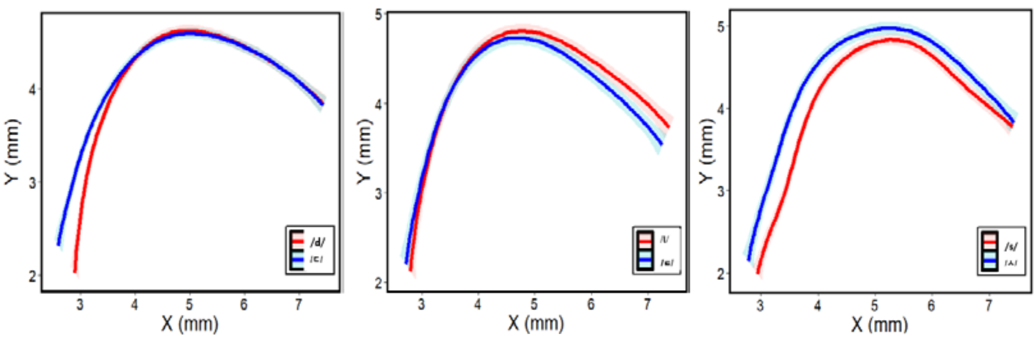
(a) stops » fricative (b) stops=fricative

Figure 3. SSANOAV Comparisons of L2 English Alveolar Stops and Fricatives
(Blue curves refer to the tongue shapes of stops [t, d], and black curves to those of a fricative [s].)

In summary, Korean L2 English speakers accurately raised the tongue tip toward the alveolar ridge to articulate English alveolars /t, d, s/, which is the targeted place of articulation. However, their production exhibited inter-speaker variations regarding the degree of heightening of the tongue blade among the three alveolars, displaying four differential types (Fig. 2).

5.3 Transfer of L1 to L2 at Sub-Phonemic Level

Table 5 presents the mean rates of three types of SSANOVA of L1 and L2 alveolar pairs concerning the positions of the tongue blade and tip. The rates were calculated by dividing the number of each type of pair (L1 Korean vs. L2 English alveolars) by the total number of comparison pairs (90 pairs). The comparison pairs were categorized into three types. Type I refers to the pattern where the tongue blade and tip are raised and positioned higher for English alveolars than Korean alveolars. Type II represents the pair pattern where the tongue blade and tip overlap between Korean and English alveolars. The last one is Type III, where Korean alveolars are articulated with further raising of the tongue blade and tip, compared to English alveolars. These three types are illustrated in Figure 4 below.



(a) Type I (b) Type II (c) Type III

Figure 4. Illustration of Three Types for the Comparison SSANOVA between Korean and English alveolars (Red curves refer to English alveolars and blue curves to Korean alveolars.)

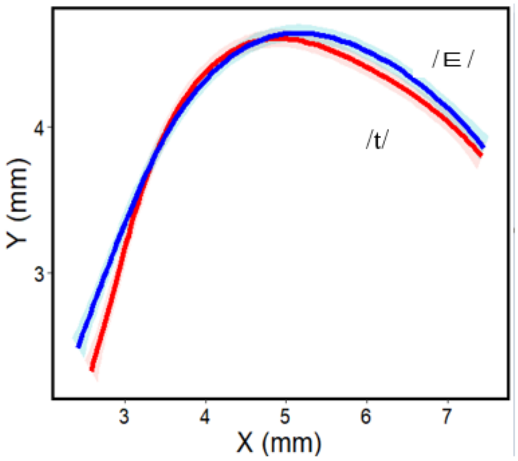
The results show that Type III is the dominant pattern, Type I occurs very frequently, and Type II is rare (50% vs. 36% vs. 14%, $F[2,29]=15.74$, $p<.001$). Specifically, it was found that L1 Korean alveolars /t^h, t, s/ are articulated with higher tongue blade and tip than L2 English counterparts /t, d, s/ most frequently. This suggests that the active articulators for Korean alveolars are the tongue blade and tongue tip, whereas English alveolars involve the raising of the tongue tip. Six Korean speakers show the consistent variation, favoring the Type III pattern over the Type I or II pattern (K1, K2, K3, K7, K8, and K9). Conversely, three Korean speakers exhibit the opposite pattern, i.e., preferring Type I to Type III (K4, K6, and K10). For one speaker (K5), the proportion of the production of Type I was equal to that of Type III.

Table 5. Mean Rates (%) and Number of Comparison Pairs between Korean Alveolars and English Alveolars Concerning the Height of Tongue Blade or Tip

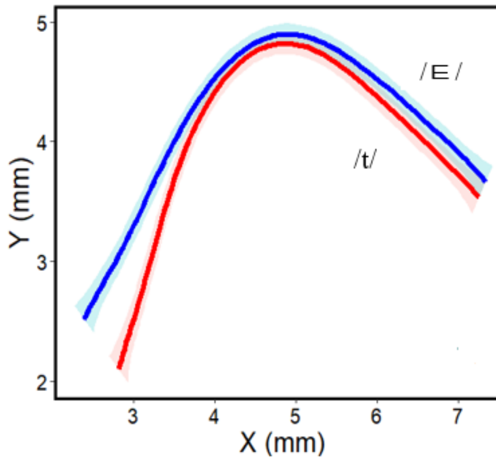
Pattern	**Type I** E >> K	**Type II** E = K	**Type III** E << K
e.g.	/t/ >> /t^h/	/t/= / t^h/	/t/ << /t^h/
% (No.)	36 (33/90)	14 (12/90)	50 (45/90)

Note: ≫ means "higher tongue front than" and = means no significant differences in tongue front placement

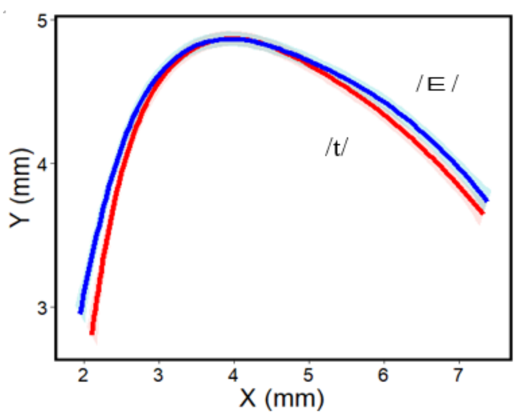
Figure 6 shows the relative positions, especially the height of the tongue blade and tongue tip for the comparison pairs consisting of L1 Korean alveolars and L2 English alveolars (e.g., /th/ 'ㅌ' vs. /t/; /t/ 'ㄷ' vs. /d/; /s/ 'ㅅ' vs. /s/) produced by ten Korean speakers. Only one SSANOVA comparison pair was selected out of nine pairs to illustrate the representative production pattern for each speaker. The blue curves represent the tongue contours for Korean alveolars (/tʰ, t, s/), and the red curves refer to the tongue shapes for English alveolars (/t, d, s/). Overall, most Korean speakers make a distinction between L1 Korean alveolars and L2 English alveolars, albeit with a minor variation across speakers, by raising the tongue front (i.e., tongue blade and tongue tip) higher toward the alveolar ridge for Korean alveolars, compared to English alveolars. This shows that Korean alveolars involve a higher likelihood of contacting the palate more with the tongue blade and tongue tip, compared to English alveolars. This split between Korean and English alveolars indicates that the active role of the tongue blade and tip in the articulation of L1 Korean does not transfer to the production of L2 English alveolars.



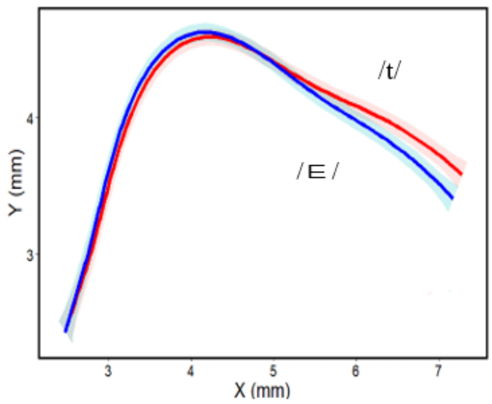
(a) K1



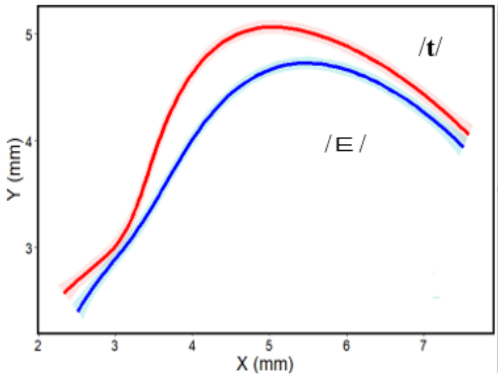
(b) K2



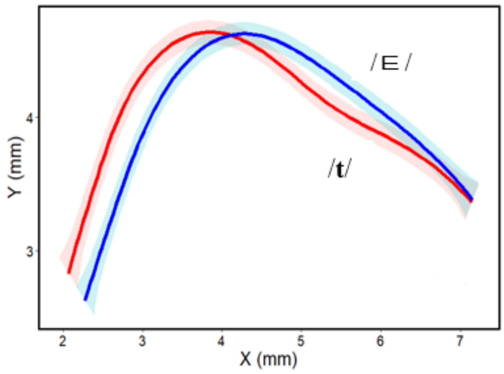
(c) K3



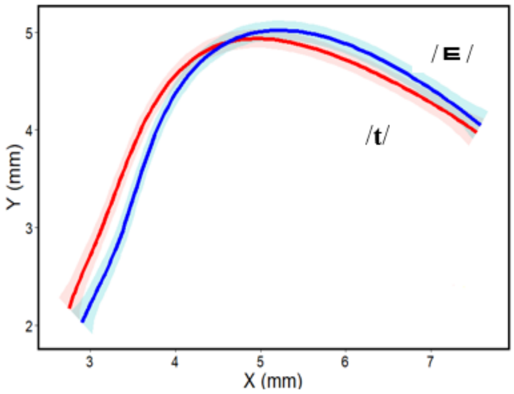
(d) K4



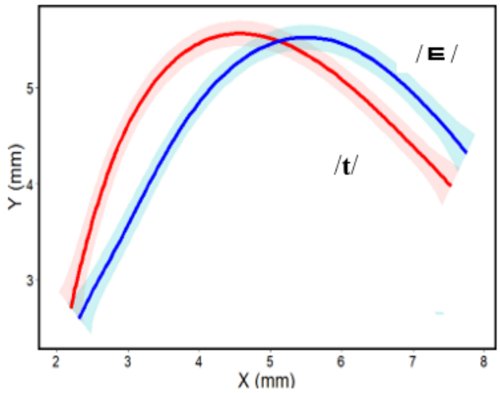
(e) K5



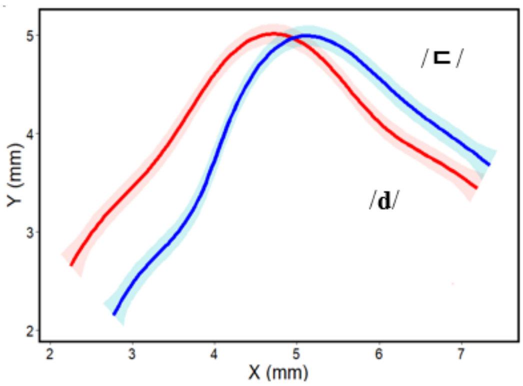
(f) K6



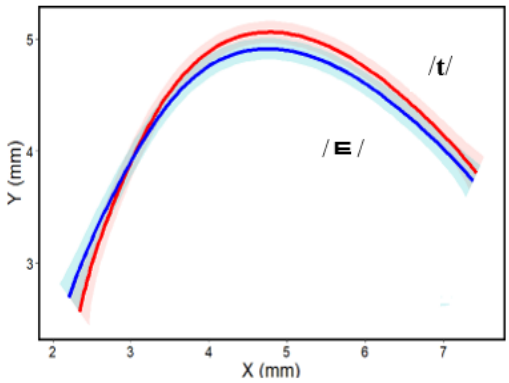
(g) K7



(h) K8



(i) K9



(j) K10

Figure. 6. Sample SSANOVA Comparisons of Korean Alveolars and English Alveolars for Ten Korean Speakers

5.3.1 English /t/ vs. Korean /tʰ/ 'ㅌ'

We examined whether the tongue front configurations show differences between Korean /tʰ/ and English /t/ through SSANOVA comparison pairs of /tʰ/ 'ㅌ' and /t/. Figure 7 shows the mean rates of the two patterns, i.e., Type I and III, among ten speakers. As seen in Figure 7, overall, Type III emerged most frequently, Type I occurred substantially, and Type II was rare (60% vs. 37% vs. 3%, $F[2,29]=20.79$, $p<.001$). The prevalence of Type III was observed for seven Korean speakers (K1, K2, K3, K6, K7, K8, and K9). Korean /tʰ/ was produced with a higher raising of the tongue blade and tip than its English counterpart /t/. The opposite pattern was found for the other three speakers (K4, K5, and K10).

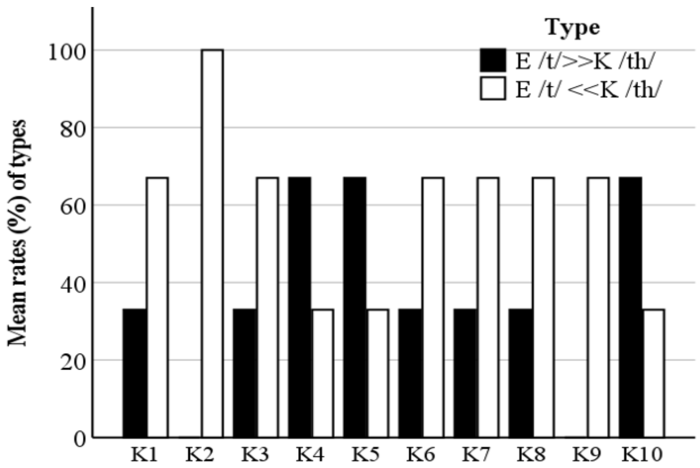
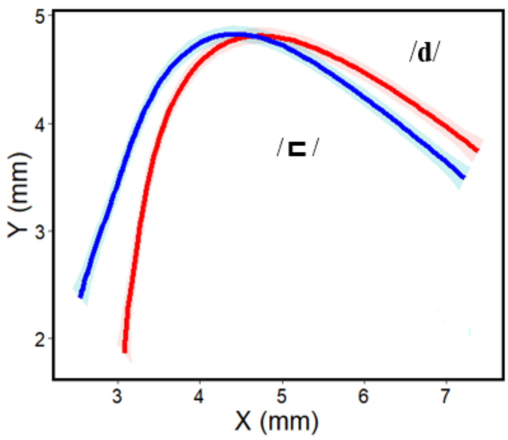


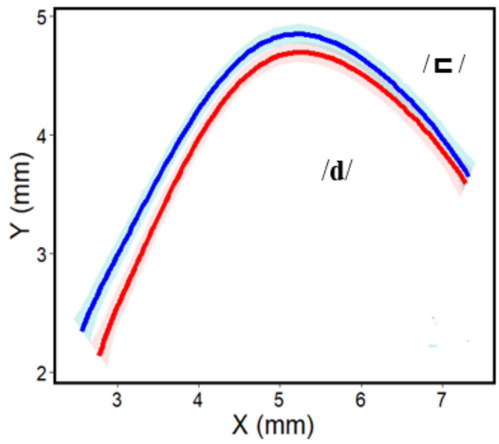
Figure 7. SSANOVA Comparisons for Korean [tʰ] and English [t] across Speakers
(Black bars refer to the rates of Type I and white bars represent the rates of Type III.)

5.3.2 English /d/ vs. Korean /t/ 'ㄷ'

In order to see whether Korean /t/ is articulated differently from English /d/ regarding the movement of the tongue blade and tip, the mean rates of the three types were calculated. Figure 8 shows the sample SSANOVA comparisons between the alveolars. It was found that Type III was dominant, then Type I intermediate, and Type II was rare (53% vs. 37% vs. 10%, $F[2,29]=10.41$, $p<.001$). This is in the same vein as the finding for the comparison pairs of Korean /tʰ/ and English /t/ as described previously. Specifically, Korean /t/ was produced with the higher raising of the tongue blade and tip than English /d/ (Type III), which was more frequent than the opposite pattern (Type I).



(a) Type I (from K1)



(b) Type III (from K2)

Figure 8. Illustration of Type I and III for the Comparison SSANOVA between Korean [ㄷ] (blue curves) and English [d] (red curve)

Figure 9 shows the mean rates of the three types of patterns by subjects. Five speakers out of ten exhibited the prevalence of Type III (K2, K6, K7, K8, and K9), whereas Type I was favored over Type III by three speakers (K4, K5, and K10). This interspeaker variation pattern indicates that Korean speakers make a distinction between L1 Korean /t/ and L2 English /d/ by manipulating the degree of raising the tongue blade and tip either in Type I or Type III manner. In any case, a greater majority of Korean speakers, Korean /t/ 'ㄷ', are involved in the higher raising of the tongue front gesture than English /d/.

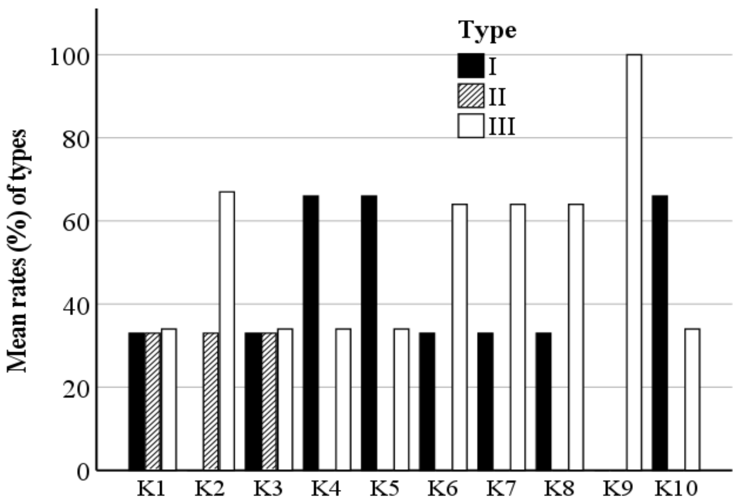
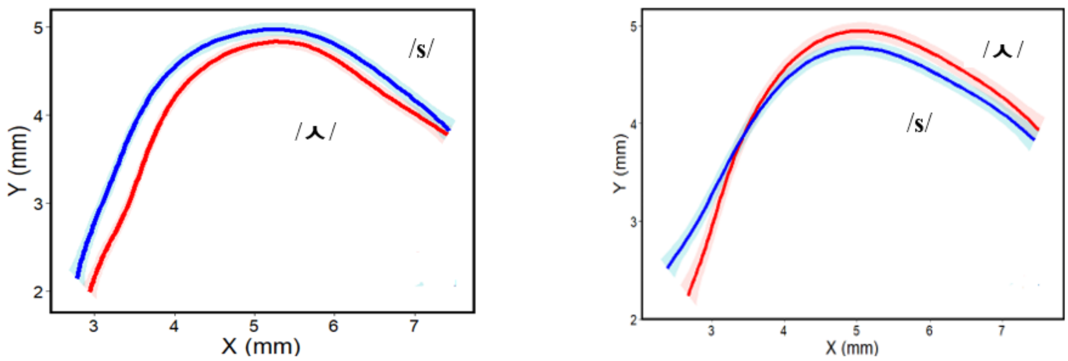


Figure 9. SSANOVA Comparisons for Korean /t/ and English /d/ across Speakers
(Black bars refer to the rates of Type I, shaded bars to the rates of Type II, and white bars to the rates of Type III.)

5.3.3 English /s/ vs. Korean /s/ 'ㅅ'

To explore the positions of the tongue front gesture in producing Korean and English alveolar fricatives /s/, the mean rates of the three types were computed and compared. Analysis exhibited that no significant difference in the rates was found among these three types (40%:23%:37%, F[2,29]=1.13, p>.05). This indicates that no dominant pattern emerged regarding the gestural kinematics of the tongue front between the alveolar fricatives in L1 and L2. This fashion of variation for fricatives is divergent from the findings for alveolar stops. One pattern is that the Korean fricative /s/ was articulated with further raising of the tongue front, compared to English /s/. The opposite pattern also accounted for a similar proportion of production cases. Another was that Korean speakers made no distinction in the raising of the tongue blade and tip between Korean and English /s/. Figure 10 shows sample patterns of Type I and III observed from different speakers.



(a) Type I (from K1) (b) Type III (from K5)

Figure 10. Illustration of Type I and III for the Comparison SSANOVA between Korean [ㅅ] (blue curves) and English [s] (red curve)

Figure 11 shows the mean rates of the three types by subjects. A group of five speakers preferred Type I to Type III (K5, K6, K7, K9, and K10), producing English /s/ with the higher placement of the tongue front region, compared to Korean /s/. Another group of three speakers displayed the opposite pattern, favoring Type III over Type I (K2, K3, and K4). K1 did not make a distinction between the two /s/s in the majority of the articulation cases. K8 showed the evenly distributed proportions of the three types.

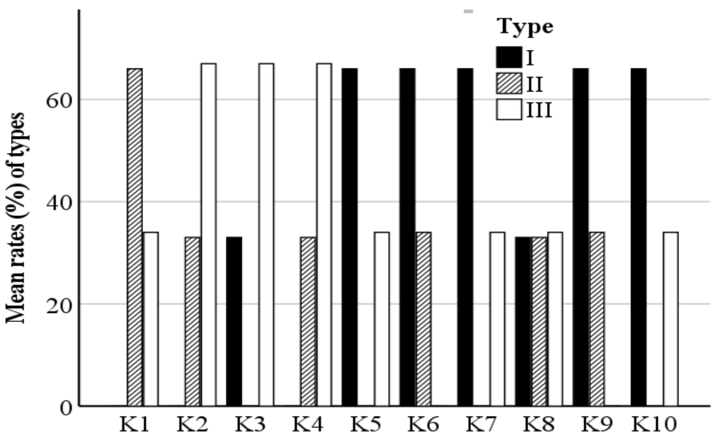


Figure 11. SSANOVA Comparisons for Korean [s] 'ㅅ' and English [s] across Speakers (Black bars refer to the rates of Type I, shaded bars to the rates of Type II, and white bars to the rates of Type III.)

6. Discussion

Korean alveolar stops are known to be denti-alveolar and characterized by the tongue front raising toward the alveolar ridge and making contact against the upper teeth and alveolar ridge (Cho and Keating 2001:166, Anderson et al. 2004). Additionally, Anderson et al. (2004) EPG study showed that Korean alveolar stops are classified as apico-laminal in the sense that the tongue blade and tip make closure against the palate. Ko (2013) suggested that the tongue blade is used as an active articulator to produce Korean alveolars, whereas English alveolars are articulated by the tongue tip as the active articulator. Due to the technical limitation of EPG, the holistic tongue shapes and/or their variation have not been fully investigated. To bridge this research gap, the current study examined whether the placement of the active articulators, i.e., the tongue blade and tip, shows variation among both L1 Korean alveolars and L2 English alveolars.

First, our ultrasound study shows that all Korean speakers raise the tongue tip toward the alveolar ridge three Korean alveolars /t^h, t, s/ which confirms previous EPG findings and aligns with their categorical, phonemic category [+alveolar]; furthermore, the magnitude of tongue blade raising shows inter-speaker variations among /t^h, t, s/ as described in previous section (See Figure 1 and Table 3). Specifically, the most common type found for five speakers out of ten is that the tongue blade is raised higher for stops /t^h, t/ than for a fricative /s/. This type can be easily interpreted to suggest that stops involve tongue front making a complete blockage of the air passage in the oral cavity, whereas a narrow passage is created to make frication for fricatives. Novel variants are cases where the tongue blade for /s/ is raised as high as that for /t, d/ (Type II) or /t^h/ is distinguished from [t, s] by being articulated with higher raising of the tongue blade. Type II pattern was observed for four speakers, whereas only one speaker showed Type III. The variation Type II indicates that many Korean speakers actively use both the tongue blade and tip to articulate /s/ as well as /t, d/. The articulatory mechanism, i.e., tongue blade raising, does not necessarily guarantee the tongue blade making closure against the alveolar ridge, however. The ultrasound machine employed in this study has a limitation of not providing a clear point of the tongue blade along the palate. Another limitation in the current study is that it is difficult to identify exactly whether the tongue tip or blade approaches the teeth. This difficulty might be due to the technical challenge of visually recording the teeth with ultrasound. Nonetheless, we classified these as alveolars rather than dentals because both the tongue blade and tip are elevated toward the alveolar ridge. Despite this technical drawback, the presence of Type II and III in our findings is significant in revealing that the production of Korean alveolars involves the gestural variation among speakers, supplementing the findings of EPG studies.

For the alveolars /t, d, s/ of L2 English, the raising of the tongue tip exactly to the alveolar ridge was achieved by all three alveolars /t, d, s/; however, the relative position of the tongue blade displays four types of inter-speaker variations (Figure 2 and Table 4). Three types of patterns were observed in an equal number of Korean L2 English speakers. Like Korean alveolars, English stops /t, d/ primarily involve the higher raising of both the tongue blade and tip, compared to /s/. This distinction stems from the difference in the articulatory mechanism between stops and fricatives. In another type, speakers use both the tongue front parts to produce /s/ as well as /t, d/. This seemingly hyper-raising of the tongue blade for English /s/ is found for Korean /s/. Additionally, for some speakers, /t/ is articulated with a higher raising of the tongue blade, compared to /d/ or /s/, which seems to parallel the production of L1 Korean alveolars. The commonality of the occurrences of Type I, II, and III between L1 and L2 alveolars might be attributable to Korean speakers' leverage of the articulatory gestures (i.e., tongue blade and tip) in L1 and L2 or transfer of gestural mechanisms to L2.

As previously mentioned, the present study follows the assumption of the Perceptual Assimilation Model (PAM, Best 1994, 1995, Best et al. 2001, Best and Tyler 2007). The PAM posits that L2 sound is perceptually mapped onto L1 sound based on similarities of constriction degree and main articulatory gestures, and that more dissimilar L2 sounds are more likely to be established. This is supported by previous perception studies (e.g., Park and de Jong 2008; 709, de Jong and Cho 2012: 364-366). They found that English /t/ was identified as Korean aspirated stop /t^h/ with 98%, and English /d/ was perceived as Korean lax stop /t/ with 84% by Korean listeners. Additionally, English /s/ was identified as Korean /s/ at 88%. This finding provides supportive evidence for PAM because L1 Korean /t^h, t, s/shares common gestural properties such as identical constriction degree at the alveolar ridge and identical main articulator (e.g., tongue tip) with L2 English /t, d, s/. Based on these perceptual results and the tenets of PAM, this study examined how Korean L2 English learners articulate English alveolars, which are perceptually assimilated to Korean alveolars.

The results in the present study show three types of patterns regarding the relative position of the tongue blade and tip for Korean and English alveolars (Table 5). A majority of comparison pairs (i.e., 86%) show the distinction made between these L1 and L2 alveolars concerning the position of these two tongue front parts, whereas only 14% tokens of pairs exhibit no distinction. This finding suggests that Korean learners of L2 English distinctly articulate L1 Korean and L2 English alveolar pairs, i.e., /t^h/-/t/, /t/-/d/, and /s/-/s/. This pattern of distinctive articulations is also consistent with the prediction of PAM. Because each of L2 English alveolars /t, d, s/ are perceptually assimilated to L1 Korean alveolars /t^h, t, s/, respectively, due to their gestural similarities, L2 alveolar categories are highly likely to be established and produced. In this respect, the current study endorses the basic premises of PAM.

Interestingly, among the three types, the dominant pattern was the case where Korean alveolars are produced with the tongue blade raising higher along the area of the alveolar ridge, compared to English alveolars (Figure 4). This indicates that the gesture of the tongue blade is more involved in the production of Korean alveolars, compared to English alveolars. Although this finding does not necessarily mean tongue blade contacting more with the alveolar ridge, it seems to confirm previous articulatory findings that the tongue blade and tip are used primarily for Korean stops, whereas English stops rely heavily on the tongue tip (Anderson et al. 2004, Cho and Keating 2001, Ko 2013). Given that English native speakers produce alveolar stops /t,d/ with the elevation and anteriorization of the tongue tip toward the alveolar ridge, our findings indicate that Korean L2 speakers are in the trajectory of developing English articulatory norms (Melo et al. 2017, Cleland and Scobbie 2021). To characterize L2 English alveolars as apical and L1 Korean alveolars as apico-laminal for Korean speakers, EPG experiments need to be conducted in further studies.

For Korean /t^h/-English /t/ comparison pairs, the prevalent pattern was that Korean /t^h/ involves both the tongue blade and tip raising higher, compared to English /t/ for a majority of Korean speakers. In this type, scrutiny reveals that a great part of the tongue body, including the tongue blade and tip, is positioned higher for Korean /t^h/ in the oral cavity (Figure 8(b)). Given the aerodynamic mechanism, the elevation of the whole tongue body for Korean /t/ induces the shrinkage of the volume of the intraoral cavity in conjunction with the elevation of the oral pressure behind the constriction point. This heightened intraoral pressure contributes to longer VOT of Korean /t^h/, compared to the VOT of English /t/. Previous acoustic studies confirm the differences in VOT between Korean aspirated stops (81ms to 103ms) and English voiceless stop /t/ (64ms to 98ms) (Lisker and Abramson 1964, Docherty 1992, Chodroff and Wilson 2017, Kim 1994, 2020).

The comparison of tongue configurations of English /d/ and Korean /t/ parallels that of English /t/ and Korean /t^h/. Five Korean speakers produced Korean /t/ with the whole tongue raised, including the tongue blade and tip, higher than English /d/ (Figure 8(b)). The much smaller volume of the oral cavity behind the closure point for Korean /t/, compared to English /d/, explains the longer VOT for the former than the latter, which is consistent with the findings documented in previous studies (Korean /t/:English /d/=30~50ms:21ms).

The pattern of the relative positions of the tongue front for English and Korean /s/ differs from that of the comparisons of stops. Unlike the stop comparisons, the rates of occurrence of the three types were similar. Specifically, some speakers produced Korean/s/s/ with the tongue front raising higher than English /s/. The opposite pattern also emerged with a similar proportion of speakers. Other speakers also failed to make a distinction between the two /s/s for the position of the tongue blade and tip.

7. Conclusion

Korean alveolars /t^h, t, s/ are produced with a different degree of raising of the tongue blade and tip, although their target place of articulation is the alveolar ridge. The present study reveals this sub-phonemic variation occurring within the phonologically same alveolar category by way of observing the tongue shapes with an ultrasound machine. L2 English alveolars /t, d, s/ also are articulated with the same place of articulation (e.g., the alveolar ridge), but the relative positions of the tongue blade and tip show interspeaker variation similar to the L1 Korean pattern. Korean speakers make a distinction between L1 Korean and L2 English alveolar stops by raising the tongue body higher for the former, compared to the latter, especially given the tongue front position.

Despite the advantages of identifying the sub-phonemic gestural configuration of Korean and English alveolars, the ultrasound experiment in this study has some technical limitations: it does not show where and how much the tongue makes contact along the palate. To supplement this aspect, future studies are needed to measure the exact place of articulation for the main active articulators (e.g., the tongue blade and tip). Furthermore, L2 speakers of various levels of L2 English proficiency should be examined to see whether their production of alveolars differs in terms of the tongue front placement.

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

