Journal of Phonetics 113 (2025) 101456

Contents lists available at ScienceDirect

Journal of Phonetics

journal homepage: www.elsevier.com/locate/Phonetics

Gestural restructuring beyond coarticulation in Korean /w/-vowel sequences: Evidence from phonetic, dialectal, and gender variation

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ARTICLE INFO

Article history:
Received 21 March 2025
Received in revised form 7 October 2025
Accepted 8 October 2025
Available online 29 October 2025

Keywords:
Gestural blending
Gestural restructuring
Coarticulation
Korean
Labiovelar glide /w/
Sound change
Dialect and gender

ABSTRACT

This study examines the articulatory patterns of Korean /w/-vowel sequences by comparing tongue dorsum movement trajectories with those of corresponding plain vowels, using Electromagnetic Articulography data from 48 speakers of Seoul and North Gyeongsang dialects. The central question is whether these sequences reflect mere coarticulation or exhibit signs of gestural restructuring in the nucleus vowel. Results reveal gradient restructuring shaped by vowel constriction degree, dialect, and gender. High vowels (/wi/-/i/) show minimal divergence, mid vowels (/we/-/e/, /wɛ/-/ɛ/) moderate divergence, and low back vowels (/wa/-/a/, /wʌ/-/ʌ/) the greatest divergence—especially in dialect- and gender-specific ways. Further analysis of the /e/-/ɛ/ merger and the recent /ʌ/-/ɨ/ split in North Gyeongsang sheds light on how vowel distinctions interact with /w/. The /we/-/wɛ/ pair shows a stronger merger than /e/-/ɛ/, supporting the view that /w/ triggers gestural restructuring of the nucleus vowel and thus plays an active role in reshaping merger trajectories. This effect is further illustrated by the /wa/-/wʌ/ and /a/-/ʌ/ contrasts, with a stronger merger in the /w/-initial context—an effect notably led by male speakers. Interestingly, North Gyeongsang males preserve the /a/-/ʌ/ contrast more robustly than the /wa/-/wʌ/ contrast, possibly due to hyperarticulation of a phonetically redefined /ʌ/ resulting from the recent /ʌ/-/ɨ/ split. These findings are interpreted within a dynamical framework of gestural blending strength (GBS), which varies by vowel constriction and coarticulatory resistance but remains stable for /w/. Overall, the results suggest that what may have begun as low-level coarticulation has evolved into systematic gestural restructuring—a gradient shift toward phonological reorganization shaped by phonetic context, sound change, and sociophonetic variation.

1. Introduction

A fundamental question in phonetics and phonology concerns how low-level articulatory processes, originally motivated by biomechanical constraints and coarticulatory dynamics, evolve into structured phonological patterns integrated within a language's sound system (e.g., Beddor, 2023; Blevins, 2004; Keating, 1984; Kingston & Diehl, 1994; Maddieson, 1997; Ohala, 1993; Solé, 2007; Zellou, 2022, inter alia). This transition is particularly pronounced in coarticulatory phenomena, where adjacent speech segments initially produce gradient and transient articulatory effects that can become stabilized into systematic, language-specific modifications surpassing mere biomechanical influences. A classic illustration of this phenomenon is vowel nasalization in English, in which the temporal and spatial extension of nasality has evolved beyond a purely phonetic effect, becoming phonologized with distinct language-specific articulatory targets (e.g., Beddor, 2023; Cohn, 1993; Solé, 2007; Zellou, 2022). Investigating the conditions that facilitate such phonetic-to-phonological transitions thus provides essential insights into the dynamic interplay between speech production mechanisms, phonological structure, and sound change (Beddor, 2009, 2023; Garrett & Johnson, 2013; Ohala, 1993; Pouplier, 2020; Tilsen, 2016).

A crucial factor influencing the phonologization of coarticulatory effects is the intrinsic phonetic properties of interacting segments (see Farnetani & Recasens, 2010, for a

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https://doi.org/10.1016/j.wocn.2025.101456
0095-4470/

comprehensive review). Vowels, for instance, differ systematically in their coarticulatory propensity based on the degree of constriction, which is often linked to vowel height and sonority: Vowels with a higher degree of constriction typically exert greater resistance to adjacent articulatory gestures than vowels with a lower degree of constriction, while simultaneously exerting a stronger influence on neighboring segments. This effect is especially pronounced in prosodically prominent contexts, such as stressed syllables or syllables produced in isolation (cf. Cho, 2004; Farnetani & Recasens, 2010; Fowler, 1981; Yun, 2006). Such articulatory interactions can be effectively captured through the concepts of gestural sliding and gestural blending (Browman & Goldstein, 1990, 1995; Iskarous & Pouplier, 2022). "Gestural sliding" refers to a type of coarticulation involving gestures that overlap temporally but operate across separate articulatory tiers, with each maintaining distinct articulatory characteristics. In contrast, "gestural blending" refers to another type of coarticulation, involving overlapping gestures that share the same articulator or articulatory set, resulting in an integrated articulatory outcome distinct from either gesture in isolation. In the framework of Articulatory Phonology, both "gestural sliding" and "gestural blending" are uniformly formalized through differences in abstract intergestural timing or gestural overlap, as represented in the gestural score, which encodes the temporal coordination and spatial integration of articulatory gestures. Given that gestural overlap is conditioned by the articulatory properties of interacting segments and modulated by speaker control (Beddor, 2023; Solé, 2007; Strycharczuk et al., 2024), recurrent systematic interactions may undergo gradual restructuring, eventually stabilizing into phonologically organized patterns and potentially leading to sound change. This restructuring can result in a phonological distinction between vowels shaped by systematic coarticulatory influences, which serve as their phonetic underpinnings, and those relatively unaffected by such interactions.

However, the extent to which a low-level phonetic process evolves into a speaker-controlled phonetic or phonological process also crucially depends on language-specific phonological and articulatory contexts (e.g., Bohn & Best, 2012; Ladefoged & Maddieson, 1996; Maddieson & Emmorey, 1985; Solé, 2007; see Cho, 2025 for a recent review). The present study investigates this phenomenon by examining the gestural dynamics of Korean /w/-vowel sequences, where the glide /w/ involves a tongue dorsum gesture overlapping (specifically gestural blending) articulatorily with the subsequent vowel. Korean offers an intriguing case due to /w/'s distinctive phonological behavior. Alongside /j/, /w/ is one of only two consonants permitted in onset clusters—a phonotactic configuration otherwise prohibited in Korean (Cheon, 2002; Lee, 1982). This raises the critical question of whether /w/ functions independently as a phonotactic exception or is integrated into a unified gestural unit with the vowel. Given that Korean generally disallows true onset clusters, it seems plausible that /w/-vowel sequences form unified articulatory gestures, effectively merging two distinct gestures. Support for this perspective also comes from Hangul orthography, representing /w/-vowel sequences as single vowel units (Kim, 2023). Furthermore, the phonological restriction against co-occurrence of /w/ with rounded back vowels like /u/ (Kim, 1968) reflects a systematic constraint involving rounding features, reinforcing the close phonological interaction between /w/ and the subsequent vowel.

Given these considerations regarding the phonological integration of coarticulatory effects, the present study investigates whether Korean /w/-vowel sequences involve transient coarticulatory interactions—as predicted by traditional sequential representations of glides and vowels (e.g., Chomsky & Halle, 1968; Clements & Hume, 1995)—or whether they reflect more stable gestural restructuring, whereby the articulatory target of the vowel is shaped to such a degree that it cannot be accounted for as a case of coarticulation, even its most exaggerated form. To this end, we compare the gestural properties of /w/-vowel sequences to those of their corresponding vowels without /w/, in order to determine whether /w/ exerts a fleeting influence confined to the early portion of the vowel or induces persistent articulatory deviations throughout its trajectory—deviations that may signal restructuring beyond the realm of coarticulatory processes.

We acknowledge that coarticulatory effects can operate along a continuum and be modulated in a language-specific manner under speaker control (cf. Cho, 2025), which may result in extreme coarticulatory effects that go beyond low-level phonetic processes. However, we posit that more distinct articulatory patterns may emerge depending on whether /w/ functions as an independent glide or participates in gestural reorganization. Specifically, if /w/ operates merely as a glide in a sequential representation, its coarticulatory influence is expected to be temporally limited—primarily affecting the onset of the vowel—and to allow the vowel gesture to return to its canonical target, especially when the syllable is produced in isolation, a hyperarticulatory context. This would align with traditional views of glide-vowel coarticulation, where adjacent segments show phonetic variation due to coarticulatory processes, even when exaggerated in a language-specific manner along a coarticulatory continuum. In contrast, if /w/ induces gestural restructuring, we expect systematic and sustained deviations in vowel articulation across its trajectory, such that the vowel in /w/-vowel sequences is realized in fundamentally different ways from its plain-vowel counterpart. This deviation may result from a language-specific enhancement of coarticulatory strength under speaker control. In such cases, these speaker-controlled patterns may be interpreted not as mere exaggerations of coarticulation along a phonetic continuum, but as evidence of gestural restructuring—a qualitatively distinct phenomenon that may indicate an ongoing phonological change.

Both scenarios can be accounted for within the framework of Articulatory Phonology (Browman & Goldstein, 1986, 1992; Goldstein et al., 2006), which conceptualizes speech as the result of dynamically coordinated gestures rather than strictly sequential segments. Within this framework, low-level coarticulation between /w/ and the following vowel can be modeled as a minimal temporal overlap between their respective vocalic gestures—potentially realized as either gestural sliding or gestural blending, as described above. In contrast, a speaker-modulated increase in gestural overlap would be modeled as a more substantial degree of overlap. Such enhanced overlap may give rise to an extreme degree of gestural blending—particularly between /w/ and the following

vowel, which share the same articulator (cf. Iskarous & Pouplier, 2022; Oh et al., 2024; Smith, 2018; Strycharczuk et al., 2024)—and could potentially evolve further, resulting in the reorganization of the two gestures into an integrated gestural unit that can no longer be accounted for by a coarticulatory process.

Furthermore, recognizing that vowels differ systematically in their coarticulatory resistance, with high vowels typically more resistant than low vowels (Cho, 2004; Farnetani & Recasens, 2010; Fowler, 1981), we also examine whether constriction degree of vowels modulates the degree of restructuring. Lastly, given that phonological patterns often interact with sociophonetic factors, especially when sound change is involved (e.g., Beddor, 2023; Kendall et al., 2023), the study explores how dialect and gender might influence the extent to which /w/-vowel sequences exhibit integrated gestural properties. Further discussion regarding the interaction with sociophonetic factors follows below.

Despite the theoretical significance of understanding the gestural dynamics of /w/-vowel sequences discussed above, previous studies on Korean have largely been limited to examining acoustic properties, particularly formant frequencies (Chang, 2017; Chang & Weiss-Cowie, 2021; Cho, 2003; Kang, 2006; Kim, Byun, & Ko, 2007; Oh, 2010b; Shon, 2022; Yang, 1993; Yun, 2005; Zhao et al., 2023). Such studies frequently debate whether /w/-vowel sequences should be analyzed as diphthongs or as a glide followed by a monophthong vowel. However, results from these studies remain inconclusive, partly due to unclear criteria distinguishing diphthongs from glide-vowel sequences and inherent limitations associated with acoustic data. While formant analyses provide valuable information about vocal tract configuration, they represent acoustic outcomes of articulatory processes rather than the gestures themselves (cf. Stevens, 1989; Stevens & Keyser, 2010). Consequently, acoustic analyses alone struggle to disentangle the dual articulatory components of /w/, namely lip rounding and tongue dorsum movement. Thus, a direct articulatory investigation is essential to comprehensively understand the gestural dynamics of /w/-vowel sequences, especially with regard to the gestural blending of the two gestures sharing the same articulator.

It is important to note, however, that the present study does not directly address the theoretical question of whether /w/-vowel sequences are diphthongal, as this issue introduces an additional layer of complexity involving both phonetic and phonological theories and descriptions of diphthongs. The classification of a sound sequence as a diphthong or a glide-vowel combination varies across languages and theoretical frameworks, often depending on factors such as phonological representations, phonetic properties, and language-specific phonotactic constraints (Chitoran, 2002; Hazen, 2000; Ladefoged, 2005; Padgett, 2008; Strycharczuk et al., 2024). For instance, Ladefoged (2005) describes how glides like [j] and [w] in English function as nonsyllabic counterparts to high vowels, complicating their distinction from diphthongs, while diphthongs themselves can still be *phonetically* characterized as having a glide component, setting aside its phonological function in the language. Marin (2017) models the degree of diphthongization resulting from different degrees blending strength suggesting that diphthongization emerges from gradient phonetic variation rather than a categorical phonological distinction (see Strycharczuk et al., 2024, for related data and discussion). This challenges the assumption that diphthongs constitute a distinct phonetic category and instead supports a continuum-based view of vowel representation. Relatedly, Chitoran (2002) conducted a perception-production study of Romanian diphthongs and vowel-vowel sequences, the latter of which may be phonetically realized as glide-vowel sequences, revealing challenges in distinguishing between the two. The study suggests that language-specific factors, such as frequency of occurrence and the need for contrast maintenance, shape both their phonetic realizations and phonological interpretations.

Thus, while the present study does not seek to classify Korean /w/-vowel sequences as either diphthongs or glide-vowel combinations, its findings would still have implications for the phonological status of /w/. If the results support an integrated gestural account of /w/-vowel organization, they would challenge the interpretation of these sequences as merely a glide /w/ followed by a vowel. Instead, they would suggest a diphthong-like structure that resists decomposition into distinct glide and vowel components, much like the English diphthongs discussed in Strycharczuk et al. (2024) (cf. Kim, 2023; Kim & Kim, 1991).

To address these issues discussed thus far, the present study investigates tongue dorsum movement trajectories and their articulatory target realizations in Korean /w/-vowel sequences (/wi, we, wɛ, wa, wʌ/) and compares them to their corresponding vowels without /w/ (/i, e, ɛ, a, ʌ/) produced in isolation (i.e., nuclei of /w/-vowel sequences vs. plain vowels). By analyzing all possible /w/-vowel combinations, this study examines how different vowels influence the articulation of /w/ and, conversely, how /w/ affects the articulation of the following vowel. Given that /w/ inherently involves a vocalic component, investigating its interaction with vowels of differing qualities, along with testing the hypothesis of gestural reorganization in /w/-vowel sequences, provides further insight into articulatory modifications that may result from distinct coarticulatory patterns as a function of vowel quality. This approach builds on prior research showing that vowels exhibit varying degrees of coarticulatory effects (e.g., Cho, 2004; Farnetani & Recasens, 2010; Recasens, 2002; Recasens, 2018). Coarticulation typically occurs at lingual regions not involved in closure or constriction formation (Recasens, 2018). Thus, the coarticulatory propensity of different vowels is likely related to their constriction degree—that is, the narrower constriction required for vowel production, the more resistant the vowel is to coarticulatory influence from neighboring segments, while simultaneously exerting stronger coarticulatory effects on adjacent sounds. For instance, the high vowel /i/ in /wi/, which requires a narrower constriction than the other vowels (/e, ɛ, a, ʌ/), may resist coarticulation more strongly while exerting a greater pull on the preceding vocalic gesture for /w/ compared to the other vowels. In particular, cross-linguistic studies have noted the distinct behavior of /i/, which tends to resist coarticulation more than other vowels while simultaneously serving as a strong coarticulatory trigger (Beddor et al., 2002; Recasens, 1999). Similarly, the mid front vowels (/e, ɛ/), which have a narrower constriction than the low back vowels (/a, ʌ/), may both resist coarticulation more strongly while exerting

greater coarticulatory effects on adjacent segments compared to the low back vowels.

Such an effect of constriction degree can be interpreted in gestural terms within the framework of a task-dynamical model underlying Articulatory Phonology. In this view, vowels with greater coarticulatory resistance (e.g., /i, e, ɛ/) may be taken to exert stronger gestural control, making their articulatory targets less susceptible to modification by neighboring gestures. Conversely, vowels with lower resistance (e.g., /a, ʌ/) may undergo greater gestural blending, allowing their articulatory trajectories to be more influenced by surrounding gestures, such as the tongue dorsum movement for /w/. In a dynamical system (Saltzman & Munhall, 1989), a vowel gesture may be specified with its own gestural blending strength (GBS), which determines how two overlapping gestures sharing the same articulator resolve conflicts, resulting in an articulatory state distinct from either individual gesture (e.g., Browman & Goldstein, 1989, 1992; Iskarous & Pouplier, 2022; Oh, et al., 2024; Smith 2018; Strycharczuk et al., 2024). The proximity of this end state to either gesture depends on the relative gestural blending strength: the greater the blending strength of a gesture, the closer the final articulatory configuration will be to that gesture. This suggests that /w/-vowel sequences may exhibit gradient levels of gestural integration (e.g., Smith, 2018), shaped by the relative gestural blending strength (GBS) between the vocalic gesture of /w/ and the nucleus vowel, which is closely related to the vowel's constriction degree. Specifically, high vowels like /i/ may have stronger GBS (with narrow constriction), minimizing the coarticulatory effect of /w/, whereas low vowels like /a/ and /ʌ/ with weaker GBS (with wider constriction) may be more susceptible to gestural blending, facilitating greater reorganization of their articulation. The results of the present study concerning the gestural restructuring possibility will thus be discussed in terms of the coarticulatory propensity of different vowels and further examined through a dynamical framework to understand how these effects may be interpreted in gestural terms.

In addition to examining how vowel quality shapes the gestural organization of /w/-vowel sequences and their coarticulatory outcomes, this study also explores how these patterns vary across two sociolinguistic factors: dialect and gender. Prior research has shown that the degree to which coarticulatory patterns become phonologized can differ across dialects (Bongiovanni, 2021; Coetzee et al., 2022; Cunha et al., 2024; Lee et al., 2013; Mielke et al., 2017) and between genders (Brunelle et al., 2020). These findings suggest that comparing coarticulatory patterns across speaker groups offers valuable insight into the extent of their phonologization. If the patterns are purely biomechanical, they should remain largely consistent across dialects and genders, aside from physiological differences related to gender. However, systematic variation across these sociolinguistic dimensions would suggest a greater degree of speaker control, pointing to potential phonologization. As discussed above, such socially conditioned patterns may undergo further reorganization over time—extending beyond the scope of coarticulation—and ultimately result in gestural restructuring. To evaluate this possibility, the present study analyzes the articulatory realization of /w/-vowel sequences across dialects and genders, aiming to determine whether the observed coarticulatory-origin patterns reflect low-level phonetic variation or socially conditioned articulatory routines indicative of emerging, language-specific restructuring and potential sound change.

Building on these sociophonetic considerations, we first focus on the /we/-/wɛ/ ('웨'-'왜') and /e/-/ɛ/ ('에'-'애') pairs. Notably, the /e/-/ɛ/ distinction has been reported as merged, particularly among younger speakers of the Seoul dialect (Cho et al., 2001; Ko, 2009; Lee & Cho, 2021). Moreover, a more recent corpus-based acoustic study (Eychenne & Jang, 2015) suggests that the merger of /e/ and /ɛ/ occurs across dialects, including Seoul and Daegu (North Gyeongsang), indicating a broader pattern of phonological change. Nevertheless, we do not rule out the possibility that subtle dialect- and gender-related differences may emerge in hyperarticulated or clear speech contexts—particularly when vowels are produced in isolation. While previous studies reporting mergers of /e/ and /ɛ/ (e.g., Chang, 2017; Cho et al., 2001; Ko, 2009; Lee & Cho, 2021), as well as /we/ and /wɛ/ (e.g., Chang, 2017; Cho, 2003; Shon, 2022; Zhao et al., 2023), examined more naturalistic contexts involving carrier sentences or longer word forms, the current study's use of isolated monosyllables may bring out articulatory differences that are otherwise neutralized in fluent speech. Moreover, Eychenne & Jang (2015) further reported that young Seoul speakers who do not distinguish /e/ and /ɛ/ in production can still perceive them differently when presented with an ambiguous sound between /e/ and /ɛ/, where F1 values distinguish them. Lower F1 values increase the likelihood of /e/ perception, suggesting that some listeners retain awareness of its traditional height distinction—an awareness that may surface in hyperarticulated production.

Sociolinguistic studies further indicate that mergers in sound change often progress differently across speaker groups (cf. Beddor, 2023; Kendall et al., 2023). Seoul speakers typically lead the way in phonetic shifts, whereas non-standard dialect speakers tend to be more conservative (cf. Cho et al., 2001; Lee et al., 2013). Female speakers also frequently lead sound changes more than male speakers (Choi et al., 2020; Kang, 2014; Oh, 2010a, 2011; see Kendall et al., 2023). These trends are particularly relevant to the historical phonetic shifts involving the /we/-/wɛ/ and /e/-/ɛ/ pairs, though the limited scope of previous studies constrains our ability to make firm predictions. Existing research indicates that Seoul speakers maintained a distinction between /we/ and /wɛ/ as recently as the early 1990s, but younger speakers no longer differentiate them (Chang, 2017; Cho, 2003; Shon, 2022; Zhao et al., 2023), a pattern that mirrors the ongoing /e/-/ɛ/ merger (Lee & Cho, 2021). Given this trajectory, it is possible that subtle distinctions or residual phonetic traces of the pre-merger contrast may still surface in isolated, hyperarticulated speech. However, due to the lack of dedicated studies on gender effects and the absence of rigorous statistical analyses in existing work (e.g., Cho, 2003; Shon, 2022), it remains an open question whether subtle distinctions or residual phonetic traces of the pre-merger contrast persist in isolated speech, and whether gender influences these mergers. If /w/-vowel sequences function as independent glide-vowel combinations, the merger patterns of /we/-/wɛ/ should align with their corresponding vowels with no /w/ (e.g., /e/-/ɛ/), once accounting for the coarticulatory influence of /w/. Alternatively, if /w/-vowel sequences undergo gestural restructuring, forming

integrated gestural units, their trajectory of change should diverge from that of the corresponding vowel without /w/. Moreover, dialect and gender may systematically interact with this restructuring process. If dialectal or gender-based differences appear in /we/-/wɛ/ but not in /e/-/ɛ/, or vice versa, this would support the view that /w/-vowel sequences have phonological representations distinct from their corresponding vowel without /w/.

The comparison between /wa/-/wʌ/ and /a/-/ʌ/ may also offer relevant insights, particularly in light of dialectal variation. In both North and South Gyeongsang Korean, the vowels /ʌ/ and /ɨ/ historically merged into an intermediate phonetic form that was distinct from either /ʌ/ or /ɨ/ (Jang & Shin, 2007; Lee & Jongman, 2016). This intermediate realization still phonetically resembled /ʌ/ especially among older speakers, leading to the impression that /ɨ/ was absent from the vowel inventory. However, more recent studies have shown that /ʌ/ and /ɨ/ have re-emerged as distinct vowels among younger speakers in these regions, reshaping the vowel contrast system in this dialect. Specifically, both /ʌ/ and /ɨ/, which initially shared an intermediate form distinct from either vowel, have shifted away from this intermediate realization in a way that enhances the distinction between /ʌ/ and /ɨ/. This development contrasts with Seoul Korean, where /ʌ/ and /ɨ/ have consistently been maintained as separate vowels across generations (Lee et al., 2017).

Crucially, this historical merger between /ʌ/ and /ɨ/ did not affect /w/-vowel sequences, as there is only /wʌ/—not /wɨ/—in the vowel system. This asymmetry raises important questions about how distinct phonological and historical contexts may shape gestural restructuring patterns. To address this, the present study examines North Gyeongsang Korean alongside Seoul Korean to investigate how gestures are organized in /w/-vowel sequences. Specifically, if Gyeongsang speakers produce the reintroduced /ʌ/ on the basis of the existing /wʌ/—as predicted by a glide-vowel decompositional view—then /wʌ/ and /ʌ/ should occupy similar regions in the vowel space as low back vowels, apart from the expected coarticulatory influence of /w/. On the other hand, if /wʌ/ is phonologically and gesturally integrated in a way that differs fundamentally from its corresponding vowel with no /w/, then a shared phonetic realization is less likely. Although younger Gyeongsang speakers no longer exhibit the /ʌ/-/ɨ/ merger, it is important to note that they are likely exposed to this merger through older speakers. As a result, they may make a conscious effort to maintain the distinction between /ʌ/ and /ɨ/, particularly when producing them in isolation. However, this type of compensatory hyperarticulation is unlikely to occur for /wʌ/, as there is no corresponding /wɨ/ form to contrast with. Therefore, even among younger Gyeongsang speakers, /wʌ/ remains a key site for observing patterns of gestural restructuring.

Since Korean distinguishes two vowels in the low back region (/a/ and /ʌ/), these possibilities can be empirically tested by examining how /ʌ/ is positioned relative to /a/ to maintain their phonological contrast and how /wʌ/ is positioned relative to /wa/. If the reintroduced /ʌ/ has developed distinct phonetic attributes due to sound change, the spacing of /a/ and /ʌ/ in Gyeongsang Korean may differ from that in Seoul Korean, which in turn may influence the extent to which /wa/-/wʌ/ patterns like /a/-/ʌ/ across dialects. This, however, does not imply that only North Gyeongsang Korean should exhibit distinct articulatory dynamics for vowels with and without /w/. Rather, dialectal differences may either enhance or suppress such distinctions, depending on phonological developments within each dialect's vowel system, shedding light on dialect-specific phonological restructuring.

Finally, the present study also includes supplementary measures—lip aperture, and F1 and F2 formant values—which complement the tongue dorsum articulatory data, particularly in evaluating convergence or divergence between the nuclei of /w/-vowel sequences and between corresponding non-/w/ vowels, which may reflect additional convergence or divergence influenced by sociophonetic factors.

In summary, this study investigates the phonetic and phonological nature of the Korean glide /w/ by analyzing its vocalic articulation and movement trajectories relative to its corresponding vowel without /w/ across various /w/-vowel sequences. Examining dialectal and gender-based variation, as well as mutual coarticulatory influences between /w/ and vowels, it explores whether and how /w/ affects the nucleus vowel's articulatory trajectory beyond typical coarticulatory processes, potentially indicating gestural restructuring. The study also examines how constriction degree of the vowels conditions these interactions, contributing to gestural restructuring. As such, it assesses whether /w/-vowel sequences function as simple glide-vowel combinations or involve integrated articulatory gestures distinct from their corresponding vowels without /w/. By comparing pairs such as /we/-/wɛ/ versus /e/-/ɛ/, which have undergone mergers across dialects, and /wa/-/wʌ/ versus /a/-/ʌ/, especially in light of the historical /ɨ/-/ʌ/ merger and subsequent split in Gyeongsang Korean, this study examines how dialect-specific phonological developments shape the articulatory and phonological status of /w/-vowel sequences. These patterns would in turn inform articulatory distinctions across dialects and genders and offer insights into the dynamics of potential sound change. Finally, the study discusses coarticulatory effects and their possible phonologization into gestural restructuring, considering how they may be modeled within a dynamical framework.

2. Methods

2.1. Materials

The materials for the present study were taken from a Korean acoustic and articulatory database, which is currently under development at the Hanyang Institute for Phonetics and Cognitive Sciences of Language (HIPCS, 2022). This database comprises both acoustic and articulatory recordings of Korean syllables and paragraphs, read by native Korean speakers representing various dialectal backgrounds and age groups. Articulatory data were collected using an Electromagnetic Articulography system (EMA, Carstens Articulograph AG501). Eight sensor coils were used to track participants' articulatory movements. Six sensor coils were attached to the tongue back, tongue middle, tongue tip, lower incisor, and the lower and upper lips around the vermilion border to track the movements of the tongue, jaw, and lips. The three tongue sensors were positioned as follows: the tongue tip sensor was placed approximately 1 cm behind the anatomical tongue tip. The tongue dorsum sensor was positioned as far back

on the tongue as possible, although the exact distance from the tip varied depending on each participant's tongue length. The tongue middle sensor was placed midway between the tip and dorsum sensors. Additionally, two sensor coils were each attached to the nasion and upper incisor to serve as reference points. The locations of the sensor coils are shown in Fig. 1.

Items spoken by 48 speakers in their twenties were taken from the database. 24 speakers (12F, 12M) were Seoul Korean speakers and 24 speakers (12F, 12M) were North Gyeongsang (henceforth N. Gyeongsang) Korean speakers. Seoul speakers lived in the Seoul metropolitan area their entire lives, while N. Gyeongsang speakers lived in N. Gyeongsang province before entering college and resided in Seoul for less than three years. No participant reported a history of speech or hearing disorder. Five pairs of glide-vowel sequences and their corresponding vowels without /w/ served as target syllables as (1):

(1)	Front vowels	Non-front vowels
	/wi/-/i/ ('위'-'이')	/wʌ/-/ʌ/ ('워'-'어')
	/we/-/e/ ('웨'-'에')	/wa/-/a/ ('와'-'아')
	/wɛ/-/ɛ/ ('왜'-'애')	

These syllables, read by Seoul and N. Gyeongsang speakers along with other possible Korean syllables, were extracted from the database. A total of 960 tokens were selected: 10 items × 2 repetitions × 2 dialects × 24 speakers. Vowels without /w/ were included for comparison with glide–vowel sequences. All target items were monosyllabic and produced in isolation, providing a clear speech context in which sounds are typically realized with their canonical or hyperarticulated forms. While some of the target syllables coincided with actual lexical items (e.g., 위, 이, 에, 왜, 애, 어, 와, 아), they were presented simply as isolated syllables, not as meaningful words. Therefore, we do not expect lexical status to have significantly affected their articulation, particularly within a hyperarticulated production context.

2.2. Measurements

The articulatory analysis focused on two measurement areas: (1) the horizontal and vertical movement trajectories of the tongue dorsum, and (2) the tongue dorsum position at the vowel midpoint and offset. For the first measure, full movement trajectories were analyzed to capture the dynamic articulatory behavior of the glide /w/ in /w/-vowel sequences, where the glide and vowel share the same articulator. These trajectories were primarily visually compared both within /w/-vowel sequences and against their corresponding vowels without /w/. Identifying the actual onset of tongue dorsum movement, typically determined using a threshold relative to peak velocity (e.g., Shaw & Chen, 2019; Son, Kim, & Cho, 2012), proved challenging in many cases. Syllables produced in isolation often exhibited preliminary articulatory behaviors that obscured a clear velocity peak, making it difficult to pinpoint the precise initiation of the movement gesture. In some tokens, the onset estimated using a 20 % peak velocity threshold occurred significantly earlier than the acoustic onset of /w/ in the acoustic signal, while in others, it was much closer. This variability

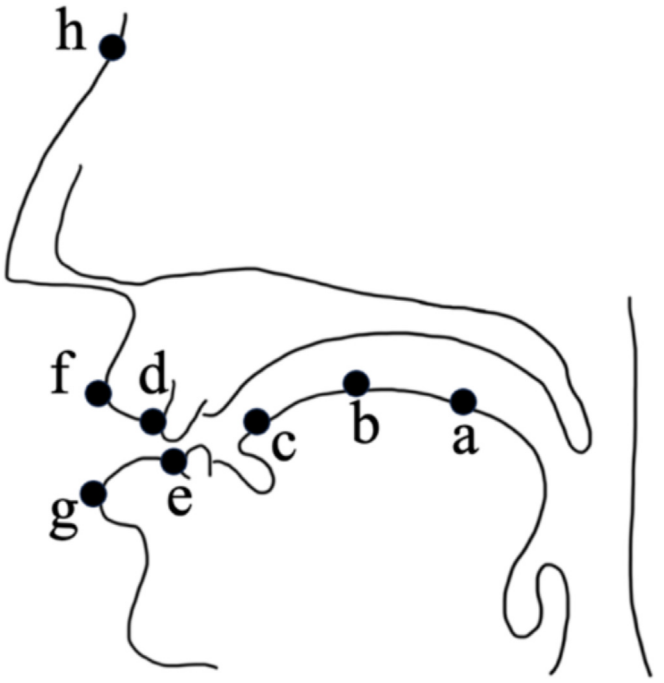


Fig. 1. locations of sensor coils: (a) tongue back, (b) tongue middle, (c) tongue tip, (d) upper incisor, (e) lower incisor, (f) upper lip, (g) lower lip, and (h) nasion.

was substantial even within the same speaker, complicating the use of conventional kinematic landmarks such as movement onset, peak velocity, or movement target as reliable articulatory events to define a movement trajectory. To address this, an analysis window was defined acoustically for each token to capture and compare tongue dorsum movement trajectories across conditions. This window spanned from 100 ms before the acoustic onset of /w/, a period expected to encompass the movement onset, to the end of formant activities. The endpoint was specifically aligned with the decay of the first formant (F1), which typically persists longer than other formants and marks the conclusion of articulatory activity associated with /w/. These criteria ensured consistency in defining the analysis window and establishing movement trajectory boundaries across all tokens. The extracted tongue movement trajectories within this window were visually examined using MVIEW (Tiede, 2005). To account for physiological differences among speakers, the horizontal and vertical tongue dorsum movement trajectories were normalized using z-scores. This normalization enabled direct comparisons across individuals by focusing on relative movement patterns rather than absolute distances.

For the second measure, the tongue dorsum position in the horizontal-vertical coordinate was analyzed at the acoustically defined vowel midpoint and offset, which were assumed to encompass the target of the vocalic gesture. For vowels without /w/, these measurements were taken directly at the vowel midpoint and offset. However, for /w/-vowel sequences, the corresponding nucleus vowel portion was estimated based on the point where the formant transition from /w/ to the vowel ended, marking the onset of a relatively steady-state formant region. This landmarking was determined through visual inspection of each token, as illustrated in Fig. 2. The vowel midpoint and offset were then determined as the midpoint

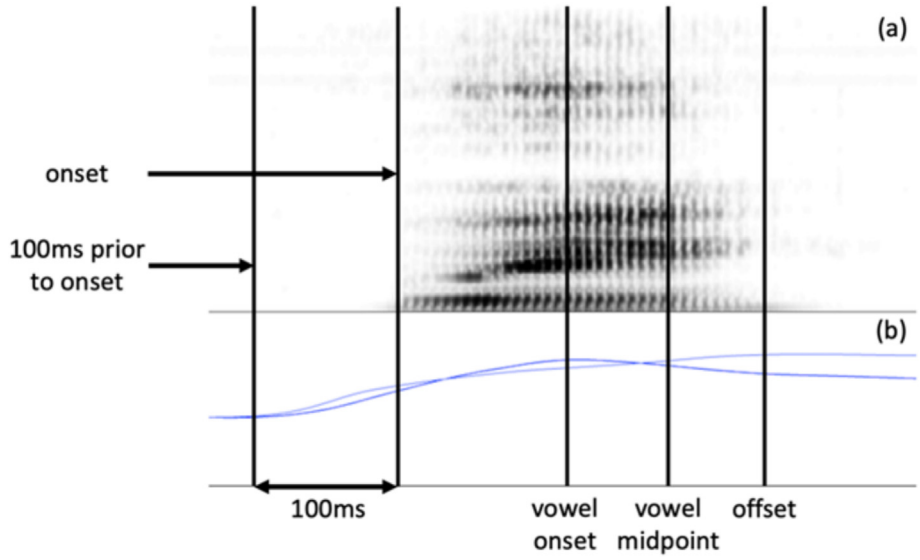


Fig. 2. The landmarks used for the analysis of the tongue dorsum and lower lip positions and formant frequencies at vowel midpoint and offset. The top panel (a) shows the spectrogram of a /we/ and the bottom panel (b) shows the tongue dorsum movement trajectories. In (b), the thicker blue line indicates the horizontal movement of the tongue dorsum and the thinner blue line indicates the vertical movement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

between this transition endpoint and the end of the /w/-vowel sequence, and the sequence's endpoint, respectively. It should be noted that neither the acoustic vowel midpoint nor the vowel offset necessarily corresponds precisely to the theoretical vowel target. However, since the syllables were produced in isolation with a substantial temporal realization, these points served as reasonable reference points, ensuring inclusion of the assumed vocalic target. The average duration of the vowel and /w/-vowel sequences are shown in Table 1 below. Moreover, this approach maintained consistency across speakers and tokens, minimizing potential variation across vowels that might otherwise introduce inconsistencies in the analysis. Overall, the analysis window showed little variability, as the acoustic onsets and offsets of the vowels were generally clear. In a few cases, the tongue dorsum trajectories appeared excessively irregular, which we believe was due to sensor errors. Participants exhibiting these abnormal patterns were excluded from the analysis.

2.3. Data analysis

The tongue dorsum trajectories of glide-vowel sequences and their corresponding vowels without /w/ were first visually inspected to identify potential differences and similarities, particularly the impact of /w/ on articulatory trajectories relative to the corresponding vowels without /w/. These visual inspections also allowed us to observe how different vowel qualities influenced the differences between /w/-vowel sequences and their corresponding vowels without /w/ across dialects (Seoul, N. Gyeongsang) and genders (female, male). To validate these observations, two separate statistical analyses were conducted for different purposes.

For the first type of analysis, we examined how nucleus vowels in /w/-vowel sequences are realized relative to their assumed articulatory targets in comparison to their corresponding vowels without /w/. To do so, we analyzed tongue dorsum position in the horizontal-vertical articulatory vowel space, considering the vowel midpoint, vowel offset, and their combined effects. Since the primary goal of this comparison is to understand how nucleus vowel target realizations may vary depending on the presence or absence of /w/, we focus on overall differences arising from these combined effects, while results for individual measurement points (Vmidpoint and Voffset) are provided in the Appendix A for completeness. To assess differences in tongue dorsum position across conditions, we conducted a Multivariate Analysis of Variance (MANOVA) with vertical and horizontal position values as the multivariate dependent variables. The independent variables included Vowel Type (presence/absence of /w/), Gender (female/male), Dialect (Seoul/N. Gyeongsang), and Timepoint (Vmidpoint/Voffset), along with their interactions.

Pillai scores were then derived from MANOVA (using the *manova* function in R's base stats), which is used to measure the degree of overlap between vowel categories in a multidimensional acoustic space (e.g., F1-F2 space in vowel studies) (e.g., Nycz & Hall-Lew, 2013). In the present study, the articulatory vowel space was represented by tongue dorsum position in the horizontal and vertical dimensions. Pillai scores were used to assess the degree of overlap between vowel categories. A Pillai score closer to 1 indicates greater separation between vowel categories, suggesting distinct articulatory patterns, while a score closer to 0 indicates more overlap, suggesting similarity in their production. The significance of these differences was evaluated using MANOVA, which provided p-values to determine whether the observed separation or overlap was statistically meaningful. Thus, these analyses, complementing the visual inspection of tongue movement trajectories, allowed us to assess whether the assumed vocalic target, as reflected in tongue dorsum position at the vowel mid and end points, was distinct or convergent between the nucleus of the /w/-vowel sequence and its plain vowel counterpart.

For the second type of analysis, we examined dynamic patterns and compared them across vowel types, modeling the differences using generalized additive mixed-effects models (GAMMs) within the R computing environment (R Core

Table 1
Mean duration (ms) of the plain vowel, /w/-vowel sequence, glide /w/, and the proportion of /w/.

vowel type	plain vowel	/w/-vowel	glide /w/	/w/ proportion
/i/	273	305	114	37 %
/e/	307	305	137	45 %
/ɛ/	275	287	125	44 %
/a/	290	285	102	36 %
/ʌ/	289	295	96	32 %

Team, 2018) using the *bam* function (mgcv package; Wood, 2019). Specifically, a set of GAMMs was constructed to model articulatory differences both between /w/-vowel sequences and between their corresponding vowels without /w/. These analyses helped determine whether and where in the time course the articulatory movement trajectories of the two vowels—such as across different /w/-vowel sequences (e.g., /we/-/wɛ/) or between the corresponding vowels without /w/ (/e/-/ɛ/)—converge or diverge within and across gender and dialect groups. Initially, a model was also included to compare the nuclei of /w/-vowel sequences with their corresponding vowels without /w/. However, this comparison was ultimately deemed invalid, as the two exhibited inherently different time course patterns: glide-vowel sequences showed clear /w/ effects and coarticulatory influences, whereas corresponding vowels without /w/ lacked such effects, particularly in the initial portion of the vowel sequence.

In the models, an interaction factor combining Vowel type, Dialect, and Gender was included as a fixed effect, along with a thin plate regression spline smooth (e.g., Wieling, 2018; Wood, 2017).[1] The models also incorporated a by-speaker factor smooth to account for individual variability over time. In addition, whenever necessary, another set of GAMMs was constructed to test the significance of interactions. These models included smooths representing differences, such as those between Seoul Korean female and male speakers or N. Gyeongsang Korean female and male speakers, as well as any other group-related differences, along with a by-speaker factor smooth.

To ensure statistical rigor, we assessed GAMM results by considering both graphical outputs and statistical significance. Specifically, periods of significant divergence in the GAMM graphs were interpreted alongside estimated degrees of freedom (EDF) and corresponding p-values for the smooth terms. A difference was considered statistically meaningful only when both the visualization indicated a sustained period of significant separation and the EDF was sufficiently high (suggesting nonlinearity) with a p-value below 0.05. When the GAMM graphs suggested divergence but the EDF values with $p > 0.05$ indicated no statistical significance, we treated such cases with caution, interpreting them as non-robust effects that do not provide strong evidence for systematic articulatory differences. This approach ensures that findings reflect statistically and linguistically meaningful patterns rather than incidental fluctuations in the movement trajectories.

[1] A thin plate spline smooth is a flexible modeling tool used to capture complex, nonlinear patterns in data, such as how tongue dorsum movement evolves over time. It works by fitting a smooth curve to the data points while incorporating a penalty for excessive bending, ensuring a balance between flexibility and simplicity to avoid overfitting (e.g., Wood, 2017).

Supplementary analyses (Appendix E). In addition to the main analyses of tongue dorsum movement trajectories and spatial characteristics, we included supplementary articulatory and acoustic measures—specifically, lip aperture (calculated as the Euclidean distance between the upper and lower lip sensors) and the first two formant frequencies (F1 and F2). These measures were taken from the same temporal landmarks of the vowel—the midpoint and offset—as described in Fig. 2, paralleling the tongue dorsum analyses. Motivated by reviewer feedback, these supplementary measures were included to provide further insight into the nature of potentially ongoing vowel mergers—specifically for the /we/-/wɛ/ (and /e/-/ɛ/) and /wa/-/wʌ/ (and /a/-/ʌ/) pairs—and to avoid drawing premature conclusions about merger status based solely on tongue dorsum data. Full methodological details and results are presented in Appendix E. In the main text, we refer to these results only where relevant in the results summary and discussion. All scripts and data analyzed in this paper is provided on this paper's OSF page at the following link: https://osf.io/r7y4k/ .

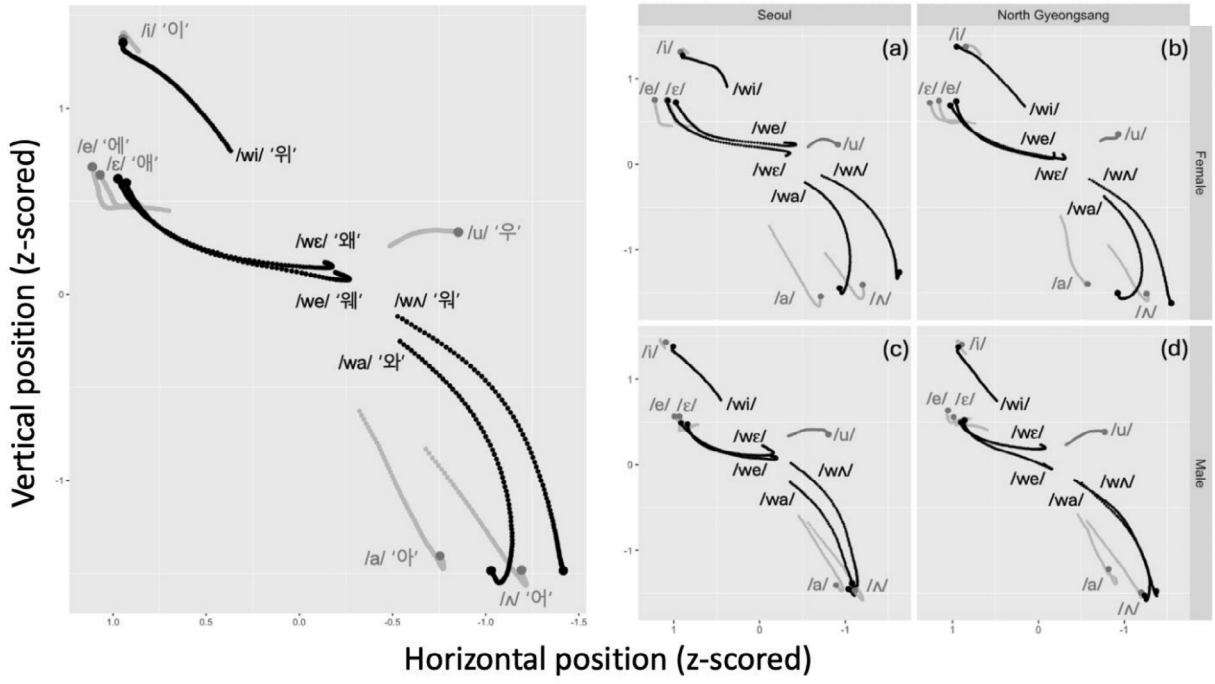
3. Results

3.1. Convergence and divergence between /w/-vowel sequences and vowels without /w/

3.1.1. /w/-vowel sequences with front vowels and plain vowel counterparts

We first examine the articulatory characteristics, focusing on tongue dorsum movement trajectories, followed by MANOVA results. Fig. 3 shows the averaged tongue dorsum trajectories across all speakers, pooled across dialects (Seoul Korean, N. Gyeongsang Korean) and genders (female, male), while Fig. 4 presents the trajectories separately for each dialect × gender group.

We begin by analyzing how movement trajectories differ near the endpoint depending on the presence or absence of the glide /w/ across vowel qualities (i.e., comparison between the nuclei of /w/-vowel sequences and their plain vowel counterparts). As shown in Fig. 3, when data are pooled across groups, a key difference emerges: the relative positioning of the endpoints varies considerably depending on vowel quality, particularly between front and back vowels. The endpoints of the front vowels /i/, /e/, and /ɛ/ in /wi/-/i/, /we/-/e/, and /wɛ/-/ɛ/ tend to converge to different degrees. Notably, the high front vowel /i/ in /wi/-/i/ exhibits a near-complete overlap at the endpoints (Fig. 3), a pattern consistently observed across groups (Fig. 4). MANOVA results using Pillai scores confirm this pattern, showing no significant distinction between /wi/ and /i/ (Pillai = 0.009, $p > 0.1$) when analyzing tongue dorsum positions, calculated as the means of position values between Vmid and Voffset, with no interaction effects involving Dialect, Gender, or



Figs. 3 and 4. **(3)** Averaged tongue dorsum trajectories of /w/-vowel sequences (black) and their vowel counterparts (gray) across all speakers, pooled across dialects (Seoul, N. Gyeongsang Korean) and genders (female, male). The round dots indicate the endpoints of the trajectories. **(4)** Averaged tongue dorsum trajectories of /w/-vowel sequences (black) and their vowel counterparts (gray) presented separately for each dialect (Seoul, N. Gyeongsang Korean) and gender (female, male). The round dots mark the endpoints of the trajectories.

Timepoint (see Appendix B for detailed MANOVA results). Table 2 shows the results of MANOVAs comparing the nuclei of various /w/-vowel sequences and their corresponding vowels without /w/.

In contrast, the mid front vowels /e/ and /ɛ/ show partial convergence between the nuclei of /w/-vowel sequences and their corresponding vowels without /w/ but do not exhibit the complete overlap seen in /wi/-/i/ (Fig. 3). For /we/-/e/, MANOVA results indicate a significant degree of divergence during the vowel (Pillai = 0.045, $p < 0.001$), with no interaction effects involving Dialect, Gender, or Timepoint. This suggests that the distinction remains generally observable across groups, with no dialect- or gender-specific patterns, as illustrated in Fig. 4.

For /wɛ/-/ɛ/, while there is no main effect of Vowel (Pillai = 0.014, $p = 0.08$), a significant Vowel × Dialect interaction is observed (Pillai = 0.018, $p = 0.03$). This effect stems from N. Gyeongsang speakers maintaining a significant distinction between /wɛ/ and /ɛ/ during the vowel (Pillai = 0.036, $p = 0.03$), whereas Seoul speakers do not (Pillai = 0.016, $p = 0.22$). As shown in Fig. 4a, Seoul female speakers exhibit complete overlap between /wɛ/ and /ɛ/ toward the end of the movement trajectories, and Seoul male speakers also show substantial endpoint approximation (Fig. 4c). In contrast, N. Gyeongsang speakers display more distinct ending contours (Fig. 4b and d). The lack of Vowel × Gender interaction in MANOVAs indicates no gender-specific effects, reinforcing that the vowel distinction is dialectal rather than gender-based—i.e., N. Gyeongsang speakers, but not Seoul speakers, maintain a distinction between the nucleus of /wɛ/ and its corresponding vowel /ɛ/ without /w/.

In summary, for front vowels, /wi/-/i/ exhibits complete convergence, while /we/-/e/ shows a small but significant divergence with no dialectal difference. In contrast, /wɛ/-/ɛ/ maintains a slight but significant distinction only in N. Gyeongsang, with no difference in Seoul. These patterns suggest varying degrees of coarticulatory influence of /w/ on the nucleus vowel, with the effect being smallest on the high front vowel /i/. Among the mid front vowels, the coarticulatory influence appears to be stronger on the traditionally higher vowel /e/ (close-mid) than on the lower vowel /ɛ/ (open-mid), though the difference remains minimal. In other words, the high vowel /i/ appears to exert greater coarticulatory resistance to /w/, leading to complete convergence during the vowel, whereas the non-high vowels /e/ and /ɛ/ exhibit weaker resistance, allowing for some modifications in vowel articulation due to /w/, with effects varying by dialect and gender.

3.1.2. /w/-vowel sequences with back vowels and plain vowel counterparts

Unlike the front vowels, however, the back vowels /ʌ/ and /a/ (/wʌ/-/ʌ/, /wa/-/a/) exhibit greater divergence depending on the presence of /w/. As shown in the bottom right corner of Fig. 3, vowels preceded by /w/ have endpoints that are noticeably further back than their corresponding vowels without /w/, indicating a significant articulatory retraction. This pattern is statistically supported by MANOVA results when analyzing tongue dorsum positions averaged across Vmid and Voffset, with significant /w/ effects for both /wa/-/a/ (Pillai = 0.102, $p < 0.001$) and /wʌ/-/ʌ/ (Pillai = 0.088, $p < 0.001$), indicating that the nucleus vowel targets in /w/-vowel sequences are further back than in their corresponding vowels without /w/, reflecting coarticulatory influences of /w/.

For /wa/-/a/, a significant interaction with Dialect is observed (Pillai = 0.036, $p < 0.01$), driven by greater divergence in N. Gyeongsang speakers (Fig. 4b, d) than in Seoul speakers

Table 2
Summary of the model outputs of the MANOVA with the vertical and horizontal position values of Vmid and Voffset of the nuclei of /w/-vowel sequences and their monophthongal counterparts as the multivariate dependent variables.

Pairs	Pillai	*F*	num *df*	den *df*	*p*
/wi/ – /i/	0.009	1.738	2	367	0.17
/we/ – /e/	0.045	8.685	2	367	<0.001***
/wɛ/ – /ɛ/	0.014	2.540	2	367	0.08
/wa/ – /a/	0.102	20.952	2	367	<0.001***
/wʌ/ – /ʌ/	0.088	17.772	2	367	<0.001***

(Fig. 4a, c). This is also reflected in the Pillai scores (N. Gyeongsang: Pillai = 0.173, $p < 0.001$; Seoul: Pillai = 0.066, $p < 0.01$). No significant Gender-related interaction is found.

For /wʌ/-/ʌ/, a significant interaction with Gender is observed (Pillai = 0.032, $p < 0.01$), driven by a divergence observed only in female speakers (Pillai = 0.224, $p < 0.001$; Fig. 4a, b), while male speakers show no distinction (Pillai = 0.018, $p > 0.1$; Fig. 4c, d). But there is also a significant three-way interaction among Vowel, Dialect, and Gender (Pillai = 0.022, $p = 0.01$), due to the dialectal variation emerging among female speakers, with Seoul females showing greater /wʌ/-/ʌ/ divergence (Fig. 4a) than N. Gyeongsang females (Fig. 4b), confirmed by higher divergence scores (Pillai = 0.292 vs. 0.190, both $p < 0.001$). Male speakers in both dialects exhibit no significant divergence.

In summary, back vowels exhibit greater divergence from their corresponding vowels without /w/ than front vowels. For /wa/-/a/, N. Gyeongsang speakers show greater divergence than Seoul speakers, with no gender difference. In contrast, for /wʌ/-/ʌ/, only female speakers show significant divergence, with Seoul females exhibiting greater separation than their N. Gyeongsang counterparts. That is, male speakers show complete convergence of /wʌ/-/ʌ/, unlike /wa/-/a/ which remains distinct for all speaker groups, though with some dialectal differences.

3.1.3. Summary and highlights

The findings reported thus far are related to influences of /w/ on the nucleus vowels, highlighting the carryover coarticulatory effect of /w/ on the nucleus vowel. However, an anticipatory effect, where the nucleus vowel influences /w/, is also evident in the articulatory trajectories shown in Figs. 3 and 4. This perspective allows for a qualitative examination of how the initial spatial placement of /w/ interacts with the following vowel. As seen in Fig. 3, the onset positions of /w/-vowel sequences generally cluster near the center of the vowel space, except in /wi/, where the onset is substantially fronted toward the /i/ target. This pattern, observed across all groups (Fig. 4a–d), suggests that /i/ exerts a particularly strong anticipatory coarticulatory influence on /w/, unlike non-high vowels, which do not show such encroachment.

These findings reinforce the bidirectional nature of gestural interactions in /w/-vowel sequences, showing that the degree of coarticulatory influence systematically varies with vowel quality as a function of constriction degree. Specifically, segments with narrower constrictions such as /i/ tend to exhibit greater resistance to coarticulation while simultaneously exerting stronger influence on adjacent segments in both directions—namely, right-to-left (anticipatory) and left-to-right (carryover) coarticulation. This variation, in turn, conditions the extent to which the nucleus vowel in /w/-vowel sequences diverges from its corresponding vowel without /w/ (e.g., /wi/ vs. /i/), highlighting the interdependence of anticipatory and carryover coarticulation and the role of vowel constriction degree in shaping this divergence.[2] Nevertheless, the results clearly show substantial divergence between /w/-vowel sequences and their corresponding vowels without /w/, even in hyperarticulated speech produced in isolation—particularly for back vowels—suggesting a possible gestural restructuring effect. Crucially, these effects are further shaped by gender, dialect, and vowel constriction degree, implying that sociophonetic and phonetic factors jointly condition the extent of coarticulatory influence and potential gestural restructuring in /w/-vowel sequences.

In the next section, we further investigate gestural restructuring by analyzing the realizations of /we/-/wɛ/ and /wa/-/wʌ/ in relation to sound change, specifically the /e/-/ɛ/ merger and the recent /ʌ/-/ɨ/ split in Gyeongsang Korean. If the articulation dynamics of phonological vowel distinctions vary depending on the presence or absence of /w/, and if these patterns are further shaped by dialectal and social factors linked to sound change, this would provide stronger evidence that /w/-vowel sequences undergo gestural restructuring rather than simply decomposing into a glide and a vowel.

3.2. Articulatory dynamics of /we/-/wɛ/ and /wa/-/wʌ/ in the context of sound changes: Merger and split

3.2.1. /we/-/wɛ/ vs. /e/-/ɛ/

The MANOVA results, based on the vertical and horizontal tongue dorsum position values as the multivariate dependent variables and calculated as the mean of two measurements taken at the vowel midpoint (Vmid) and offset (Voffset) (see Appendix C for detailed MANOVA results), provide no evidence of phonetic distinction between /e/ and /ɛ/ (Pillai = 0.004, $p > 0.1$) or between /we/ and /wɛ/ (Pillai = 0.002, $p > 0.1$). There is no significant interaction involving Dialect, Gender, or Timepoint for either comparison. These results suggest that the two vowel pairs are fully merged across dialects and genders.

These mergers are further reflected in the tongue dorsum movement trajectories illustrated in the upper panels of Figs. 5a and 6a, which have been redrawn and zoomed in for these vowel comparisons. Recall that, in interpreting these

[2] While the anticipatory effects observed here—particularly the asymmetry between high and non-high vowels—are indeed intriguing, we do not elaborate on them further in the present discussion due to methodological limitations. Specifically, because /w/ is produced in syllables spoken in isolation, its articulatory onset is tightly coupled only with that of the following vowel, making it difficult to determine the precise initiation point of the /w/ gesture. This poses challenges in accurately capturing the timing and extent of anticipatory coarticulation beyond the qualitative patterns noted here. For this reason, we have focused our analysis on carryover effects, whose articulatory onset and directionality are more clearly defined in our data. Nonetheless, anticipatory effects warrant further investigation in future work using methods better suited to resolving fine-grained gestural timing.

results, we considered the trajectories to be significantly distinct only when the GAMM visualizations revealed a sustained period of significant difference and the estimated degrees of freedom (EDF) were high, with a corresponding p-value below 0.05. These figures, with data pooled across all speakers, reveal substantially overlapping trajectories between /e/ and /ɛ/ as well as /we/ and /wɛ/, particularly towards the latter portion of the movements, aligning with the MANOVA results. However, further analysis of vowel articulation dynamics using GAMMs reveals some discrepancies between the /we/-/wɛ/ and /e/-/ɛ/ mergers.

For /e/-/ɛ/, as shown in the lower panels of Fig. 5a, the GAMM results indicate some distinction between /e/ and /ɛ/ in the horizontal dimension during the first half of the tongue dorsum movement trajectories. Specifically, /e/ is initiated from a more fronted position than /ɛ/, consistent with the general distinction between close-mid and open-mid vowels, aligning with the pre-merger vowel distinction in Korean. However, this distinction becomes much attenuated and its significance disappears as the articulation approaches the vowel targets, in line with the MANOVA results. When analyzed separately by group, only two groups—Seoul female and N. Gyeongsang male speakers—exhibit this distinction. As illustrated in Fig. 5b, e, both groups show significant differences in the horizontal dimension during the earlier part of the trajectories, while N. Gyeongsang males also exhibit a significant distinction in the vertical dimension.

For /we/-/wɛ/, in contrast to /e/-/ɛ/, there is no significant distinction when data are pooled across speakers, as shown in Fig. 6a. However, when analyzed separately by group, one group—N. Gyeongsang male speakers—shows some initial distinction in the articulatory movement trajectory in the vertical dimension, as seen in Fig. 6e. For this group, too, the later part of the trajectories ultimately merges, in line with the MANOVA results.

In summary, MANOVA results of tongue dorsum position indicate complete mergers of /e/-/ɛ/ and /we/-/wɛ/ across dialects and genders, with movement trajectories showing substantial overlap—particularly in the later portions of the vowel. These patterns were corroborated by supplementary lip aperture analyses (see Appendix E), which also revealed no significant differences between the vowel pairs, with or without /w/. However, dynamic GAMM analyses of tongue dorsum trajectories uncovered an initial horizontal distinction between /e/ and /ɛ/ among Seoul female and North Gyeongsang male speakers, while /we/ and /wɛ/ exhibited a brief but significant vertical distinction only among North Gyeongsang males. Supplementary analyses of formant frequencies (Appendix E) further supported this asymmetry induced by /w/: an acoustic distinction persisted between /e/ and /ɛ/, but not between /we/ and /wɛ/. These results suggest that certain speaker groups (Seoul females and North Gyeongsang males) retain traces of the pre-merger contrast, but the strategies for doing so differ depending on the presence of /w/—pointing to a possible reorganization of gestural structure in the /w/-vowel context.

3.2.2. /wa/-/wʌ/ vs. /a/-/ʌ/

The results of MANOVAs with the vertical and horizontal tongue dorsum position values of Vmid and Voffset as the multivariate dependent variables (see Appendix D for detailed MANOVA results) show generally clear distinction between /a/ and /ʌ/ (Pillai = 0.203, $p < 0.001$) or /wa/ and /wʌ/ (Pillai = 0.212, $p < 0.001$), but these two pairs, too, show some differences in terms of how the vowel contrast interacts with Gender or Dialect.

For /a/-/ʌ/, there is a significant interaction with Dialect (Pillai = 0.028, $p < 0.01$) and Gender (Pillai = 0.050, $p < 0.001$), but no three-way interaction of Vowel × Dialect × Gender (Pillai = 0.001, $p = 0.88$). The significant Vowel × Dialect interaction reflects a difference in the degree of distinction between /a/ and /ʌ/ across dialects, with /ʌ/ being more retracted than /a/. While speakers of both dialects maintain a robust contrast, the distinction is more pronounced among N. Gyeongsang speakers (Pillai = 0.272 vs. 0.167, both $p < 0.001$).

The significant Vowel × Gender interaction reflects a much clearer distinction in female speakers compared to male speakers, as indicated by a substantial difference in Pillai scores (Pillai = 0.344 vs. 0.080, both $p < 0.001$). In contrast with the dialectal difference whose magnitude is relatively small (ΔPillai = 0.105), this gender-related difference is considerably larger (ΔPillai = 0.264), indicating that gender plays a stronger role than dialect in the /a/-/ʌ/ distinction—specifically, female speakers maintain a clearer /a/-/ʌ/ distinction than male speakers across both dialects.

The /wa/-/wʌ/ contrast also generally shows /wʌ/ being more retracted than /wa/, aligning with their corresponding vowels /a/-/ʌ/. However, it exhibits some important differences compared to the /a/-/ʌ/ contrast. This time, there is a significant interaction with Gender (Pillai = 0.119, $p < 0.01$), but not with Dialect (Pillai = 0.013, $p = 0.08$). The gender effect arises because only female speakers maintain a robust /wa/-/wʌ/ distinction (Pillai = 0.542, $p < 0.001$), whereas male speakers, despite distinguishing vowels /a/ and /ʌ/ in the absence of /w/, show no significant distinction between /wa/ and /wʌ/ (Pillai = 0.026, $p = 0.08$). This indicates an unexpected tongue dorsum merger of /wa/-/wʌ/ among male speakers, but not of /a/ and /ʌ/.

The patterns observed in the MANOVA results based on tongue dorsum position values—averaged across the vowel midpoint and offset—are consistent with the overall tongue dorsum movement trajectories. As shown in Fig. 8d, e, male speakers of both dialects exhibit greater convergence between /wa/ and /wʌ/ near the end of the movement trajectories, a pattern that contrasts with the clearer distinction observed in the /a/-/ʌ/ pair. A closer examination of the tongue dorsum movement trajectories, using zoomed-in views in Figs. 7 and 8 along with GAMM analyses, reveals broadly similar patterns for both /a/-/ʌ/ and /wa/-/wʌ/. However, a particularly striking gender difference emerges. Consistent with the MANOVA results, female speakers in both dialects maintain a clear distinction between /a/ and /ʌ/, as well as between /wa/ and /wʌ/, as shown in Figs. 7b, c, 8b, and c. This distinction is evident in both the vertical and horizontal dimensions in the GAMM analyses (lower panels of these figures), showing that /ʌ/ is consistently positioned further back than /a/, regardless of the presence of /w/. Moreover, female speakers maintain this distinction not only toward the end of the movement but throughout the entire trajectory from its onset. However, the fact that female speakers preserve the /a/-/ʌ/ and /wa/-/wʌ/ distinctions does not

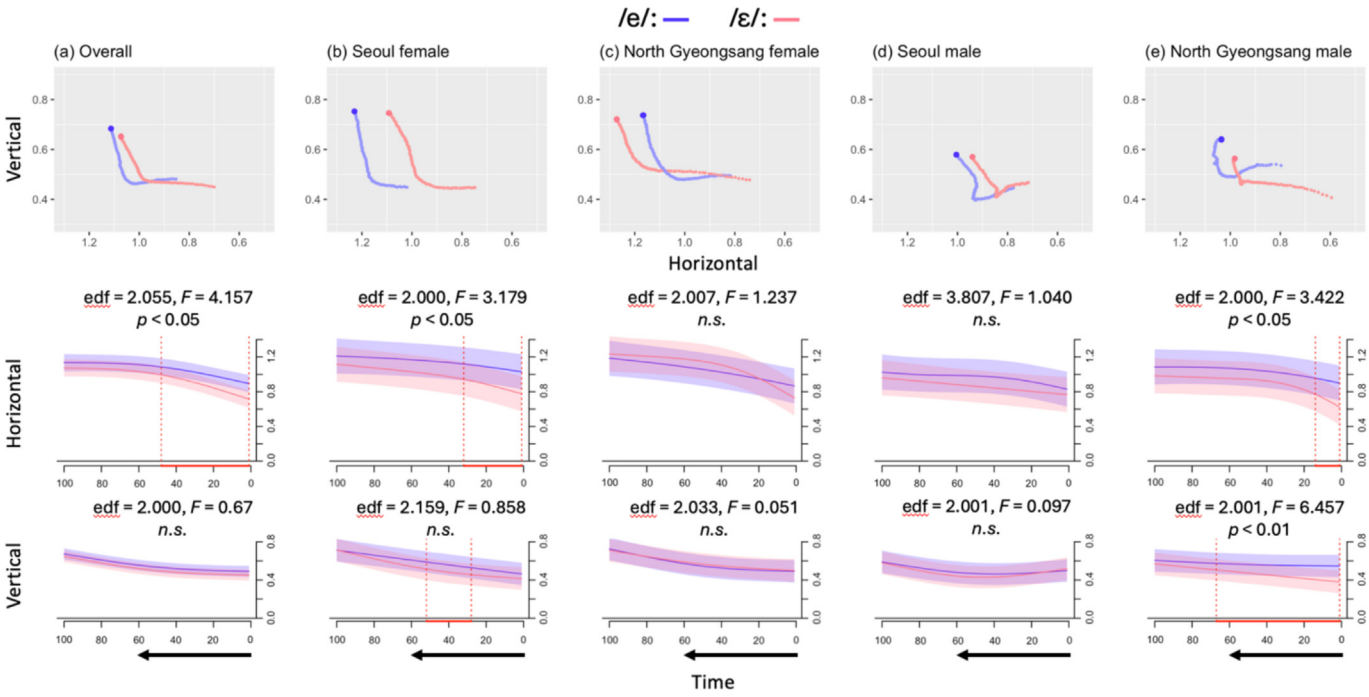


Fig. 5. Trajectory plots (top row) and GAMM smooth plots (middle and bottom rows) of /e/ (blue) and /ɛ/ (red). The trajectory plots illustrate the mean tongue dorsum movement trajectories throughout /e/ and /ɛ/ productions, with the dot at the end indicating the endpoint of the trajectory. The GAMM smooth plots below each trajectory plot display the GAMM smooths of the horizontal (middle row) and vertical (bottom row) movements of the tongue dorsum. In the GAMM smooth plots, the time progresses from right to left. The red line overlaid on the x-axis highlights the temporal window during which /e/ and /ɛ/ exhibit differences. The *p* values indicate whether these differences are significant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

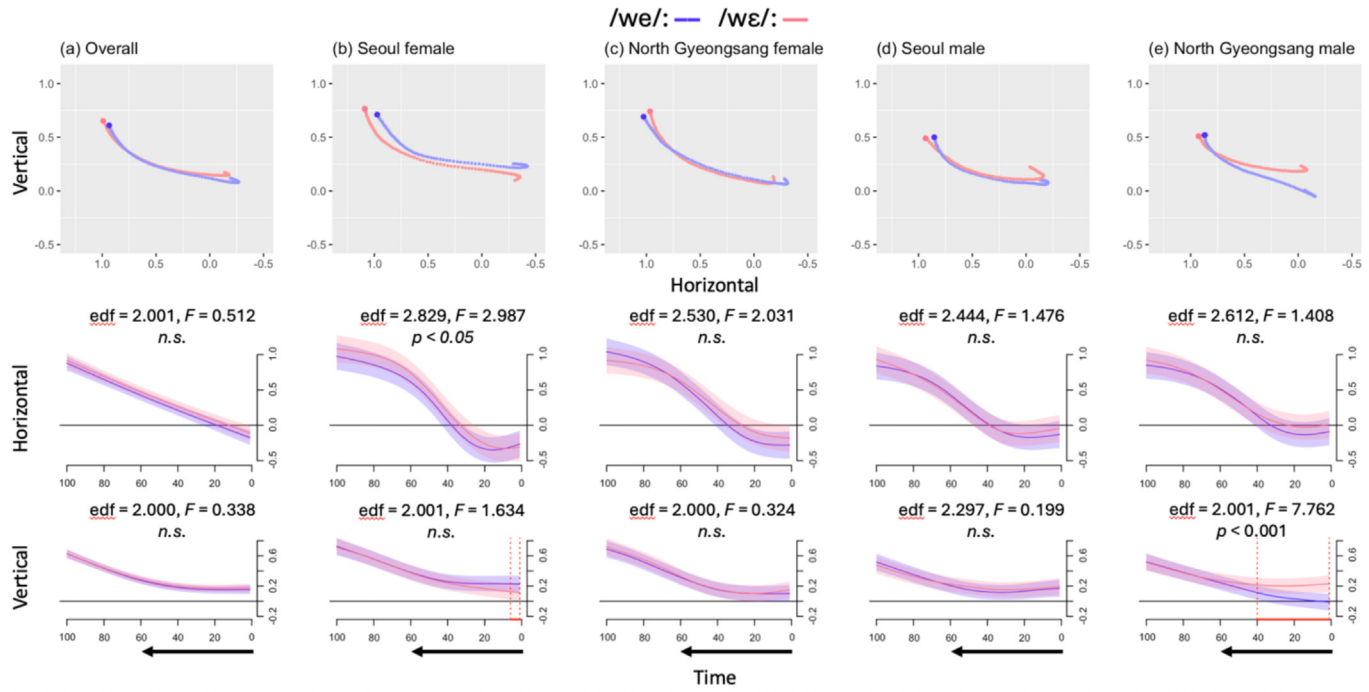


Fig. 6. Trajectory plots (top row) and GAMM smooth plots (middle and bottom rows) of /we/ (blue) and /wɛ/ (red). The trajectory plots illustrate the mean tongue dorsum movement trajectories throughout /we/ and /wɛ/ productions, with the dot at the end indicating the endpoint of the trajectory. The GAMM smooth plots below each trajectory plot display the GAMM smooths of the horizontal (middle row) and vertical (bottom row) movements of the tongue dorsum. In the GAMM smooth plots, the time progresses from right to left. The red line overlaid on the x-axis highlights the temporal window during which /we/ and /wɛ/ exhibit differences. The *p* values indicate whether these differences are significant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

diminish the influence of /w/. Recall that, as noted in Section 3.1 (Fig. 4a, b), vowel pairs with and without /w/ exhibit distinct articulatory trajectories.

The distinction between /a/-/ʌ/ and /wa/-/wʌ/ is not unexpected, as these vowels are contrastive phonemes. However, despite /ʌ/ in Gyeongsang dialects being a relatively recent devel-

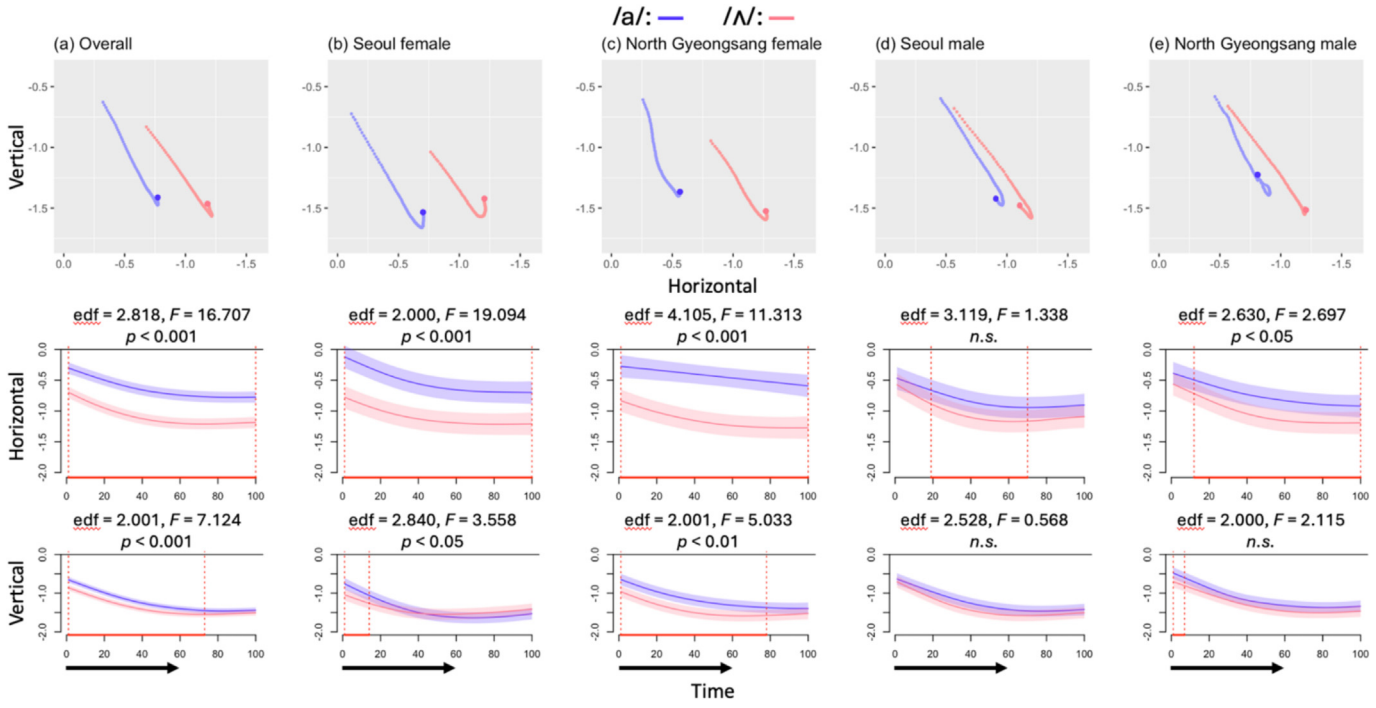


Fig. 7. Trajectory plots (top row) and GAMM smooth plots (middle and bottom rows) of /a/ (blue) and /ʌ/ (red). The trajectory plots illustrate the mean tongue dorsum movement trajectories throughout /a/ and /ʌ/ productions, with the dot at the end indicating the endpoint of the trajectory. The GAMM smooth plots below each trajectory plot display the GAMM smooths of the horizontal (middle row) and vertical (bottom row) movements of the tongue dorsum. In the GAMM smooth plots, the time progresses from left to right. The red line overlaid on the x-axis highlights the temporal window during which /a/ and /ʌ/ exhibit differences. The *p* values indicate whether these differences are significant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

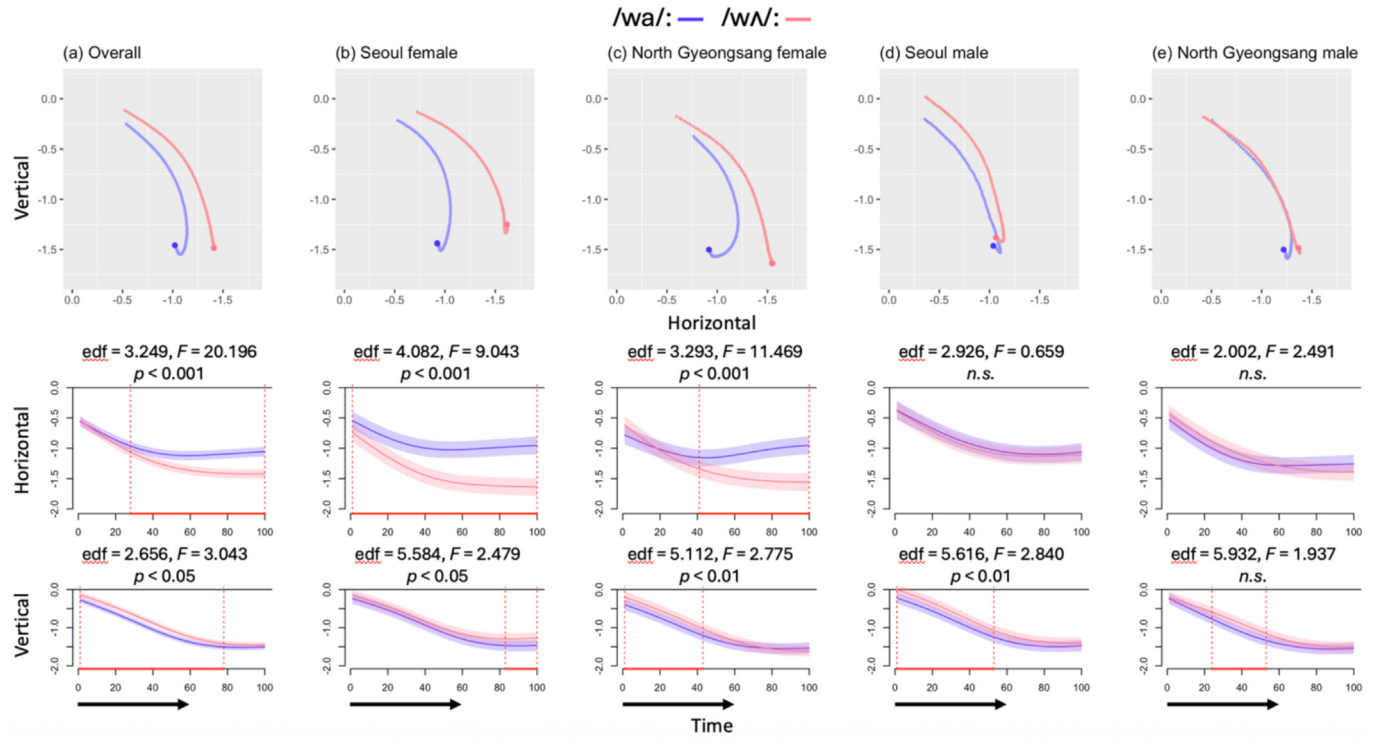


Fig. 8. Trajectory plots (top row) and GAMM smooth plots (middle and bottom rows) of /wa/ (blue) and /wʌ/ (red). The trajectory plots illustrate the mean tongue dorsum movement trajectories throughout /wa/ and /wʌ/ productions, with the dot at the end indicating the endpoint of the trajectory. The GAMM smooth plots below each trajectory plot display the GAMM smooths of the horizontal (middle row) and vertical (bottom row) movements of the tongue dorsum. In the GAMM smooth plots, the time progresses from left to right. The red line overlaid on the x-axis highlights the temporal window during which /wa/ and /wʌ/ exhibit differences. The *p* values indicate whether these differences are significant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

opment among younger speakers following the historical merger of /ʌ/-/ɨ/, the striking similarities between female speakers of Seoul and N. Gyeongsang Korean suggest that /ʌ/ is phonologically treated the same in both groups. More striking is the pattern among male speakers. Compared to females, males show much weaker differentiation between the vowel pairs, with some additional dialectal variation. As shown in Figs. 7d, e (for /a/-/ʌ/) and 8d, e (for /wa/-/wʌ/), this distinction varies by dialect.

For /a/-/ʌ/, N. Gyeongsang male speakers show some horizontal separation, with /ʌ/ positioned further back (Fig. 7e), though the difference is much smaller than in females. In contrast, Seoul males show no clear distinction (Fig. 7d)—i.e., while the GAMM graph suggests some divergence, the statistical results do not confirm a significant difference for Seoul males. For /wa/-/wʌ/, the pattern is reversed. N. Gyeongsang males show no distinction between the two vowels (Fig. 8e), whereas Seoul males exhibit some differentiation, but only in the vertical dimension. However, this distinction by Seoul males fades in the later phase of the movement (Fig. 8d), indicating a merger in the tongue dorsum target.

Thus, in the horizontal dimension of the tongue dorsum movement, while female speakers in both dialects show a clear backness distinction for both /a/-/ʌ/ and /wa/-/wʌ/, this contrast is much weaker among male speakers for /a/-/ʌ/ and disappears entirely for /wa/-/wʌ/. In other words, the presence of /w/ effectively neutralizes the backness distinction in /wa/-/wʌ/ for male speakers, whereas female speakers continue to maintain it—consistent with the MANOVA results based on tongue dorsum position values averaged across the vowel midpoint and offset.

Finally, a comparison of the four groups in terms of the /wa/-/wʌ/ distinction (Fig. 8b–e) reveals a hierarchical trend: Seoul females show the strongest contrast, followed by N. Gyeongsang females, then Seoul males, with N. Gyeongsang males exhibiting the weakest distinction. Notably, Seoul speakers of both genders maintain a greater /wa/-/wʌ/ distinction than their N. Gyeongsang counterparts. However, a striking dialectal asymmetry emerges when comparing /wa/-/wʌ/ with /a/-/ʌ/: for /a/-/ʌ/, the pattern reverses—N. Gyeongsang speakers, particularly females, show a stronger distinction than Seoul speakers, as evidenced by movement trajectories (Fig. 7b vs. c, d vs. e) and GAMM results.

In summary, both /a/-/ʌ/ and /wa/-/wʌ/ exhibit clear articulatory contrasts in tongue dorsum trajectories, but these contrasts vary systematically by gender and dialect.

- *Gender differences.* Results from MANOVA and GAMM indicate clear gender-related patterns along the tongue dorsum dimension. Female speakers in both dialects consistently maintain a backness contrast along the horizontal dimension in both /a/-/ʌ/ and /wa/-/wʌ/, despite the fact that /ʌ/ in the Gyeongsang dialect only recently re-split from its historical merger with /ɨ/. Male speakers, on the other hand, show a weaker /a/-/ʌ/ distinction and, notably, a merger between /wa/ and /wʌ/ across dialects.
- *Dialectal Differences.* GAMM results further reveal dialectal variation. For /a/-/ʌ/, Gyeongsang male speakers show a horizontal tongue dorsum distinction, whereas Seoul male speakers show a merger. In the case of /wa/-/wʌ/, both dialect groups display general convergence; however, Seoul speakers exhibit an initial tongue dorsum difference along the vertical dimension, which disappears as the articulation approaches the vowel target.

However, it should be noted that the observed merger of /wa/ and /wʌ/ in tongue dorsum trajectories across both dialects was not corroborated by the supplementary analyses. That is, data from lip aperture and formant frequencies (Appendix E) clearly maintained a distinction between the two vowels. This indicates the merger is limited to the tongue dorsum dimension and is not evident in other phonetic dimensions. This finding aligns with the existing literature, as, to the best of our knowledge, no previous studies suggested an ongoing merger between /wa/ and /wʌ/.

Nevertheless, the tongue dorsum data highlight meaningful dialectal asymmetries: Seoul speakers show greater distinction in /wa/-/wʌ/, whereas North Gyeongsang speakers show greater contrast in /a/-/ʌ/, likely due to the recent split of /ʌ/ from /ɨ/, after its historical merger with /ɨ/, as further discussed in the General Discussion. Overall, these findings indicate that /w/ systematically modulates articulatory dynamics, and that gender and dialect interact to shape the degree of distinction. Importantly, the resulting articulatory patterns diverge from those of their corresponding vowels without /w/, supporting the view that /w/-vowel sequences undergo gestural restructuring.

4. General discussion

The present study investigated the articulatory characteristics of Korean /w/-vowel sequences by comparing their gestural realizations with those of their corresponding vowels without /w/, as produced by 24 young female and 24 male speakers of Seoul and North Gyeongsang Korean in their twenties. The primary goal was to determine whether these sequences function as independent glide-vowel combinations or exhibit evidence of gestural restructuring, influencing the articulatory realization of vowels beyond what is expected from typical coarticulatory processes—particularly when produced in isolation, a hyperarticulated context. This investigation was further framed within the context of ongoing sound change, specifically examining /we/-/wɛ/ versus /e/-/ɛ/, which have undergone a merger across dialects, and /wa/-/wʌ/ versus /a/-/ʌ/, with particular attention to the unique phonological status of /ʌ/ following its historical merger and subsequent split with /ɨ/ in Gyeongsang Korean. Overall, the results demonstrate that the articulatory dynamics of /w/-vowel sequences do not simply mirror those of their corresponding vowels without /w/; rather, they exhibit distinct patterns shaped by multiple interacting factors: phonetic variation in coarticulatory processes as a function of the vowel's constriction degree, phonological conditioning related to recent sound changes, and sociophonetic influences, including dialectal and gender-based variation. In the remainder of the discussion, we summarize the main findings and assess their implications for the gestural restructuring hypothesis, integrating insights from a dynamical perspective.

4.1. Gestural restructuring: Convergence and divergence of vowels with and without /w/

The analysis of tongue dorsum trajectories revealed systematic patterns of vowel convergence and divergence between the nucleus vowels in /w/-vowel sequences and their

corresponding vowels without /w/, shaped by vowel quality, dialect, and gender. These findings were further supported by MANOVA analyses of vowel midpoint and offset positional values, which reflect vowel targets. The MANOVAs were conducted using Pillai scores to quantify the degree of separation between vowels produced with and without /w/.

Front vowels (/i, e, ɛ/) generally exhibited similar tongue positions between /w/-vowel sequences and their corresponding vowels without /w/. The high front vowel pair (/wi/-/i/) showed complete convergence, indicating that /w/ had minimal or no articulatory influence, providing no evidence of gestural restructuring. In contrast, mid front vowel pairs (/we/-/e/ and /wɛ/-/ɛ/) displayed small but statistically significant divergences, influenced by dialect. Specifically, the /we/-/e/ pair consistently showed some divergence across both dialects, whereas the /wɛ/-/ɛ/ pair exhibited noticeable divergence only among North Gyeongsang speakers, with Seoul speakers showing no significant differentiation. For these mid front vowels with /w/, the divergence from their corresponding vowels without /w/ was primarily due to some small tongue retraction (a less fronted position), consistent with expected coarticulatory effects from the tongue dorsum retraction associated with /w/. Crucially, however, this retraction was not confined to the early phase of movement trajectories, where low-level coarticulatory influences would typically be expected. Instead, it persisted even during the production of the vowel. Considering that the target syllables were produced in isolation, this suggests a more stable articulatory adjustment beyond transient coarticulatory effects on the mid front vowels.

Low back vowels (/a, ʌ/) exhibited significantly greater divergence between /w/-vowel sequences and their corresponding vowels without /w/, with more retracted tongue dorsum positions when preceded by /w/. This pattern was consistently observed in vowel midpoint and offset positions, suggesting an articulatory adjustment that extends beyond a low-level coarticulatory effect. However, the degree of divergence varied by dialect and gender. Dialectally, North Gyeongsang speakers showed greater divergence for /wa/-/a/ than Seoul speakers. Gender-wise, female speakers exhibited a clear divergence for /wʌ/-/ʌ/ (but larger for Seoul than for N. Gyeongsang), whereas male speakers showed no divergence for /wʌ/-/ʌ/. These findings, along with the persistence of /w/'s effect on back vowels into the later phase of articulation and substantial separation throughout the articulatory trajectories from the onset, suggest significant vowel adjustments conditioned by /w/ and further shaped by dialectal and gender-based variation.

As discussed in the introduction section, such articulatory adjustments could be interpreted in the theoretical framework of Articulatory Phonology (Browman & Goldstein, 1986, 1992; Goldstein et al., 2006). In particular, it was hypothesized that the coarticulatory nature of /w/-vowel sequences, driven by gestural blending, could lead to gestural restructuring beyond what is typically expected from low-level coarticulation. Such restructuring would yield an integrated gestural representation for the vocalic gesture, with surface articulatory movement trajectories distinct from those of its corresponding vowel without /w/. The articulatory divergence patterns observed in this study between vowels in /w/-vowel sequences and their corresponding vowels without /w/ indeed lend general support to the gestural restructuring hypothesis.

However, as noted above, gestural restructuring was conditioned by the constriction degree of the vowel. The high front vowel pair (/wi/-/i/) exhibits complete convergence, mid front vowel pairs (/we/-/e/ and /wɛ/-/ɛ/) show moderate but significant divergence, and low back vowel pairs (/wa/-/a/ and /wʌ/-/ʌ/) display the most robust divergence. This pattern reflects the gradient relationship between the constriction degree of the vowel and coarticulatory resistance (Cho, 2004; Farnetani & Recasens, 2010; Recasens, 2002), where the nucleus vowel's constriction degree influences divergence in a systematic manner. High front vowels, with narrower constriction, resist coarticulatory influence from /w/, explaining the shared vowel targets between /wi/ and /i/. In contrast, low back vowels, with wider constriction, exhibit weaker coarticulatory resistance, allowing /w/ to exert a greater influence, ultimately leading to gestural restructuring. Mid front vowels represent an intermediate case between these two extremes. This gradient nature of divergence suggests that gestural restructuring is inherently tied to the phonetic effects of coarticulation and may not be interpreted as a fully categorical phonological process. This issue will be further explored in Section 4.3 in conjunction with how gestural restructuring may be understood in dynamical terms.

In addition to the constriction-based account, the gradient nature of gestural restructuring—as noted by a reviewer—may reflect, at least in part, the direction of tongue dorsum movement in both /w/ and the following vowel. The directionality relationship is protagonistic when /w/ is followed by a back vowel (/a/ or /ʌ/), facilitating the backing impact of /w/, and antagonistic when /w/ is followed by a front vowel, resulting in opposing movements. Even among back vowels, protagonism may vary: our data show that /a/ is more central and less retracted—thus less protagonistic—than /ʌ/, potentially explaining the greater divergence in the former (/wʌ/-/ʌ/) than in the latter (/wa/-/a/) (see Figs. 3 and 8). For front vowels, however, the effects of horizontal directionality should be minimal, as /i/, /e/, and /ɛ/ are similarly fronted (see Fig. 3). Yet, substantial convergence differences that remain between /w/-initial and plain high vowels suggest gradient differences between high and non-high vowels, which are better accounted for by constriction degree than by movement directionality. We therefore propose that the degree of lingual constriction plays a primary role in shaping gestural convergence and restructuring, though it is further conditioned by movement directionality.

Lastly, the gradient nature of gestural restructuring may also reflect differences in coarticulatory resistance tied to vowel constriction location along the front–back dimension. As Recasens (2018) notes, resistance depends not only on constriction degree but also on its location: dorsopalatal vowels like /i/ and /e/ (with anterior constriction) resist coarticulation more than back vowels like /u/ and /a/ (with dorsovelar or pharyngeal constriction). Here again, among front vowels, constriction degree matters: /i/ may resist more than /e/ due to its higher constriction degree, contributing to lesser divergence in /wi/ compared to /we/ or /wɛ/. Beyond front vowels, however, the divergence differences between the front pairs (/we/-/e/, /wɛ/-/ɛ/) and the

low-back pairs (/wa/-/a/, /wʌ/-/ʌ/) may also stem from constriction location: /e/ and /ɛ/ involve dorsopalatal constriction, whereas /a/ and /ʌ/ are more posterior. This likely results in greater resistance to restructuring in /w/-vowel sequences with front vowels than with back vowels.

Taken together, these observations suggest that while constriction degree serves as the primary determinant of coarticulatory constraints—and thus strongly influences the degree of gestural restructuring—other factors, most notably the directionality of tongue dorsum movement and the location of constriction, also play supplementary roles in shaping the degree and nature of gestural integration. These interacting constraints help account for the gradient patterns observed in gestural restructuring, a point to which we return in Section 4.3.

4.2. Further evidence for gestural restructuring from sound change in /we/-/wɛ/ and /wa/-/wʌ/

4.2.1. Gestural restructuring and sound change in /we/-/wɛ/

A complementary perspective on phonological restructuring emerges in the context of sound changes from examining whether the phonetic distinction between /w/-vowel sequences (/we/-/wɛ/ and /wa/-/wʌ/) aligns with or deviates from that of their corresponding vowels without /w/ (/e/-/ɛ/ and /a/-/ʌ/). As introduced earlier, relevant sound changes include the /e/-/ɛ/ merger across dialects and the recent /ʌ/-/ɨ/ split, which followed an earlier /ʌ/-/ɨ/ merger in Gyeongsang Korean. In this regard, we hypothesized that /w/-vowel sequences have undergone phonological restructuring rather than simply functioning as glide-vowel combinations if either or both of the following conditions hold: (1) the phonetic distinction of /w/-vowel sequences, such as /we/-/wɛ/, follows a merger pattern distinct from that of their corresponding vowels /e/-/ɛ/; and (2) /ʌ/ in /wʌ/ patterns differently from its corresponding vowel without /w/, particularly in Gyeongsang Korean, where /ʌ/ recently re-entered the vowel inventory as a distinct vowel separate from /ɨ/. We suggest that our results provide partial support for these predictions, with stronger evidence for the latter case, as discussed below.

MANOVA results based on tongue dorsum targets, supplemented by linear mixed-effects regression analyses of lip aperture, indicate a complete merger between /we/ and /wɛ/, as well as between /e/ and /ɛ/. The absence of distinct patterns based on the presence or absence of /w/ therefore offers no additional support for the gestural restructuring account. However, GAMM analyses of articulatory dynamics, further supplemented by formant-based MANOVA results, reveal subtle but significant differences conditioned by the presence of /w/: a slight distinction persists in the /e/-/ɛ/ pair in the absence of /w/—early in the movement trajectory—but not in its presence in the /we/-/wɛ/ pair, suggesting the preservation of minimal traces of the pre-merger distinction for /e/-/ɛ/.

Thus, there is some evidence that the presence of /w/ influences merger patterns in a way that aligns, at least partially, with predictions of the gestural restructuring hypothesis. But the effect is further modulated by dialect and gender. The /e/-/ɛ/ distinction is most prominent among Seoul female and North Gyeongsang male speakers. Only North Gyeongsang male speakers further maintain a /we/-/wɛ/ distinction, making them the only group that preserves the /e/-/ɛ/ contrast both with and without /w/. As noted by a reviewer, this may reflect a more conservative speech pattern by North Gyeongsang male speakers, who appear more resistant to ongoing sound change. Still, the finding that the /e/-/ɛ/ contrast is clearer than the /we/-/wɛ/ contrast—even within this conservative group—suggests that the trajectory of the /e/-/ɛ/ merger is shaped by the presence or absence of /w/, aligning—albeit subtly—with the gestural restructuring account.[3]

It is also worth noting that ongoing merger patterns may not always reflect the role of constriction degree in shaping articulatory diverging patterns. MANOVA results show a distinction between /we/ and /e/, but convergence between /wɛ/ and /ɛ/. This is counterintuitive: if /e/ is more constricted than /ɛ/, reflecting the pre-merger distinction, it should resist coarticulation with /w/ more, promoting greater /we/-/e/ convergence—but we observe the opposite. A likely explanation is that historical vowel height no longer determines gestural coordination, presumably due to the widespread /e/-/ɛ/ merger. Instead, a residual horizontal distinction persists: /e/ retains a more fronted tongue posture early in its trajectory, unlike /ɛ/, /we/, or /wɛ/. This fronting for /e/ reduces affinity with /we/, limiting convergence independently of the constriction-based effect. In contrast, the similar articulatory profiles of /ɛ/, /we/, and /wɛ/ facilitate their convergence. Thus, the observed asymmetry may be better explained by present-day tongue fronting at least for this particular case than by vowel height or constriction degree. From this perspective, /e/ resists merging with /we/ due to fronting, while /ɛ/, /wɛ/, and /we/ more readily converge. Though tentative, this suggests that gestural restructuring is shaped more by present-day articulatory similarity than by traditional pre-merger phonological categories.

Taken together, although the evidence for a uniform gestural restructuring account for /we/ and /wɛ/ is mixed—particularly in relation to the ongoing merger of /e/ and /ɛ/—we propose that patterns in tongue dorsum trajectories and formant frequencies suggest that /w/ exerts a holistic influence on the articulatory dynamics of /w/-vowel sequences, making them at least subtly distinct from their corresponding vowels without /w/. In particular, the stronger merger pattern observed in /we/-/wɛ/ compared to /e/-/ɛ/ indicates that /w/ may promote merger by altering the temporal and spatial coordination of gestures, consistent with a restructuring account involving /w/. Such differences, particularly among certain dialectal or gender-based speaker groups, further suggest that ongoing vowel merger patterns and speaker-specific variation also shape gestural restructuring.

[3] The reason for this asymmetry is not entirely clear, but the /e/-/ɛ/ contrast appears to be more clearly marked in orthography, potentially eliciting hyperarticulation in plain vowel contexts. Specifically, while the contrast is overtly represented as 'ㅇ|' (/e/) vs. 'ㅇ||' (/ɛ/), it becomes less visually salient in the diphthongs 'ㅞ' (/we/) vs. 'ㅙ' (/wɛ/), where the distinction is distributed across two elements: the glide /w/ is encoded by different consonant–vowel combinations ('ㅜ' vs. 'ㅗ'), and the following vowel by 'ㅔ' (/e/) vs. 'ㅐ' (/ɛ/). As a result, the /e/-/ɛ/ contrast in /w/-initial forms is less isolated and may receive weaker visual reinforcement. This pattern is particularly prominent in the productions of Seoul female speakers, and therefore this may also align with Labov's "Gender Paradox" (2001), which notes that female speakers tend to favor prestige forms and preserve standard contrasts more reliably, especially in contexts involving conscious monitoring. This is likely relevant here, as the target syllables were produced in isolation and presented with clear orthographic cues. A similar orthographic effect may also contribute to the reduced /we/-/wɛ/ distinction observed in North Gyeongsang male speakers. In their case, however, the asymmetry between /w/-vowel sequences and their plain counterparts may also reflect a more conservative tendency of this group—a sociophonetic factor distinct from the contrast-preserving tendencies of Seoul female speakers—warranting further investigation.

4.2.2. Gestural restructuring and sound change in /wa/-/wʌ/

Turning to the low back vowels, the results for /wa/-/wʌ/ vs. /a/-/ʌ/ provide stronger support for the gestural restructuring hypothesis, revealing a robust difference in tongue dorsum movement trajectories. The contrast between /wa/ and /wʌ/ arises through distinct articulatory paths, deviating substantially from the /a/-/ʌ/ pattern. Here again, the extent of deviation varies systematically by dialect and gender. A key finding is that male speakers, across both dialects, retain some tongue dorsum distinction between /a/ and /ʌ/, but exhibit a merger between /wa/ and /wʌ/ in tongue dorsum movement—particularly toward the end of the articulatory trajectory. This suggests that the /a/-/ʌ/ contrast is modulated by the presence of /w/. Nevertheless, lip aperture measurements still indicate distinctions in both /wa/-/wʌ/ and /a/-/ʌ/ for male speakers. In contrast, female speakers consistently maintain the /a/-/ʌ/ contrast regardless of /w/ presence and across both articulatory dimensions, supporting sociophonetic findings that women tend to produce more distinct speech—consistent with Labov's Gender Paradox (2001) and prior research (e.g., Byrd, 1994; Henton, 1983; Oh, 2011; Whiteside, 1996; Whiteside & Irving, 1998).

Another interesting finding in the low back vowel context is the asymmetry in how dialect influences the /wa/-/wʌ/ and /a/-/ʌ/ distinctions. Specifically, MANOVA results (with Pillai scores) for the tongue dorsum show that, for the /wa/-/wʌ/ contrast, female speakers showed a greater distinction than males, and within each gender group, Seoul speakers exhibited a larger /wa/-/wʌ/ distinction than North Gyeongsang speakers. However, for the /a/-/ʌ/ contrast in the absence of /w/, the pattern was reversed: North Gyeongsang speakers exhibited a larger /a/-/ʌ/ distinction than Seoul speakers, regardless of gender. This suggests that while Seoul speakers enhance the contrast when /w/ is present, North Gyeongsang speakers do so in its absence.

This asymmetry between the /wa/-/wʌ/ and /a/-/ʌ/ pairs across dialects suggests that speakers of both dialects treat these vowel targets differently but adjust their articulation in distinct ways depending on the presence or absence of /w/. This clearly indicates that the pairs are structured differently as a function of /w/, and aligns with the gestural restructuring hypothesis. But the underlying factors that may contribute to this asymmetry remain unclear. One possibility is that it stems from the recent reintroduction of /ʌ/ into the vowel inventory of Gyeongsang Korean. Gyeongsang speakers, particularly females, may be hyperarticulating /ʌ/ to reinforce its phonemic status, positioning it more distinctly within the vowel system. This may indicate an ongoing stabilization process in which speakers enhance the phonetic distinction between /a/ and /ʌ/, both occupying the low back vowel region, to reinforce the contrast as /ʌ/ re-emerges. In contrast, the opposite trend is observed for /wa/-/wʌ/, where North Gyeongsang speakers, particularly males, exhibit greater overlap than their Seoul counterparts. This suggests that the presence of /w/ modifies the underlying contrast between vowels, potentially setting /w/-vowel sequences on a different trajectory of sound change than their plain-vowel counterparts. Specifically, for North Gyeongsang male speakers, hyperarticulation of /ʌ/—likely reflecting its recent re-emergence as a distinct vowel in the inventory—appears to reinforce the contrast between /a/ and /ʌ/. However, this strengthened distinction does not extend to the /wa/-/wʌ/ pair, where the contrast between /wʌ/ and /wa/ appears to be weakening. In this case, the presence of /w/ appears to facilitate a merger between /wʌ/ and /wa/, particularly along the tongue dorsum dimension.

The general merging patterns of /a/-/ʌ/ and /wa/-/wʌ/ among male speakers offer further insight into the progression of these changes along the tongue dorsum dimension, which is particularly striking given that no previous studies on the Korean vowel system have reported evidence of such a merger. Although speculative, the /a/-/ʌ/ tongue dorsum merger, evident among males, appears to have originated with Seoul male speakers and is now spreading to their Gyeongsang counterparts, assuming that the more complete overlap observed among Seoul males reflects a more advanced stage of the change. This interpretation aligns with previous observations that Seoul speakers—representing the standard dialect—often lead sound changes ahead of non-standard dialects (e.g., Cho et al., 2001; Lee et al., 2013). That is, although the precise mechanisms behind these changes remain unclear, it is not uncommon for non-standard dialects such as Gyeongsang to undergo changes that ultimately bring them closer to Seoul Korean, as seen in other domains such as the stop laryngeal contrast. Here again, the slower progression among Gyeongsang male speakers may be tied to the phonological history of Gyeongsang Korean, where /ʌ/, having been reintroduced more recently, may be produced more distinctly by North Gyeongsang males than by Seoul speakers. Thus, for North Gyeongsang male speakers, the merger appears more advanced in /wa/-/wʌ/ than in /a/-/ʌ/. Because /wʌ/ has remained stable in the vowel system without undergoing the same sound change as /ʌ/ in the cycle of the /ʌ/-/ɨ/ merger and split, there may have been less pressure to maintain a clear distinction for /wʌ/ compared to /ʌ/ in the vowel space.

Taken together, these findings highlight how dialectal history and gender interact in shaping the articulation of /ʌ/, with some speakers adopting merger patterns while others reinforce contrast depending on their linguistic background and social positioning within the sound change. The role of social positioning may be evident in how female speakers of Gyeongsang Korean, like those in other non-standard dialects, tend to approximate standard pronunciations, contributing to dialect leveling (Labov, 1990). This explains why, despite the relatively recent re-split of /ʌ/ from /ɨ/ in Gyeongsang Korean, North Gyeongsang female speakers exhibit contrastive patterns between the /a/-/ʌ/ and /wa/-/wʌ/ pairs that closely resemble those of Seoul female speakers, whereas male speakers in the same dialect group show signs of a potential merger.[4]

[4] This gender asymmetry may reflect broader articulatory strategies, with male speakers tending to relax and female speakers tending to maintain phonological contrasts. Such divergence suggests that male speakers may be initiating a phonetic shift characterized by reduced articulatory effort—leading to a merger pattern that is not purely biomechanical, but socially and phonetically conditioned. Although female speakers are generally known to lead sound change, male-led sound changes of this type are not unprecedented, especially when the shift involves vernacular variants, reduced articulatory clarity, or forms associated with covert prestige in non-standard or community-driven settings (Trudgill, 1972; Labov, 2001; see also Eckert, 2018; Kendall et al., 2023, for related discussion). Thus, in the context of the present study, we propose that the merger of /a/ and /ʌ/—which appears to be initiated through the merger of /wa/-/wʌ/— is led by male speakers from both Seoul and the seemingly more conservative group of North Gyeongsang males. Whether this merging tendency will eventually lead to a full phonological merger that reshapes the vowel inventory of the dialect, however, remains an open question.

Crucially, a key finding of the present study is that /w/-vowel sequences do not simply mirror their corresponding vowels in the absence of /w/ but exhibit distinct articulation patterns shaped by gender, dialect, and vowel quality in relation to ongoing sound changes. The more apparent phonetic merger of /we/-/wɛ/ compared to /e/-/ɛ/ during the early phase of articulatory movement, along with the selective neutralization observed in the tongue dorsum trajectories of /wa/-/wʌ/ but not as clearly in /a/-/ʌ/, further supports the view that /w/ affects articulatory dynamics in ways that go beyond the scope of typical coarticulatory processes. Together, these patterns reinforce the hypothesis of gestural restructuring.

4.3. Refining the gradient nature of gestural restructuring

As discussed thus far, the observed divergence between vowels with and without /w/ and the comparison of /we/-/wɛ/ and /wa/-/wʌ/, taken together, provides strong evidence for gestural restructuring of the vowel in /w/-vowel sequences than merely reflecting local coarticulation. As discussed in Section 4.1, however, the assumed restructuring process exhibits a gradient nature of divergence, which appears to be closely tied to the vowel's degree of lingual constriction, as well as supplementary factors such as constriction location and the directionality of gestural movement.

This raises an important question: Do these patterns simply reflect an enhanced coarticulatory effect that extends beyond what is typically expected from a low-level coarticulatory process? Or do they indicate a more fundamental phonological process of gestural restructuring, forming an integrated gestural unit distinct from that of the corresponding vowel without /w/?

While enhanced coarticulation and gestural restructuring may appear to be opposing perspectives, they are not mutually exclusive. Both assume that speakers actively regulate /w/-vowel sequences along a continuum of gestural blending. At one end, if /w/-vowel coarticulation were purely mechanical, its influence would peak early and fade as the vowel progresses, particularly in hyperarticulated contexts where coarticulatory resistance is heightened (e.g., Cho, 2004; Farnetani & Recasens, 2010; Fowler, 1981), resulting in minimal gestural blending. At the other, speakers actively shape /w/-vowel articulation beyond biomechanical coarticulation, resulting in substantial gestural blending and eventually stabilizing into a structured gestural distinction. Such stabilization can be interpreted as a language-specific enhancement of coarticulation, encoded in phonetic grammar (cf. Cho & Ladefoged, 1999; Keating, 1985; see Cho, 2025, for further discussion). However, as discussed above in Section 4.1, some cases show that the degree of divergence between the nuclei of /w/-vowel sequences and their corresponding plain vowels exceeds what can be accounted for by coarticulation—even in its most exaggerated form. This allows us to characterize such patterns as instances of phonological restructuring, resulting in an integrated gestural representation that goes beyond phonetic effects.

In either case, the key takeaway remains the same: speakers actively regulate vowel articulation with /w/ to maintain systematic organization and contrast with corresponding vowels without /w/. Whether as a language-specific coarticulatory specification encoded in phonetic grammar or as phonological restructuring encoded in the lexicon, both interpretations fall under speaker-controlled processes. The systematic control of phonologized coarticulation is well established (e.g., Beddor, 2023; Cho et al., 2017; Hoole & Honda, 2011; Kingston & Diehl, 1994; Lindblom, 1967, 1990; Solé, 2007; Zellou, 2022). A relevant example is vowel nasalization, which, in languages like American English, extends beyond a biomechanical effect to a phonologized process, integrating coarticulatory influence into the phonological system (Beddor, 2023; Cho et al., 2017; Cohn, 1993; Solé, 2007; Zellou, 2022). This example closely parallels the present findings on /w/-vowel sequences: what may have originated as a low-level coarticulatory effect now appears to be systematically integrated into the phonological system—possibly taking a further step toward becoming an integrated gestural unit that can no longer be adequately explained as mere coarticulation.

As such, the phonologization of coarticulatory effects in /w/-vowel sequences may vary across languages, necessitating cross-linguistic investigation to understand how different phonological systems incorporate such gestural restructuring. Korean, however, appears particularly conducive to such phonologization. As noted in the introduction, it prohibits consonant clusters in syllable onsets except for glides (/w/ and /j/), potentially facilitating their integration into the following vowel and promoting gestural reorganization while reducing phonological exceptions. In addition, /w/ is restricted from co-occurring with rounded back vowels /u/ and /o/, likely due to their shared articulatory features. This close interaction between /w/ and the vocalic system in Korean may have further driven gestural restructuring in /w/-vowel sequences. This also aligns with the view that /w/ is not an independent glide but an integral part of a diphthong in Korean (Kim, 2023; Kim & Kim, 1991).

4.3.1. Gestural restructuring and gestural blending strength (GBS)

An intriguing aspect of the gestural restructuring process discussed here is that its phonologization appears to have developed selectively, shaped by the vowel's inherent coarticulatory propensity associated with the constriction degree of the vowel, suggesting a selective phonologization of coarticulatory processes. Thus, the gradient nature highlights the role of phonetic constraints in shaping phonological patterns (cf. Hayes et al., 2004). This phonetics-phonology interplay aligns with Articulatory Phonology (Browman & Goldstein, 1992; Goldstein et al., 2006; Iskarous & Pouplier, 2022), which integrates articulatory gestures as both physical articulatory units and phonological contrast units. Crucially, gestures unfold over time, inherently overlapping due to the temporal coordination of speech movements.

This framework naturally accounts for the gradient nature of coarticulatory influences, as articulatory actions inherently interact with adjacent gestures that differ in their articulatory composition. More broadly, Articulatory Phonology provides a systematic approach to specifying gradient phonetic details (e.g., Browman & Goldstein, 2000; Cho, 2001; Gafos, 2002; Goldstein et al., 2006; Iskarous & Pouplier, 2022; Pastätter, 2017; Pastätter & Pouplier, 2017; Shaw et al., 2011; Smith, 2018). Within this model, the degree of gestural integration or blending can be modulated in response to phonetic proper-

ties, with constriction degree of the vowel shaping coarticulatory propensity and guiding the restructuring process, ultimately leading to a gradient rather than categorical shift in gestural representation.

To account for this gradient restructuring, we propose a model that explicitly integrates phonetic detail into phonological gestural representations. This approach builds on the well-established concept of **gestural blending strength (GBS)** (e.g., Browman & Goldstein, 1989, 1992; Iskarous et al., 2012; Iskarous & Pouplier, 2022; Oh et al., 2024; Pouplier, 2020; Saltzman & Munhall, 1989; Smith, 2018; Strycharczuk et al., 2024), which describes how overlapping gestures with shared articulatory components interact, determining which gesture exerts dominant control (higher GBS), which plays a more passive role (lower GBS), and how their interaction shapes the gestural end state. Crucially, GBS is not merely a phonetic parameter in a dynamical system; rather, it is subject to language-specific modulation (Iskarous et al., 2012; Iskarous & Pouplier, 2022) and can play a phonological role (Oh et al., 2024; Smith, 2018; Strycharczuk et al., 2024).

Specifically, Smith (2018) proposes the Gestural Harmony Model, in which vowel harmony occurs when a dominant vowel gesture extends its activation to adjacent vowels, influencing their articulatory properties such as tongue position. A key factor in this model is gestural blending strength (GBS), which determines how overlapping gestures with conflicting targets interact. Gestures with greater blending strength exert dominant control, shaping the resulting vowel quality. Applying this model to vowel height harmony across languages (e.g., Nzebi, Servigliano Italian), Smith (2018) shows that blending strength systematically governs interactions among high, mid, and low vowels. When a high vowel gesture (narrow constriction) overlaps with a low vowel gesture (wider constriction), the outcome depends on their relative blending strengths, which may be language-specific. If the high vowel has greater blending strength, which is likely due to its gestural strength (with narrow constriction), the result is a higher vowel, and vice versa. This framework captures the gradient and systematic nature of vowel harmony, moving beyond feature-based models by incorporating fine-grained articulatory interactions as a core component of phonological representation. (See Oh et al., 2024, for a similar discussion on how differences in GBS contribute to incomplete palatalization in Russian compared to fully specified underlying palatal gestures.)

Strycharczuk et al. (2024) demonstrate that diphthongization in Northern Anglo-English is better characterized as a gradient, dynamical phenomenon rather than a categorical one. Within their task-dynamic framework, vowel variation is modeled using two distinct articulatory targets with different constriction degrees. Diphthong-like trajectories emerge when these targets are realized with asymmetrical constriction strengths, resulting in either an onglide (weaker initial gesture) or an offglide (weaker final gesture). In this view, the term “glide” reflects the relatively reduced realization of one of the target gestures in the two-target model—potentially due to a lower gestural blending strength (GBS) associated with the weaker gesture, even when the blending ratio remains constant—rather than the presence of a distinct segmental category.

The present study’s findings essentially align with this perspective, suggesting a parallel mechanism underlying the gestural restructuring of /w/-vowel sequences. In both frameworks, the nucleus vowel gesture serves as the primary articulatory target, while the tongue dorsum gesture for /w/ functions as an external coarticulatory force. The extent of restructuring depends on constriction degree, which modulate the degree of gestural integration through relative gestural blending strength (GBS). This interaction can be interpreted within a dynamical system where GBS varies as a function of constriction degree of the vowel (which corresponds to gestural strength), while the GBS of /w/ remains constant. (Note that the GBS used in the present study follows the Gestural Harmony Model proposed by Smith (2018), in which GBS appears to be treated as an inherent property of each segment, with the assumption that each segment is assigned a fixed, segment-specific GBS value.)

Crucially, just as diphthongs emerge through the gradual differentiation of articulatory targets rather than a categorical reorganization, the gestural restructuring of /w/-vowel sequences in Korean can be understood as a graded modulation of blending strength. This comparison suggests that GBS offers a unifying account of how articulatory dynamics shape vowel variation across languages, whether in the form of diphthongization in English or the restructuring of /w/-vowel sequences in Korean. That is, gestural blending is driven by biomechanical constraints such as constriction degree, which may also be linked to the degree of sonority, and the gestures are eventually stabilized into an integrated gestural unit language specifically. As a result, the following outcomes observed in this study may emerge as outlined in Fig. 9.

We further illustrate the gestural timing (i.e., overlap) relationship between /w/ and the following vowel in Fig. 10. In /w/-vowel sequences, the gestures are assumed to be coupled in an anti-phase relationship, as shown in Fig. 10a, b, with the tongue dorsum gesture for /w/ initiating before that of the vowel, regardless of the vowel's identity. This abstract sequential coupling yields a diphthong-like temporal structure; however, the actual articulatory outcome may vary depending on the degree of overlap between the two gestures, which may be under speaker control in a given language.

Fig. 10a illustrates minimal gestural overlap, potentially resulting in limited coarticulation. This pattern is often attributed to default low-level biomechanical constraints, although such coarticulatory processes may still be subject to speaker control (cf. Cho, 2025). Fig. 10b shows a greater degree of overlap, reflecting an extended coarticulatory effect that likely involves more active, speaker-specific modulation, thus going beyond simple biomechanical coupling. Finally, Fig. 10c depicts near-complete gestural overlap, exceeding the range expected from even extended coarticulatory processes. This pattern is interpreted as a case of gestural restructuring, as proposed in the present study—where the original gestures for /w/ and the following vowel are reorganized into an integrated gestural unit, such that the individual identities of the component gestures are no longer preserved.

Importantly, because each gesture retains a degree of temporal autonomy in its execution, the /w/ gesture may remain active throughout the production of the vowel rather than

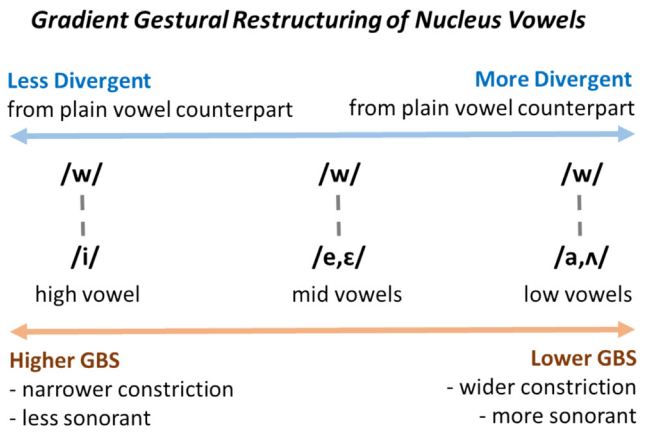


Fig. 9. A schematic illustration of gradient gestural restructuring along a continuum of varying gestural blending strength (GBS), modeled as a function of constriction degree and possibly linked to sonority. GBS for /w/ is assumed to remain constant, and the /w/ and vowel gestures are assumed to be anti-phase coupled. Dashed line indicates a blending of tongue dorsum gesture shared by /w/ and a vowel.

deactivating at vowel onset—potentially applying to all three cases illustrated in Fig. 10. This sustained co-activation may give rise to gestural blending (rather than gestural sliding) due to the shared articulator (i.e., the tongue dorsum), such that the resulting articulatory trajectory is shaped by the relative GBS of /w/ and the following vowel. This gestural blending exhibits a gradient pattern as a function of the gestural blending strength (GBS) associated with the vowel involved, as schematized in Fig. 9. For example, in the context of the front high vowel /i/, as in /wi/, the nucleus closely resembles that of its /w/-less counterpart /i/, reflecting /i/'s strong GBS, corresponding to the left end of Fig. 9. Thus, the entire vocalic portion remains effectively divided into an initial /w/-like component and a later /i/-like component, indicating partial, rather than full, gestural integration. By contrast, for back vowels, greater gestural integration tends to occur due to their weaker GBS, as represented on the right end of Fig. 9—though this pattern is further modulated by gender and dialectal factors, as observed in the present study. Such blending may initially arise from physiological and biomechanical constraints, but it can, over time, lead to language-specific gestural restructuring shaped by speaker control. As the two gestures become increasingly synchronized and overlap more extensively—as illustrated in Fig. 10c—they may ultimately be reorganized into a stable, integrated articulatory unit.

Here, another fundamental question arises: Does the varying degree of gestural restructuring emerge dynamically based on gestural interactions once the gestural blending strength values of the interacting gestures are determined? Or is it lexically specified with a newly developed integrated gestural representation as we have proposed? This question is beyond the scope of the present study, as our findings do not directly address it; thus, both possibilities remain plausible. We therefore limit our discussion to outlining these possibilities while presenting our preferred interpretation.

The first possibility is that the gradient effects in /w/-vowel sequences may arise from dynamical interactions, where constriction degree influences gestural strength. Rather than being lexically specified, these patterns likely emerge through speaker-controlled modulation of gestural parameters, reflecting language-specific articulatory adjustments rather than categorical phonological encoding. (This aligns with the notion that phonetic processes can be language-specifically governed or specified within phonetic grammar (e.g., Cho & Ladefoged, 1999; Keating, 1985), as briefly noted above.) Within the task-dynamic model of speech production, intergestural conflict is resolved through blending, where overlapping gestures create an intermediate target state (Browman & Goldstein, 1989, 1992; Goldstein et al., 2006; Iskarous & Pouplier, 2022). This state reflects a weighted average of the gestures' individual articulatory targets, with influence determined by their relative gestural strengths. Once dynamical parameters such as stiffness and target values are specified for each gesture along with its blending strength, the end state emerges naturally within the dynamical system (see Smith, 2018; Smith & O'Hara, 2021, Strycharczuk et al., 2024, for related discussion).

However, our findings suggest that coarticulatory effects, adequately explained by the relative gestural blending strength (GBS) among dynamically linked gestures, have evolved into structured phonological patterns, ultimately resulting in gestural reorganization, importantly in a language-specific manner. This implies that phonological encoding, rather than purely emergent dynamical processes, plays a crucial role within the phonological system. Given that such integrated gestural units directly contribute to syllable formation and lexical repre-

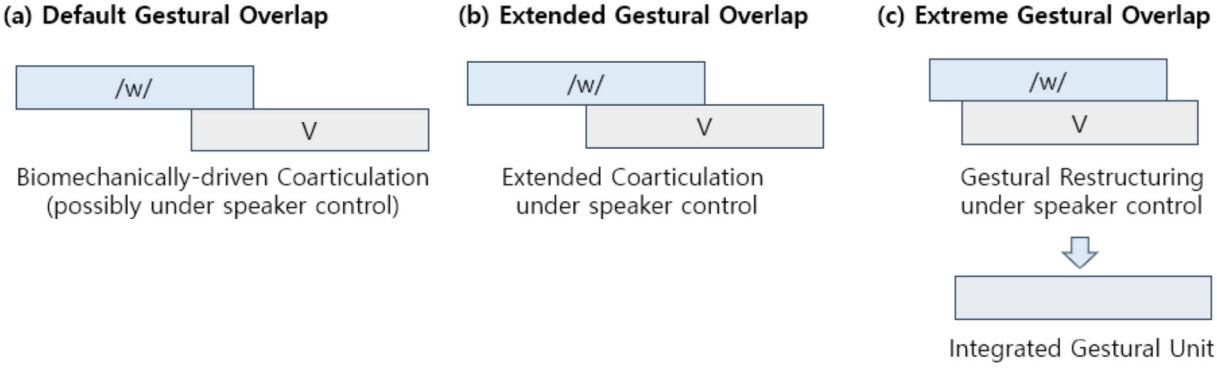


Fig. 10. Schematic representation of the degrees of gestural overlap, illustrating their assumed relationship to varying degrees of coarticulation and gestural restructuring. Note that for simplicity, all gestures are shown with equal activation time, though in theory their durations may differ depending on segment type, reflecting both intrinsic vowel length and language-specific temporal organization.

sentation, it is likely that they are lexically specified. Consequently, we propose that gestural properties resulting from restructuring is stored in the lexicon, aligning with the view that fine phonetic details regarding gestural realization and intergestural timing are lexically encoded (cf. Cho, 2001; Gafos, 2002; Yun, 2006). Nevertheless, the precise mechanism through which gestural information is represented within the lexicon remains an open question that warrants further investigation.

Lastly, beyond purely phonetic conditioning, our findings demonstrate that dialectal and gender-based factors also contribute to shaping the restructuring process—particularly through their interaction with the degree of GBS. The segment-specific variation in GBS provides an important phonetic basis for the observed putative sound change, especially with respect to the putative ongoing merger of back vowels. Of course, the present data, drawn only from speakers in their 20s, cannot conclusively determine whether the observed gestural restructuring constitutes an ongoing sound change that will eventually reshape the vowel inventory of the dialect. Moreover, as a reviewer noted, our data do not establish whether the observed gestural restructuring yields perceptual consequences that would facilitate reorganization of the vowel inventory. This caution is especially warranted because articulatory variation can remain acoustically/perceptually stable when it falls within a quantal region, where relatively large articulatory differences map onto relatively small acoustic differences (e.g., Stevens, 1989). Even so, the robust pattern whereby female speakers—particularly in Seoul—exhibit larger divergences between vowels with and without /w/, most clearly in the back-vowel space and in proportion to the degree of GBS, is at least consistent with an incipient, phonetic-level sound change. On this interpretation, women lead the change, in line with well-documented gender asymmetries in linguistic innovation (Labov, 2001; Kendall et al., 2023). Given that our sample is restricted to speakers in their twenties, however, converging perceptual evidence together with broader apparent-time and/or longitudinal data will be needed to determine whether this restructuring is propagating toward categorical reorganization of the dialect's vowel system. This variation, whether perceptually distinctive or not, poses a challenge for gestural restructuring models based on GBS, particularly if GBS varies as a function of vowel's gestural strength within a dynamical system. The key question is: how can such a model account for additional gradience arising from socially conditioned factors that shape surface outcomes? This remains a general challenge for sociophonetic and sound change research (Beddor, 2023; Kendall et al., 2023). But in this case, a dynamical framework incorporating speaker modulation of GBS could help address this variation by predicting how social-indexical factors interact with phonetic and phonological conditioning, ultimately shaping whether gestural restructuring stabilizes or weakens across speaker groups. Future research could refine this model by examining whether dialects or gender groups systematically adjust GBS thresholds or the extent to which the dominant vowel accommodates coarticulatory influences, eventually shaping divergent paths of phonological reorganization.

5. Conclusion

This study investigated the articulatory characteristics of Korean /w/-vowel sequences, demonstrating that they undergo gestural restructuring rather than functioning as simple glide-vowel combinations. The findings reveal a systematic pattern of divergence from their corresponding vowels without /w/, conditioned by constriction degree of the vowel: high front vowels with narrower constriction show minimal distinction while low back vowels with wider constriction undergo the most extensive restructuring. This gradient effect aligns with the role of gestural blending strength (GBS) in a dynamical system, where the degree of gestural integration is modulated by the constriction degree of the vowel which can be translatable into GBS. The results suggest that gestural restructuring, rather than functioning as a purely categorical phonological process, emerges through speaker-controlled modulation of coarticulatory interactions. This process is shaped by the intrinsic phonetic properties of the vowel, giving rise to its gradient realization at the surface.

Further evidence for restructuring comes from the interaction of /w/-vowel sequences with ongoing sound changes. While /we/-/wɛ/ mirrors the /e/-/ɛ/ merger, it exhibits an even stronger neutralization effect, particularly among North Gyeongsang male speakers, suggesting that /w/ enhances merger dynamics. In contrast, /wa/-/wʌ/ shows systematic articulatory divergence from /a/-/ʌ/, with dialect- and gender-based patterns revealing sociophonetic influences on gestural organization. This pattern is particularly interesting given the special status of /ʌ/ in North Gyeongsang Korean, where the emergence of /ʌ/ has reshaped vowel contrasts. The results also reveal the merger of /a/-/ʌ/ and /wa/-/wʌ/, which we did not envisage, possibly led by male speakers, further highlighting how social and historical factors shape phonological restructuring. Crucially, however, these social factors do not override the underlying gestural restructuring process but rather modulate its extent, reinforcing the view that the phonologization of coarticulatory effects unfolds in a gradient manner within a dynamical system—one that must account for both phonetically and sociophonetically driven gradience.

CRediT authorship contribution statement

Dae-yong Lee: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sahyang Kim:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Taehong Cho:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We would like to thank all the Seoul and North Gyeongsang speakers for participating in the study. We also thank all the members of HIPCS for their valuable comments and suggestions. This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2021S1A5C2A02086884) awarded to T. Cho. This work was partly supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No. 2020-0-01373, Artificial Intelligence Graduate School Program (Hanyang University)) and the research fund of Hanyang University (HY-2023).

Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.wocn.2025.101456.

References

Beddor, P. S. (2009). A coarticulatory path to sound change. *Language, 85*, 785–821.
Beddor, P. S. (2023). Advancements of phonetics in the 21st century: Theoretical and empirical issues in the phonetics of sound change. *Journal of Phonetics, 98* 101228.
Beddor, P. S., Harnsberger, J. D., & Lindemann, S. (2002). Language-specific patterns of vowel-to-vowel coarticulation: Acoustic structures and their perceptual correlates. *Journal of Phonetics, 30*(4), 591–627. https://doi.org/10.1006/jpho.2002.0177.
Blevins, J. (2004). *Evolutionary phonology: The emergence of sound patterns.* Cambridge University Press.
Bohn, O. S., & Best, C. T. (2012). Native-language phonetic and phonological influences on perception of American English approximants by Danish and German listeners. *Journal of Phonetics, 40*(1), 109–128.
Bongiovanni, S. (2021). On covariation between nasal consonant weakening and anticipatory vowel nasalization: Evidence from a Caribbean and a non-Caribbean dialect of Spanish. *Laboratory Phonology, 12*(1), 1–30.
Browman, C. P., & Goldstein, L. (1986). Towards an articulatory phonology. *Phonology, 3*, 219–252.
Browman, C. P., & Goldstein, L. (1989). Articulatory gestures as phonological units. *Phonology, 6*, 201–251.
Browman, C. P., & Goldstein, L. (1990). Gestural specification using dynamically-defined articulatory structures. *Journal of Phonetics, 18*(3), 299–320.
Browman, C. P., & Goldstein, L. (1992). Articulatory phonology: An overview. *Phonetica, 49*, 155–180. https://doi.org/10.1159/000261913.
Browman, C. P., & Goldstein, L. (1995). Dynamics and articulatory phonology. In R. F. Port & T. V. Gelder (Eds.), *Mind as Motion. Explorations in the Dynamics of Cognition* (pp. 175–194). Cambridge, MA: MIT Press.
Browman, C. P., & Goldstein, L. (2000). Competing constraints on intergestural coordination and self- organization of phonological structures. *Les Cahiers de l'ICP. Bulletin de la communication parlée, 5*, 25–34.
Brunelle, M., Tân, T. T., Kirby, J., & Giang, ã. L. (2020). Transphonologization of voicing in Chru: Studies in production and perception. *Laboratory Phonology, 11*(1), 1–33.
Byrd, D. (1994). Relations of sex and dialect to reduction. *Speech Communication, 15* (1–2), 39–54.
Chang, S. E. (2017). Enhancement effects of clear speech and word-initial position in Korean glides. *The Journal of the Acoustical Society of America, 141*(6), 4188–4199.
Chang, S. E., & Weiss-Cowie, S. (2021). Hyper-articulation effects in Korean glides by heritage language learners. *International Journal of Bilingualism, 25*(1), 3–20.
Cheon, S. Y. (2002). Glides as consonants in Korean. *Language Research, 38*(2), 619–646.
Chitoran, I. (2002). A perception-production study of Romanian diphthongs and glide-vowel sequences. *Journal of the International Phonetic Association, 32*(2), 203–222.
Cho, S. M. (2003). An acoustic study of Korean vowel system. *Korean Language and Culture, 24*, 427–441.
Cho, T. (2001). Effects of morpheme boundaries on intergestural timing: Evidence from Korean. *Phonetica, 58*(3), 129–162.
Cho, T. (2004). Prosodically conditioned strengthening and vowel-to-vowel coarticulation in English. *Journal of Phonetics, 32*(2), 141–176.
Cho, T. (2025). Advancements of Phonetics in the 21st century: Phonetic universals, language variation, and phonetic grammar. *Journal of Phonetics, 111* 104126.
Cho, T., Jun, S. A., Jun, S., & Ladefoged, P. (2001). The vowels of Cheju. *Korean Journal of Linguistics, 26*(4), 801–819.
Cho, T., Kim, D., & Kim, S. (2017). Prosodically-conditioned fine-tuning of coarticulatory vowel nasalization in English. *Journal of Phonetics, 64*, 71–89.
Cho, T., & Ladefoged, P. (1999). Variation and universals in VOT: Evidence from 18 languages. *Journal of Phonetics, 27*, 207–229.
Choi, J., Kim, S., & Cho, T. (2020). An apparent-time study of an ongoing sound change in Seoul Korean: A prosodic account. *PLoS One1, 15*(10) e0240682.
Chomsky, N., & Halle, M. (1968). *The sound pattern of English*. New York: Harper and Row.
Clements, G. N., & Hume, E. V. (1995). The internal organization of speech sounds. In J. Goldsmith (Ed.), *The handbook of phonological theory* (pp. 245–306). Blackwell.
Coetzee, A. W., Beddor, P. S., Styler, W., Tobin, S., Bekker, I., & Wissing, D. (2022). Producing and perceiving socially structured coarticulation: Coarticulatory nasalization in Afrikaans. *Laboratory Phonology, 13*(1), 1–43.
Cohn, A. C. (1993). The status of nasalized continuants. In Huffman & Krakow (Eds.), *Nasals, nasalization, and the velum* (pp. 329–367). San Diego: Academic Press.
Cunha, C., Hoole, P., Voit, D., Frahm, J., & Harrington, J. (2024). The physiological basis of the phonologization of vowel nasalization: A real-time MRI analysis of American and Southern British English. *Journal of Phonetics, 105* 101329.
Eckert, P. (2018). *Meaning and linguistic variation: The third wave in sociolinguistics.* Cambridge University Press.
Eychenne, J., & Jang, T. Y. (2015). On the merger of Korean mid front vowels: Phonetics and phonological evidence. *Journal of the Korean Society of Speech Sciences, 7*(2), 119–129.
Farnetani, E., & Recasens, D. (2010). Coarticulation and connected speech processes. In W. J. Hardcastle, J. Laver, & F. E. Gibbon (Eds.), *The handbook of phonetic sciences* (2nd edition. Oxford: Blackwell.
Fowler, C. A. (1981). Production and perception of coarticulation among stressed and unstressed vowels. *Journal of Speech, Language, and Hearing Research, 24*(1), 127–139.
Gafos, A. I. (2002). A grammar of gestural coordination. *Natural Language & Linguistic Theory, 20*(2), 269–337.
Garrett, A., & Johnson, K. (2013). Phonetic bias in sound change. In C. L. Y. Alan (Ed.), *Origins of sound change: Approaches to phonologization* (pp. 51–97). Oxford University Press.
Goldstein, L., Byrd, D., & Saltzman, E. (2006). The role of vocal tract gestural action units in understanding the evolution of phonology. In M. Arbib (Ed.), *Action to language via the mirror neuron system* (pp. 215–249). Cambridge University Press.
Hayes, B., Kirchner, R., & Steriade, D. (Eds.). (2004). *Phonetically based phonology.* Cambridge University Press.
Hazen, K. (2000). A methodological suggestion on /aj/ ungliding. *American Speech, 75* (2), 221–224.
Henton, C. G. (1983). Changes in the vowels of received pronunciation. *Journal of Phonetics, 11*, 353–371.
Hoole, P., & Honda, K. (2011). Automaticity vs. feature-enhancement in the control of segmental F0. In *Where do phonological features come from? Cognitive, physical and developmental bases of distinctive speech categories* (pp. 131–172). John Benjamins Publishing Company.
Iskarous, K., & Pouplier, M. (2022). Advancements of phonetics in the 21st century: A critical appraisal of time and space in Articulatory Phonology. *Journal of Phonetics, 95* 101195.
Iskarous, K., McDonough, J., & Whalen, D. H. (2012). A gestural account of the velar fricative in Navajo. *Laboratory Phonology, 3*(1), 195–210. https://doi.org/10.1515/lp-2012-0011.
Jang, H., & Shin, J. (2007). An acoustic study on the generational difference of the monophthongs in the Daegu dialect. *Malsori, 57*, 16–30.
Kang, H. S. (2006). An acoustic study of the perceptual significance of F2 transition of /w/ in English and Korean. *Speech Sciences, 13*(4), 7–21.
Kang, Y. (2014). Voice onset time merger and development of tonal contrast in Seoul Korean stops: A corpus study. *Journal of Phonetics, 45*, 76–90.
Keating, P. A. (1984). Phonetic and phonological representation of stop consonant voicing. *Language*, 286–319.
Keating, P. A. (1985). Universal phonetics and the organization of grammars. In V. A. Fromkin (Ed.), *Phonetic linguistics: Essays in Honor of Peter Ladefoged* (pp. 115–132). Orlando FL: Academic Press.
Kendall, T., Pharao, N., Stuart-Smith, J., & Vaughn, C. (2023). Advancements of phonetics in the 21st century: Theoretical issues in sociophonetics. *Journal of Phonetics, 98* 101226.
Kim, C. W. (1968). The vowel system of Korean. *Language, 44*(3), 516–527.
Kim, C. W. (2023). Korean glides. *Studies in Linguistics, 68*, 29–39.
Kim, C. W., & Kim, H. Y. (1991). The character of Korean glides. *Studies in the Linguistic Sciences, 21*(2), 113–125.
Kim, W., Byun, G., & Ko, M. (2007). The acoustic analysis of diphthongs of Jeju dialect speakers in their 20s, 50s, and 70s and their diphthong inventories. *Speech Sciences, 14*(4), 99–114.
Kingston, J., & Diehl, R. L. (1994). Phonetic knowledge. *Language, 70*(3), 419–454.
Ko, I. (2009). The merger of ey /e/ and ay /ɛ/ of Seoul Korean. *Language Information, 10* (10), 73–89.
Labov, W. (1990). The intersection of sex and social class in the course of linguistic change. *Language Variation and Change, 2*(2), 205–254.
Labov, W. (2001). *Principles of linguistic change: Social factors* (Vol. 2) Oxford: Blackwell.
Ladefoged, P. (2005). *A course in phonetics* (5th ed.). Boston, MA: Thomson Wadsworth.
Ladefoged, P., & Maddieson, I. (1996). *The sounds of the world's languages* (Vol. 1012) Oxford: Blackwell.
Lee, B.-G. (1982). A well-formedness condition on syllable structure. In I.-S. Yang (Ed.), *Linguistics in the morning calm* (pp. 489–506). Seoul, Korea: Hanshin Publishers.
Lee, H., & Jongman, A. (2016). A diachronic investigation of the vowels and fricatives in Korean: An acoustic comparison of the Seoul and South Kyungsang dialects. *Journal of the International Phonetic Association, 46*(2), 157–184.

Lee, H., Politzer-Ahles, S., & Jongman, A. (2013). Speakers of tonal and non-tonal Korean dialects use different cue weightings in the perception of the three-way laryngeal stop contrast. *Journal of Phonetics, 41*(2), 117–132.
Lee, H., Shin, W., & Shin, J. (2017). A sociophonetic study on high/mid back vowels in Korean. *Phonetics and Speech Sciences, 9*(2), 39–51.
Lee, Y. C., & Cho, S. (2021). The merger of /e/ and /ɛ/ in Seoul Korean tracing speakers born from the 1930s to the 1960s. *Studies in Linguistics, 61*, 1–16.
Lindblom, B. (1967). Vowel duration and a model of lip mandible coordination. *Speech Transmission Laboratory Quarterly Progress Status Report, 4*, 1–29.
Lindblom, B. (1990). Explaining phonetic variation: A sketch of the H & H theory. *Speech Production and Speech Modeling, 55*, 403–439.
Maddieson, I. (1997). Phonetic universals. In J. Laver & W. J. Hardcastle (Eds.), *The handbook of phonetic sciences* (pp. 619–639). Oxford: Blackwells.
Maddieson, I., & Emmorey, K. (1985). Relationship between semivowels and vowels: Cross-linguistic investigations of acoustic difference and coarticulation. *Phonetica, 42*(4), 163–174.
Marin, S. N. (2017). *Vowel to vowel coordination, diphthongs and articulatory phonology* PhD Thesis. Yale University.
Mielke, J., Carignan, C., & Thomas, E. R. (2017). The articulatory dynamics of pre-velar and pre-nasal /æ/-raising in English: An ultrasound study. *The Journal of the Acoustical Society of America, 142*(1), 332–349.
Nycz, J., & Hall-Lew, L. (2013). Best practices in measuring vowel merger. *Proceedings of Meetings on Acoustics*, 20.
Oh, E. (2010). Speaker Gender and the degree of coarticulation. *Korean Journal of Linguistics, 35*(3), 743–766.
Oh, E. (2011). Effects of speaker gender on voice onset time in Korean stops. *Journal of Phonetics, 39*(1), 59–67.
Oh, M. (2010). /w/-variants in Korean. *Phonetics and Speech Sciences, 2*(3), 65–73.
Oh, S., Shaw, J., Durvasula, K., Kochetov, A., & Shaw, J. A. (2024). Russian assimilatory palatalization is incomplete neutralization. *Laboratory Phonology, 15*(1).
Ohala, J. J. (1993). The phonetics of sound change. In C. Jones (Ed.), *Historical linguistics: Problems and perspectives* (pp. 237–278). Routledge: London.
Padgett, J. (2008). Glides, vowels, and features. *Lingua, 118*(12), 1937–1955.
Pastätter, M. (2017). *The effect of coarticulatory resistance and aerodynamic requirements of consonants on syllable organization* PhD Thesis. LMU Munich Germany.
Pastätter, M., & Pouplier, M. (2017). Articulatory mechanisms underlying onset-vowel organization. *Journal of Phonetics, 65*, 1–14.
Pouplier, M. (2020). Phonologization in the dynamic approach to speech. *Laboratory Phonology: Journal of the Association for Laboratory Phonology, 11*(1), 1–25.
R Core Team (2018). *R: A language and environment for statistical computing [Computer software]*. R Foundation for Statistical Computing https://www.R-project.org/.
Recasens, D. (1999). Lingual coarticulation. In W. J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theory, data and techniques* (pp. 80–104). Cambridge University Press.
Recasens, D. (2002). An EMA study of VCV coarticulatory direction. *The Journal of the Acoustical Society of America, 111*(6), 2828–2841.
Recasens, D. (2018). Coarticulation. In *Oxford research encyclopedia of linguistics*. https://doi.org/10.1093/acrefore/9780199384655.013.416.
Saltzman, E., & Munhall, K. G. (1989). A dynamical approach to gestural patterning in speech production. *Ecological Psychology, 1*(4), 333–382.
Shaw, J. A., & Chen, W. R. (2019). Spatially conditioned speech timing: Evidence and implications. *Frontiers in Psychology, 10*, 2726.
Shaw, J. A., Gafos, A. I., Hoole, P., & Zeroual, C. (2011). Dynamic invariance in the phonetic expression of syllable structure: A case study of Moroccan Arabic. *Laboratory Phonology, 2*(2), 307–336.
Shon, S. (2022). *A study on the formant trajectory of Korean diphthongs* PhD Thesis. Hanyang University.
Smith, C. (2018). *Harmony in gestural phonology* PhD Thesis. The University of Southern California.
Smith, C., & O'Hara, C. (2021). Learnability of derivationally opaque processes in the Gestural Harmony Model. *Proceedings of SCiL, Vol. 4*.
Solé, M.-J. (2007). Controlled and mechanical properties in speech: A review of the literature. In M.-J. Solé, P. S. Beddor, & M. Ohala (Eds.), *Experimental approaches to phonology* (pp. 302–321). Oxford University Press.
Son, M., Kim, S., & Cho, T. (2012). Supralaryngeal articulatory signatures of three-way contrastive labial stops in Korean. *Journal of Phonetics, 40*(1), 92–108.
Stevens, K. N. (1989). On the quantal nature of speech. *Journal of Phonetics, 17*(1), 3–45.
Stevens, K. N., & Keyser, S. J. (2010). Quantal theory, enhancement and overlap. *Journal of Phonetics, 38*(1), 10–19.
Strycharczuk, P., Kirkham, S., Gorman, E., & Nagamine, T. (2024). Towards a dynamical model of English vowels. Evidence from diphthongisation. *Journal of Phonetics, 107* 101349.
The Hanyang Institute for Phonetics and Cognitive Sciences of Language (2022). *Dynamics of speech production through articulatory DB construction.*
Tiede, M. (2005). *MVIEW: Software for visualization and analysis of concurrently recorded movement data*. New Haven, CT: Haskins Laboratories.
Tilsen, S. (2016). Selection and coordination: The articulatory basis for the emergence of phonological structure. *Journal of Phonetics, 55*, 53–77.
Trudgill, P. (1972). Sex, covert prestige and linguistic change in the urban British English of Norwich. *Language in Society, 1*(2), 179–195.
Whiteside, S. P. (1996). Temporal-based acoustic-phonetic patterns in read speech: Some evidence for speaker sex differences. *Journal of the International Phonetic Association, 26*(1), 23–40.
Whiteside, S. P., & Irving, C. J. (1998). Speakers' sex differences in voice onset time: A study of isolated word production. *Perceptual and Motor Skills, 86*(2), 651–654.
Wieling, M. (2018). Analyzing dynamic phonetic data using generalized additive mixed modeling: A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *Journal of Phonetics, 70*, 86–116.
Wood, S. (2017). *Generalized additive models: An introduction with R* (2nd ed.). Boca Raton: CRC Press.
Wood, S. (2019). *mgcv: Mixed GAM Computation Vehicle with Automatic Smoothness Estimation version 1.8-38 from CRAN* (1.8-38) [R]. https://rdrr.io/cran/mgcv/.
Yang, B. G. (1993). An acoustical study of Korean diphthongs. *Malsori, 25*(1), 3–26.
Yun, G. (2006). The effects of lexical frequency and stress on coarticulation. *Proceedings of the Annual Meeting of the Berkeley Linguistics Society, 32*(1), 441–452.
Yun, Y. (2005). Phonetic analysis of the Korean glides [w] and [ɥ]*. *Korean Journal of Linguistics, 30*(2), 395–421.
Zellou, G. (2022). *Coarticulation in phonology.* Cambridge University Press.
Zhao, D., Park, J., & Seong, C. (2023). Acoustic characteristics of glides and nuclear vowels of Korean diphthongs in coarticulation condition. *Hanguel, 84*(1), 5–43.