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Individual differences in language acquisition: The impact of study abroad on native English speakers learning Spanish

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ABSTRACT

This study investigated the acquisition of lenition in Spanish voiced stops (/b, d, g/) by native English speakers during a study-abroad program, focusing on individual differences and influencing factors. Lenition, characterized by the weakening of stops into fricative-like ([β], [ð], [ɣ]) or approximant-like ([β̞], [ð̞], [ɣ̞]) forms, poses challenges for L2 learners due to its gradient nature and the absence of analogous approximant forms in English. Results indicated that learners aligned with native speakers in recognizing voicing as the primary cue for lenition, yet their productions diverged, favoring fricative-like over approximant-like realizations. This preference reflects the combined influence of articulatory ease, acoustic salience, and cognitive demands.

Individual variability in learners' trajectories highlights the role of exposure to native input and sociolinguistic engagement. Learners benefitting from richer, informal interactions with native speakers showed greater alignment with native patterns, while others demonstrated more limited progress. However, native input alone was insufficient for learners to internalize subtler distinctions such as place of articulation and stress. These findings emphasize the need for combining immersive experiences with targeted instructional strategies to address articulatory and cognitive challenges. This study contributes to the understanding of L2 phonological acquisition and offers insights for designing more effective language learning programs to support lenition acquisition in Spanish.

1. Introduction

Studying abroad is widely recognized as an effective way to enhance language proficiency, offering learners a unique opportunity to immerse themselves fully in the target language environment. These experiences provide access to authentic communication, deeper cultural insights, and regular practice with native speakers. However, despite the general success of such programs, not all learners demonstrate the same level of improvement. While some individuals quickly develop fluency, accuracy, and ease of communication, others may struggle to make significant progress. This variation underscores the importance of individual differences in language acquisition during study abroad. Factors such as cognitive abilities, motivation, prior language experience, and the extent of social interaction with native speakers can all influence the outcomes of immersion experiences.

This study investigates how native speakers of English acquire lenition—a phonological process in Spanish where voiced stops (/b, d, g/) weaken into fricative ([β], [ð], [ɣ]) or approximant ([β̞], [ð̞], [ɣ̞]) forms—within the context of study-abroad experiences. For example, the word *abogado* 'lawyer' is often pronounced [a.βo.ɣa.ðo] or [a.β̞o.ɣ̞a.ð̞o], reflecting lenited realizations of all three underlying stops. Absent from English phonology, lenition presents a significant challenge for L2 learners. By analyzing individual differences, this research examines learners' developmental trajectories and compares their patterns to those of native speakers, offering insights into the impact of immersive language-learning environments on phonological acquisition.

2. Literature review

2.1. L2 acquisition of Spanish voiced stops

Lenition, or consonant weakening, is a central phonological process

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in Spanish, particularly affecting voiced stops /b/, /d/, and /g/. These stops undergo weakening in most positions, except in phrase-initial or post-nasal contexts, and for /d/, after laterals (Hualde, 2005; 2011). This weakening process is gradient in nature, meaning that voiced stops can transform into fricatives [β], [ð], [ɣ], approximants [β̞], [ð̞], [ɣ̞], or be deleted entirely (Hualde 2011; Eddington 2011). The degree of lenition depends on factors such as phonetic context, speech rate, and formality (Ortega Llebaria 2004; Eddington 2011; Colantoni and Marinescu 2010; Carrasco, Hualde and Simonet 2012).

Lenition is most frequently observed in word-medial intervocalic positions, with coronals like /d/ demonstrating a greater tendency toward weakening compared to labials or dorsals (Bybee, 2001; Colantoni and Marinescu, 2010). Additionally, lenition is more prominent in unstressed syllables (Cole, Hualde and Iskarous, 1999; Lavoie, 2001; Ortega-Llebaria, 2004; Nagle, 2014). However, the influence of factors such as place of articulation remains complex. While some studies support the heightened susceptibility of coronals to lenition (Bybee, 2001; Colantoni and Marinescu, 2010), others (Carrasco et al., 2012; Kaplan, 2010; Rao, 2015; Recasens, 2016; McLeod, 2020; Broś et al., 2021) suggest this pattern is not consistently observed. For instance, Recasens (2016) found that velar stops (/g/) undergo lenition more frequently than dental (/d/) and labial (/b/) stops. This hierarchy—velars being more prone to lenition than dentals, and dentals more than labials—may stem from differences in articulatory effort and aerodynamic properties. Velars, with their more open constriction and lower airflow resistance, are inherently more susceptible to weakening, whereas labials, involving tighter closures and greater resistance, are less prone to lenition. Similarly, McLeod (2020) reported that while labial stops are realized as the least weakened of the spirant approximants, velar stops are the most frequently weakened. Social factors, such as speaker age and gender, play a significant role in shaping lenition variability. Limanni (2021) investigates whether gender differences influence the degree of lenition of Mexican Spanish voiced stops (/b, d, g/) in conversational speech. The findings suggest that male speakers consistently exhibit greater lenition than female speakers, though the difference is not statistically significant. A study by Rogers and Mirisis (2018) on voiceless stop lenition in Chilean Spanish in Concepción highlights similar patterns. Analyzing 4419 intervocalic tokens of /p, t, k/, the study found lenition to be pervasive, with 98 % of tokens partially voiced and 54 % fully voiced. Male speakers exhibited significantly greater lenition than females, and younger speakers showed more lenition compared to older groups, aligning with sociolinguistic trends favoring relaxed speech among younger males. These findings underscore that lenition is not solely a phonological process but also reflects social identity and adapting to conversational contexts.

For native English speakers learning Spanish, mastering lenition is notably challenging (Díaz-Campos, 2004; Shively, 2008). Studies consistently show that learners struggle to achieve target-like pronunciation of approximant allophones [β̞], [ð̞], and [ɣ̞], whether learning takes place in the classroom or during study abroad (Díaz-Campos, 2006; Elliott, 1997; Zampini, 1994, 1998). This difficulty is partly due to the lack of direct equivalents in English, particularly for /b/ and /g/. Although English /d/ undergoes flapping in post-tonic intervocalic positions—a process somewhat analogous to lenition—this often interferes with learners' acquisition of Spanish /d/ lenition. The tendency to substitute the tap [ɾ] for [ð] or [ð̞], due to English flapping, contributes to a foreign accent, as Spanish treats /ɾ/ as a separate phoneme (Alvord and Christiansen, 2012). Prior research indicates that learners are more likely to lenite the bilabial /b/ than the dental /d/ or velar /g/ (Face and Menke, 2009). González-Bueno (1995) found that learners more frequently lenite /g/ and /b/ than /d/, with /d/ posing the greatest difficulty. Similarly, Zampini (1994) observed that learners struggled the most with leniting /d/, reinforcing the notion that it is the most challenging phoneme in this process. Such variability in learner success may also reflect the representational status of the target: phonological contrasts are often acquired more robustly than subtle phonetic details, particularly in study abroad settings where input may be variable (Nagle and Zárate-Sández, 2024).

However, findings across studies are not always consistent regarding which of the three segments poses the greatest challenge. From an aerodynamic perspective, one might expect more posterior stops like /g/ to resist lenition, as they typically generate higher intraoral pressure (Ohala, 1974; Javkin, 1977). Yet Kingston (2008) observes that /g/ lenited more often—perhaps due to a greater likelihood of incomplete velar closure. Additionally, phonetic context likely contributes to these discrepancies: the degree of lenition is highly sensitive to surrounding segments, and different studies may elicit the target sounds in environments that favor greater or lesser constriction. Variation in study design and segmental context may thus partly account for the divergent findings reported in the literature.

Another issue arises from the confusion between orthography and phonology, particularly with the substitution of the bilabial stop /b/ for the labiodental fricative [v], in words spelled with orthographic {v}. This mispronunciation stems from English phonology and hypercorrection, where learners mistakenly equate spelling with pronunciation. Furthermore, some Spanish speakers, particularly in formal contexts, may produce the labiodental fricative [v] as an allophonic variant of /b/ , though this is not phonemically contrastive; such realizations have been observed among instructors originally from Spain, Mexico, Costa Rica, Chile, and El Salvador (Stevens, 2000). Learners who adopt this feature from regions like Chile may find it difficult to master the standard Spanish /b/, adding another layer of complexity (Zampini, 1994; Face and Menke, 2009; Alvord and Christiansen, 2012).

Syllable stress also plays a role. Both Zampini (1994) and Face & Menke (2009) noted that learners tend to produce stops in stressed syllables but lenite more in unstressed syllables, likely due to the reduced articulatory effort required in the latter. Word position adds another layer of complexity. Learners generally produce lenited forms more often in word-internal positions than at word-initial boundaries, suggesting that lenition across word boundaries is particularly difficult to acquire (Face and Menke, 2009). This may result from learners treating words as isolated units rather than part of a continuous speech stream.

Speaking style further affects lenition production. Native speakers typically lenite more in informal, rapid speech than in formal settings. Zampini (1994) found that learners produced lenited forms more frequently in conversational speech than in formal tasks, likely due to the focus on communication rather than pronunciation. However, Alvord and Christiansen (2012) found no significant difference between story reading and word reading tasks, suggesting that other factors including proficiency differences may interact with formality and thus the variation across studies.

As learners become more proficient, their ability to produce lenited forms improves. Face and Menke (2009) examined L2 acquisition of Spanish spirants (/b, d, g/) at three proficiency levels—fourth-semester Spanish learners, graduating Spanish majors, and Ph.D. students. They found that lenition develops progressively, with more advanced learners producing lenited forms more frequently and consistently. Across all levels, learners showed greater accuracy in word-internal positions, and advanced learners were less influenced by syllable stress, demonstrating a more native-like lenition pattern. Shea and Curtin (2006, 2011) similarly observed that learners' production of stops and approximants in Spanish became more native-like as proficiency increased. Salinas (2015) further supported these findings, noting that advanced learners exhibited greater lenition than low-intermediate learners, particularly in word-internal and unstressed positions. Additionally, advanced learners showed a reduced influence of orthography ({b} vs. {v}), producing patterns more aligned with native speakers.

Cabrelli Amaro (2017) investigated how late L1 English / L2 Spanish learners acquire spirantization of voiced stops, testing the hypothesis that acquisition aligns with the prosodic hierarchy. Learners initially produce postvocalic approximants at syllable onsets (word-medial position), then at prosodic word onsets (word-initial position). Advanced learners exhibit target-like continuants across prosodic levels, with a lenition degree approaching that of native speakers as proficiency grows. However, learner outcomes are not uniform. Nagle (2017) tracked the pronunciation of Spanish [β] among English-speaking learners over a year, revealing varying trajectories, with some learners improving and others regressing, highlighting the dynamic and individual nature of L2 phonological development.

Mirisis (2021) found that L2 learners' proficiency significantly influenced their production of Spanish intervocalic voiced approximants ([β̞], [ð̞], [ɣ̞]), with higher proficiency associated with increased spirantization and target-like production. First-year learners produced these approximants 23 % of the time, with limited spirantization, as evidenced by a mean intensity difference of 13.72 dB, reflecting a greater degree of oral constriction than native speakers (average mean intensity difference of 11.26 dB). Third-year learners showed slight improvement, producing approximants 27 % of the time, but with less spirantization (mean intensity difference of 14.87 dB). Fourth-year learners demonstrated the most progress, producing approximants 41 % of the time with a mean intensity difference of 12.80 dB, closer to the native speaker average. However, learners across all proficiency levels produced approximants less frequently and with less spirantization compared to native speakers, highlighting the challenges of acquiring these sounds in L2 Spanish.

Together, these studies underscore the complexity of lenition for L2 learners, highlighting the interplay of phonetic, orthographic, sociolinguistic, and proficiency-related factors in shaping the acquisition of Spanish phonology.

2.2. Study abroad and Spanish voiced stop acquisition

The impact of learning contexts on second language acquisition has been well-documented. Collentine and Freed (2004) pointed out notable differences between at-home (AH) classroom learning, intensive domestic immersion (IM), and study abroad (SA). In AH settings, students benefit from structured tasks that help with grammar and vocabulary but often lack opportunities to develop communicative fluency. IM, which combines classroom learning with real-life interaction, brings learners closer to the target language environment, but they remain surrounded by their native language culture. SA, by contrast, immerses learners in authentic language environments, offering more significant improvements in oral fluency, sociolinguistic competence, and real-world communication compared to both AH and IM contexts.

However, research on the effects of SA on phonological acquisition—particularly lenition—yields mixed results. For example, Díaz-Campos (2006) compared L2 learners of Spanish in study abroad and regular classroom settings, focusing on their production of intervocalic voiced fricatives [β, ð, ɣ], the lenited variants of Spanish voiced stops. The findings showed that learners across both settings struggled to produce these fricatives accurately, with only 22 % accuracy overall. Furthermore, students performed better in conversational tasks (28 %) than in read-aloud tasks (13 %), suggesting that informal speech styles may encourage more target-like pronunciations. Surprisingly, regular-classroom students outperformed their study-abroad counterparts, producing target-like fricatives 37 % of the time compared to just 11 % for the SA group. This unexpected result points to the potential benefits of formal language instruction for phonological accuracy, particularly for challenging segments like voiced fricatives. It also highlights that studying abroad may not always produce superior phonological outcomes.

Similarly, Lord (2010) investigated the effects of immersion and explicit instruction on the acquisition of Spanish /b/, /d/, and /g/, focusing on both fricative and occlusive allophones. In this study, participants in an eight-week immersion program showed improvements in producing these sounds, with those receiving prior instruction achieving higher accuracy. Nevertheless, neither group reached native-like proficiency, particularly with fricatives, underscoring the importance of both instruction and immersion for L2 phonological development, while also revealing that they may not be sufficient for achieving high levels of accuracy.

Another study by Alvord and Christiansen (2012) examined the acquisition of spirantization of /b, d, g/ by adult learners who spent two years abroad in Spanish-speaking countries. The study sought to identify whether learners had successfully acquired spirantization and to explore the influence of factors such as prior Spanish instruction, cultural integration, language use, empathy, musical training, and motivational intensity on their production of target-like pronunciations shortly after returning. The results showed that most learners produced target-like approximants over 80 % of the time, with cultural integration, Spanish use, empathy, and motivational intensity serving as significant predictors of accurate spirantization. Interestingly, learners with musical training also performed better. The study concluded that long-term immersion, paired with individual learner characteristics, plays a critical role in acquiring spirantization. Notably, this group of learners had a more extended and unique experience abroad, devoting two years to church and community service rather than engaging in traditional study abroad programs.

Bongiovanni et al. (2015) investigated the effects of short-term study abroad on learners' production of lenited voiced stops. Using the relative intensity difference between the consonant and the following vowel to measure lenition, the study found that learners in an at-home context produced more approximant-like realizations of /b/ than their SA counterparts, both before and after the study period. However, the SA group showed significant improvement in producing /d/ over time, aligning with the AH group by the program's end. No significant changes were observed for /g/ in either group. These findings suggest that while studying abroad can promote progress in the acquisition of certain voiced stops, such as /d/, the overall acquisition of lenition remains complex and may require longer-term exposure or specific instruction, particularly for sounds like /b/ and /g/.

Although these studies demonstrate some gains in phonological acquisition during or after study abroad, they also highlight methodological issues. Solon and Long (2018) noted that many studies lacked AH comparison groups and identified other limitations, such as small sample sizes and inconsistent assessment measures. Their findings showed that while some learners make phonological gains during SA, these improvements are not universal, and the acquisition of regional or dialect-specific features can be inconsistent. Nagle and Zárate-Sández (2024) similarly argue that individual differences—such as the quality of input, learners' depth of engagement, and the phonological complexity of the target structure—strongly mediate pronunciation gains during SA. They emphasize that the acquisition of gradient or low-salience features like spirantization is particularly difficult without sustained exposure and may not arise from incidental learning alone.

Similarly, Moore et al. (2021)'s review of SA programs echoed these challenges, pointing to variability in study design and outcome measures. Despite these issues, they concluded that SA programs provide valuable opportunities for learners to improve speaking confidence and fluency through increased interaction in immersive environments. However, the phonological benefits of SA are not always clear-cut and may depend on additional factors, such as individual learner traits and the specific phonological features being acquired. This theoretical perspective aligns with the current study's focus on individual differences in the development of lenition, highlighting the need to model subphonemic change at a fine-grained level.

Another concern is the lack of methodological consistency in quantifying the degree of lenition across studies. Many studies, such as Alvord and Christiansen (2012), rely on spectrographic analysis to categorize lenited forms into discrete classifications (e.g., stop vs. non-stop). In contrast, others, like Bongiovanni et al. (2015), use more fine-grained acoustic measurements, such as calculating the intensity difference between the target segment and the following vowel, offering a more continuous and detailed account of lenition. This inconsistency complicates cross-study comparisons and raises questions about the validity of each method in capturing the nuanced, gradient nature of lenition, ultimately making it difficult to generalize findings across different learning contexts.

3. This study

In a departure from previous methods, this study introduces a novel approach to quantifying the lenition of Spanish voiced stop consonants (/b, d, g/) among native English speakers during a study-abroad program. Our primary goals are to (1) track individual learner trajectories in the acquisition of lenition, (2) assess how patterns evolve longitudinally across segments, and (3) evaluate whether phonological feature posteriors offer a principled and interpretable means of quantifying L2 lenition. We employed the deep learning model Phonet (Vásquez-Correa et al., 2019), which calculates posterior probabilities of key phonological features related to lenition, such as continuant and sonorant, from acoustic data. To provide a benchmark for comparison, a control group of native Spanish speakers is included, allowing us to assess how closely L2 learners' lenition patterns approach those of native speakers.

Given the variability in individual outcomes noted in previous studies, this study places a strong emphasis on tracking individual differences in the acquisition process. Participants were recorded before their departure, multiple times throughout their stay abroad, and again one year after returning. This longitudinal design enables us to monitor the progression of lenition for each learner, offering insights into individual variation in both the pace and extent of phonological acquisition. By capturing development at multiple points in time, we aim to present a more detailed picture of how study-abroad experiences impact L2 phonological growth and the role individual factors play in shaping the acquisition of lenition.

3.1. Phonological features and lenition

Lenition in Spanish voiced stops (/b, d, g/) involves a shift from fully occluded stops to fricative-like or approximant variants, which can be characterized by the features [continuant] and [sonorant] (Clements and Hume, 1995; Mielke, 2008; Hayes, 2009). Stops are [–continuant, –sonorant], while lenited forms are [+continuant, +sonorant], reflecting a reduction in oral constriction and increased vocal tract openness. These features, along with others such as [consonantal] and [syllabic], provide a principled way to group sounds into natural classes that participate in phonological processes (Hayes, 2009). For instance, English voiceless stops (/p, t, k/) share [–syllabic, –voice, –continuant, –sonorant], leading to aspiration patterns, whereas Spanish /b, d, g/ undergo spirantization to [+continuant, +sonorant] variants in intervocalic contexts.

Our study leverages posterior probabilities for [continuant] and [sonorant] to quantify lenition. This approach provides a gradient, data-driven measure of spirantization, allowing for finer resolution of variability and change than categorical transcription or binary coding would permit.

3.2. Phonetic gradience and posterior probability

Lenition processes like spirantization in Spanish are inherently gradient, often varying in degree across speakers, contexts, and tokens. Traditional phonetic transcription and binary coding schemes frequently obscure this variability, leading researchers to adopt more fine-grained computational approaches to model it. One such approach involves analyzing the posterior probabilities of phonological features, which allows continuous estimation of how strongly a segment exhibits properties like [continuant] or [sonorant].

Early work using forced alignment systems (e.g., Yuan and Liberman, 2009) demonstrated that log-probability scores derived from alignments could reveal subtle phonetic variation. For example, their study on English /l/ found gradient realizations (e.g., light vs. dark /l/) that aligned with both categorical and continuous variation. This approach was extended in later work (Yuan and Liberman, 2011) to model similar gradient shifts in other segmental contrasts.

Parallel developments in machine learning have enabled even more flexible modeling of phonetic gradience. Support Vector Machines (SVMs) have been used to classify sociophonetic variation such as rhoticity (McLarty et al., 2019), while random forest models have captured regional variants of English based on acoustic input (Villarreal et al., 2020). Cohen Priva & Gleason (2020) compared different modeling strategies to represent lenition patterns across large American English corpora, finding that surface forms alone—regardless of phonological context—can reliably reflect lenition.

In our study, we take a different approach by modeling not surface segment labels, but phonological feature activations via posterior probabilities from Phonet. Unlike categorical systems or alignment-based log scores, Phonet estimates how strongly each 10 ms frame exhibits a particular feature (e.g., [continuant], [sonorant]). These probabilities enable us to trace subphonemic gradience in the realization of Spanish /b, d, g/—capturing fricative-like patterns ([+continuant, –sonorant]) or approximant-like ones ([+continuant, +sonorant]). This method offers a principled and scalable way to quantify spirantization in learner speech.

3.3. Phonet

Phonet's use of posterior probabilities allows for a more nuanced, gradient analysis of phonological features, complementing traditional acoustic measures (Tang et al., 2023). It has proven effective in quantifying lenition, particularly with Spanish voiced stops, and has also been used to assess speech impairments in Parkinson's patients (Vásquez-Correa et al., 2019; Wayland et al., 2023, 2024b).

Phonet operates by analyzing log energy distributed across triangular Mel filters, calculated over 25-ms windowed frames of the input signal. These sequences are processed by two bidirectional GRU (Gated Recurrent Unit) layers that model past and future states of the signal simultaneously. The second GRU layer's output is passed through a time-distributed dense layer, resulting in a sequence output of the same length as the input. The final classification is handled by a time-distributed SoftMax output layer, which assigns phonological classes to each sequence.

In this study, we used a version of Phonet configured to output posterior probabilities for 23 phonological features and 26 phonemes, following the configuration used in Tang et al. (2023). The model was trained using a single network and optimized with the Adam optimizer (Kingma and Ba, 2014). Following Vásquez-Correa et al. (2019), a weighted categorical cross-entropy loss function was applied to address class imbalance. Further details on the model structure and training can be found in Tang et al. (2023).

3.4. Data

Data comes from the LANGSNAP project (Mitchell, Romero, and Richard, 2014; MacWhinney, 2000). The dataset consisted of recordings of 27 L1 British English speakers spending an academic year abroad in Spain ($n = 18$) or Mexico ($n = 9$) as part of a university Spanish program. The students were recorded before going abroad, every three months while abroad, after returning to Britain, and a year after the end of the study abroad. Almost all learners were placed as teaching assistants or exchange students; those in Mexico were typically assigned to universities, while those in Spain were placed in primary or secondary schools. One participant undertook a workplace internship. Ten native Spanish speakers (eight from Spain, and two from Mexico) studying at the same university were also included as comparison data. The speakers performed a picture description task, where they were shown a series of drawings and asked to tell the story depicted in their own words. There were three different stories. The L2 Spanish speakers performed the task for each story twice across the six recording sessions, and the L1 Spanish speakers performed the task once for each story in one sitting.

The LANGSNAP corpus offers a rare longitudinal dataset with recordings at six timepoints over two years, supporting fine-grained developmental analyses. While the sample size is modest, the data were collected under standardized conditions using consistent elicitation tasks and equipment, yielding high-quality audio suitable for acoustic and computational analysis. The picture-description task elicits natural, connected speech while maintaining comparability across sessions. Study abroad datasets are often associated with variability in learner backgrounds and learning conditions; however, the standardized recording setup, task uniformity, and longitudinal design of LANGSNAP help mitigate these concerns. In particular, the ability to track intra-speaker change across timepoints allows us to model phonological development within individuals, which is especially valuable when inter-speaker variability is high. Although the dataset was not originally designed for spirantization research, its structure, consistency, and longitudinal scope make it uniquely suited for examining change over time in L2 phonological production.

3.5. Methods

The audio files and transcripts were forced-aligned using the Montreal Forced Aligner (McAuliffe et al., 2017). This data became the Phonet input. As described in Section 3.3, Phonet outputs posterior probabilities for 23 phonological features (e.g., [continuant], [sonorant], [nasal], [voice]) at 10 ms intervals. These probabilities range from 0 to 1 and represent the model's confidence that a particular phonological feature is active in each frame of the signal. This study focused on the [continuant] and [sonorant] features, which distinguish stop-like from approximant-like realizations of Spanish /b, d, g/. Canonical stops are [–continuant, –sonorant], while their lenited counterparts are [+continuant, +sonorant]. Accordingly, higher posterior values for these features indicate more spirantized (i.e., lenited) productions.

To minimize coarticulatory effects, only the middle third of each phone (as aligned by MFA) was retained. Posterior probabilities for each feature were then averaged within this portion, yielding a single value per phone per feature. This approach enables a gradient, subphonemic measure of lenition, capturing fine-grained variability in segmental realization.

Fig. 1 presents the Phonet posteriorgram for a representative learner's token of *quedaba* [ke.ða.βa] 'was remaining' or 'used to stay', displaying posterior probabilities for all 23 features over time. Warmer colors indicate higher posterior values. The [continuant] and [sonorant] rows show increased activation during the medial /d/ and /b/, consistent with lenited realizations. These higher posteriors reflect more open, approximant-like articulations, in contrast to the low values expected for fully occluded stops.

Fig. 2 illustrates the [continuant] and [sonorant] trajectories for the same token, segmented by phone. The medial stops /d/ and /b/ exhibit lenited realizations: /b/ shows a high and stable [continuant] posterior (≈ 0.95), while /d/ displays greater fluctuation and peaks around 0.7. Both segments show similarly high [sonorant] values. This pattern reflects the greater constriction typically associated with /d/ compared to /b/, even when both undergo lenition, and aligns with prior findings on asymmetries in spirantization (e.g., Bongiovanni et al., 2015).

Unlike categorical transcriptions or binary coding schemes, posteriorgram-based features allow for continuous modeling of L2 phonological development—particularly useful for capturing the gradient, variable nature of lenition. This representation is also more robust to classification noise and interspeaker variation, as it preserves within-category phonetic detail that is often lost in discrete analyses.

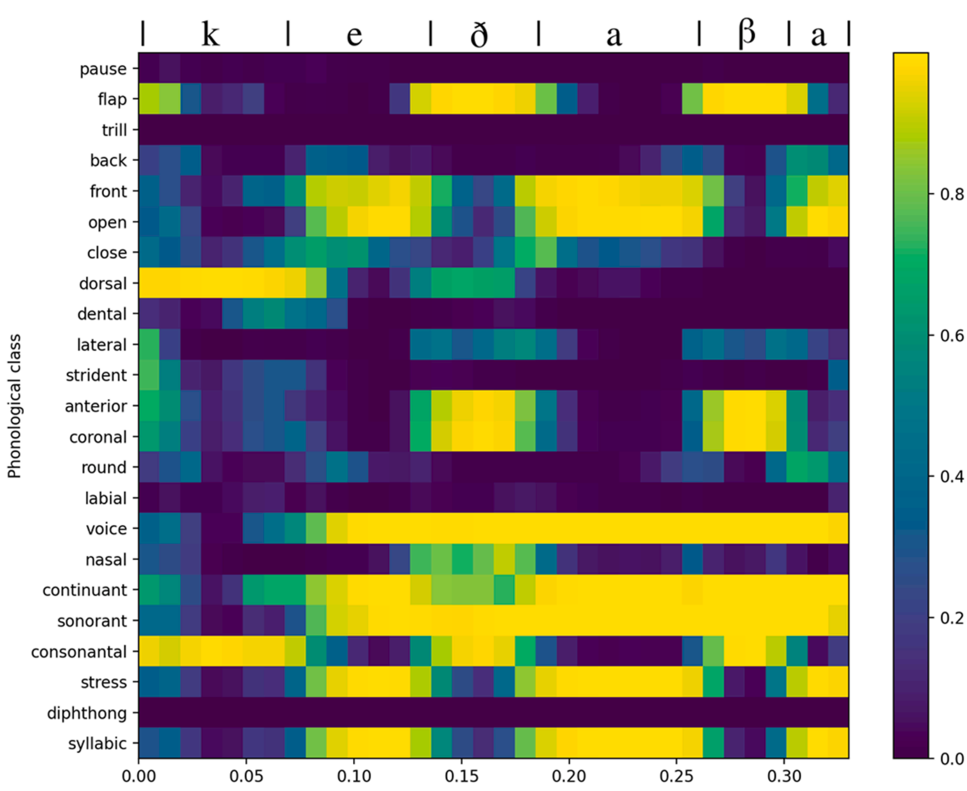

Fig. 1. Posteriorgram output from Phonet for a representative token of quedaba [ke.ða.βa] 'was remaining' or 'used to stay', showing posterior probabilities for 23 phonological features over time.

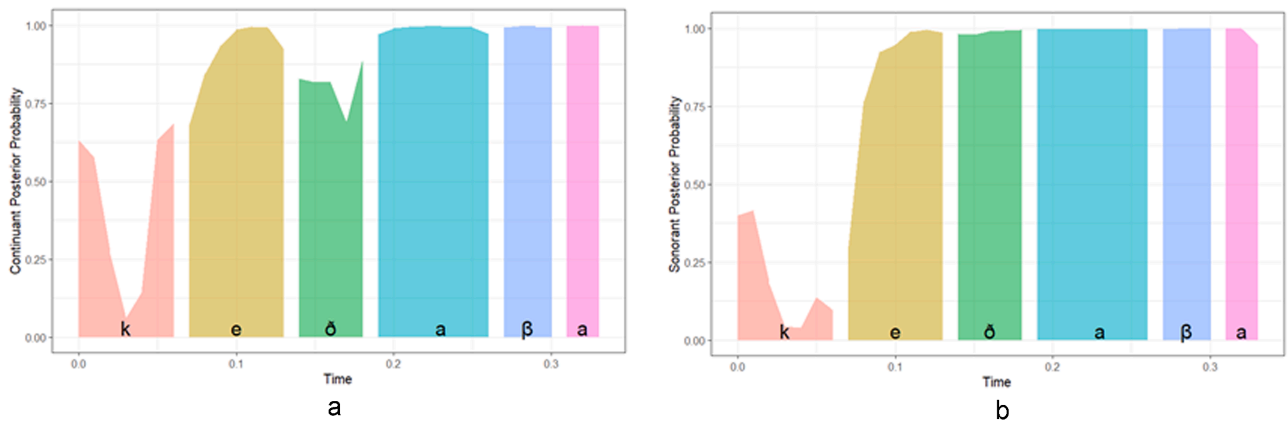

Fig. 2. Posterior probability trajectories for the features [continuant] (top) and [sonorant] (bottom) in a learner's token of quedaba [ke.ða.βa] ('was remaining' or 'used to stay') segmented by phone.

3.6. Statistical analysis

Linear mixed effects models were run in R (R Core Team, 2024) using the *lmer* package (Bates et al., 2014). To examine the effects of the different factors on posterior probability, growth development analyses (Nagle, 2017) were run. Different models were run for L2 learners and native speakers. These analyses start with a minimal model of just dependent variable ~ intercept + (1| random effect) and add additional predictors one at a time until either the model fails to converge or additional factors add no explanatory power to the model. Predictors were added in the same order as in the final model in Wayland et al. (2024a). After all fixed effects were added, interactions with the recording session were also added. Predictors were also contrast-coded using the same schema, except for session, which was treated as continuous instead of categorical. Following Nagle (2017), for the L2 models, the session was converted to a continuous linear variable, with the pretest set to 1, the first abroad session set to 2, etc., through all six recording times. It was also included as a random slope. The session was excluded for the native models. By calculating the difference in variance between the smaller and larger models as a percentage of variance in the smaller model, the amount of variation associated with the additional factor in the larger model could be estimated.

Additionally, individual trajectories were calculated using the pre-test, post-test, and delayed post-test data for each speaker. As in Nagle (2017), the trajectory was considered positive if the average posterior probability increased by >0.05, negative if the average posterior probability decreased by >0.05, and flat if the average posterior probability did not change >0.05 in either direction.

4. Results

4.1. Continuant posterior probability

4.1.1. L2 speakers

The maximal model that added explanatory power to the model was:

$$\begin{aligned}&\mathit{continuant.postprob} \sim \mathit{session}(1.5\%) + \mathit{stress}(1.1\%)\\&+\mathit{voicing}(3.5\%) + \mathit{placeofarticulation}(0.1\%)\\&+\mathit{wordposition}(0.1\%) + \mathit{precedingvowel}(1.6\%)\\&+\mathit{followingvowel}(0.1\%) + \mathit{session}:\mathit{stress}(<0.1\%)\\&+\mathit{session}:\mathit{voice}(<0.1\%) + (1+\mathit{session}|\mathit{speaker})\end{aligned}$$

The values in parentheses represent the amount of variation in continuant posterior probability that can be explained by the given factor. Among these, voicing emerged as the most significant predictor, accounting for 3.5 % of the variation. Smaller contributions from session (1.5 %), stress (1.1 %), and preceding vowel (1.6 %) indicate that developmental patterns over time and positional contexts also influenced learners' productions, though to a lesser extent. Finally, the effects of word position (0.1 %), place of articulation (0.1 %), and following vowel (0.1 %) were negligible. These results highlight the importance of voicing while also pointing to the influence of secondary factors like stress and vowel context.

4.1.2. Native speakers

The maximal model that added explanatory power was quite minimal:

$$\begin{aligned}&\mathit{continuant.postprob} \sim \mathit{stress}(1.8\%)\\&+\mathit{voicing}(18.7\%) + \mathit{place}(0.1\%) + (1|\mathit{speaker})\end{aligned}$$

Unlike non-native speakers, for whom multiple factors influence continuant posterior probability, only voicing (18.7 %), stress (1.8 %), and place (0.1 %) emerged as significant predictors for native speakers. Other factors, such as word position and coarticulatory influences, did not contribute meaningfully. Additionally, voicing played a much larger role than for L2 speakers.

4.2. Sonorant posterior probability

4.2.1. L2 speakers

For sonorant posterior probability, the maximal model that added explanatory power to the model was:

$$\begin{aligned}&\mathit{sonorant.postprob} \sim \mathit{session}(2\%) + \mathit{stress}\ (1.7\%)\\&+\mathit{voicing}(21.4\%) + \mathit{place}(1.9\%) + \mathit{wordposition}(<0.1\%)\\&+\mathit{precedingvowelheight}(4.5\%) + \mathit{followingvowelheight}(0.2\%)\\&+\mathit{session}:\mathit{stress}(<0.1\%) + \mathit{session}:\mathit{voice}(0.1\%) + (1+\mathit{session}|\mathit{speaker})\end{aligned}$$

Voicing accounted for the largest share of variation (21.4 %), while preceding vowel height (4.5 %), session (2 %), place (1.9 %), and stress (1.7 %) contributed moderately. Other factors, such as word position (< 0.1 %) and following vowel height (< 0.1 %), had minimal effects. Interaction terms, including session × stress (<0.1 %) and session × voicing (0.1 %), explained negligible variation.

4.2.2. Native speakers

For native speakers, the maximal model predicting sonorant posterior probability was:

$$\mathit{sonorant.postprob} \sim \mathit{stress}\ (1.6\%) + \mathit{voicing}\ (21.1\%) + \mathit{place}(0.2\%) + (1|\mathit{speaker}).$$

Voicing accounted for the majority of the variation (21.1 %). Stress contributed modestly (1.6 %), while place had negligible effects (0.2 %).

4.3. Individual trajectories

4.3.1. Continuant posterior probability

Fig. 3 shows the average continuant posterior probability across all stops at each test time for each L2 speaker (grey). The black line is the average continuant posterior probability across all stops for all ten native speakers.

As earlier mentioned, a difference in average posterior probability

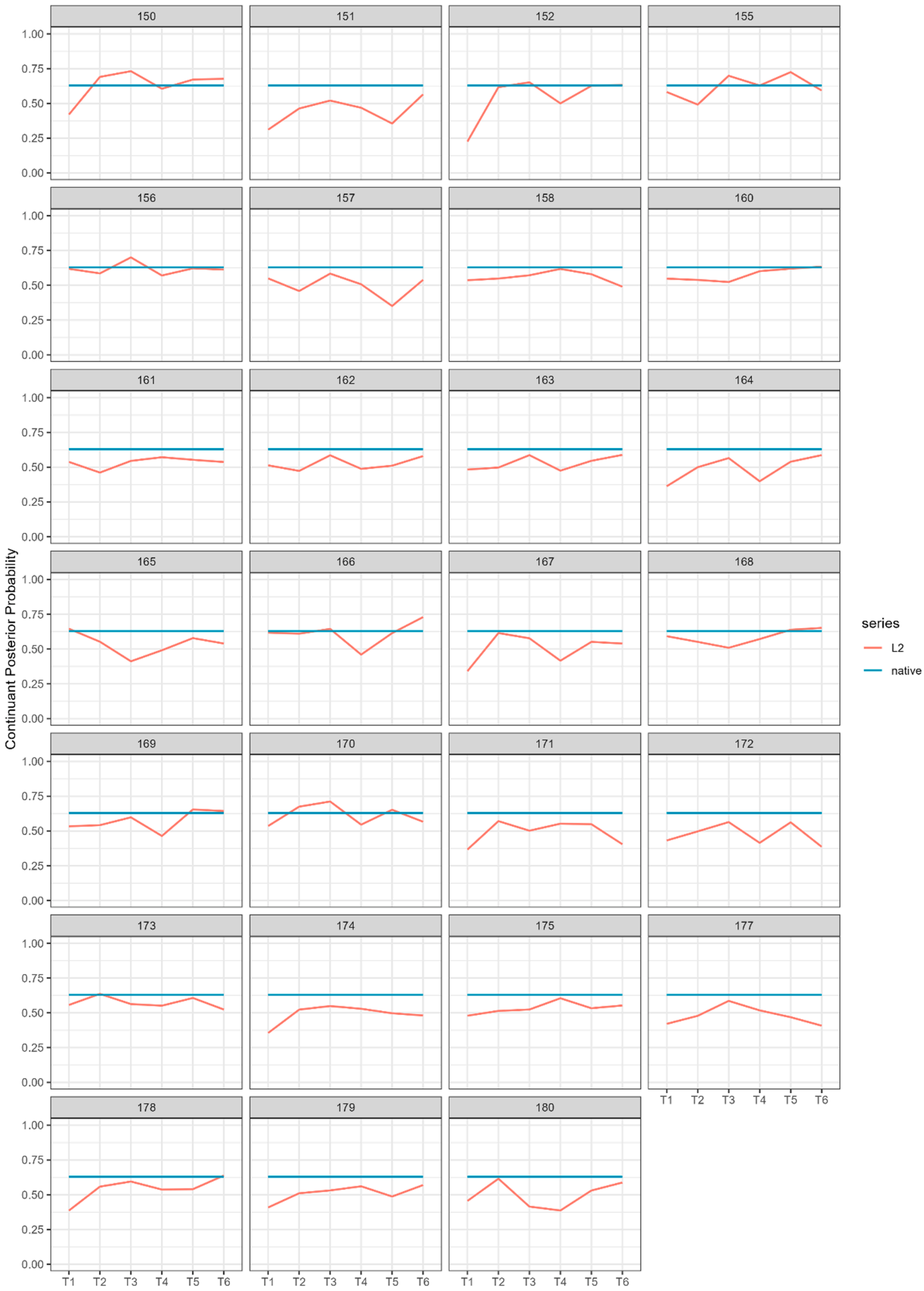

Fig. 3. Individual development trajectories for continuant posterior probability for native (blue) and L2 (red) speakers.

between the delayed posttest and the pretest larger than ±0.05 was considered a positive or negative trajectory, respectively. A difference between −0.05 and 0.05 was considered a flat trajectory. Six speakers (150, 151, 152, 158, 172, 173) had a negative trajectory, meaning the average continuant posterior probability was smaller at the delayed posttest than at the pretest. Nine speakers had flat trajectories (156, 160, 161, 164, 165, 168, 169, 170, 175) and twelve had positive trajectories (155, 157, 162, 163, 166, 167, 171, 174, 177, 178, 179, 180).

4.3.2. Sonorant posterior probability

Fig. 4 shows the individual trajectories for sonorant posterior probability. The same cutoff of 0.05 difference between pretest and delayed posttest was used to determine trajectory direction. Three speakers had negative trajectories (155, 161, 180), sixteen speakers had flat trajectories (156, 157, 158, 160, 162, 163, 165, 166, 168, 169, 170, 171, 172, 173, 175, 179), and the remaining eight speakers had positive trajectories (150, 151, 152, 164, 167, 174, 177, 178).

Fig. 5 shows the distribution of changes between pretest and delayed posttest for all L2 speakers and both features. Change in continuant is on the x-axis and change in sonorant is on the y-axis. Four speakers increased on both features (167, 174, 177, 178), and six speakers increased on one feature (157, 162, 163, 166, 171, 179). Five speakers increased one feature but decreased on the other (150, 151, 152, 155, 180). Eight speakers showed little to no change on either feature (156, 160, 165, 168, 169, 170, 175), and four showed no change on one feature and negative change on the other (158, 161, 172, 173).

5. Discussion

This study examined the acquisition of lenition in Spanish voiced stops (/b, d, g/) by native English speakers during a study-abroad program, focusing on individual differences in developmental trajectories. Lenition, characterized by the weakening of stops into fricative-like ([β], [ð], [ɣ]) or approximant-like ([β̞], [ð̞], [ɣ̞]) forms, poses significant challenges for L2 learners due to its gradient nature and the absence of analogous approximant forms in English phonology.

Our findings suggested that voicing is the dominant factor influencing lenition for both native and non-native speakers. For native

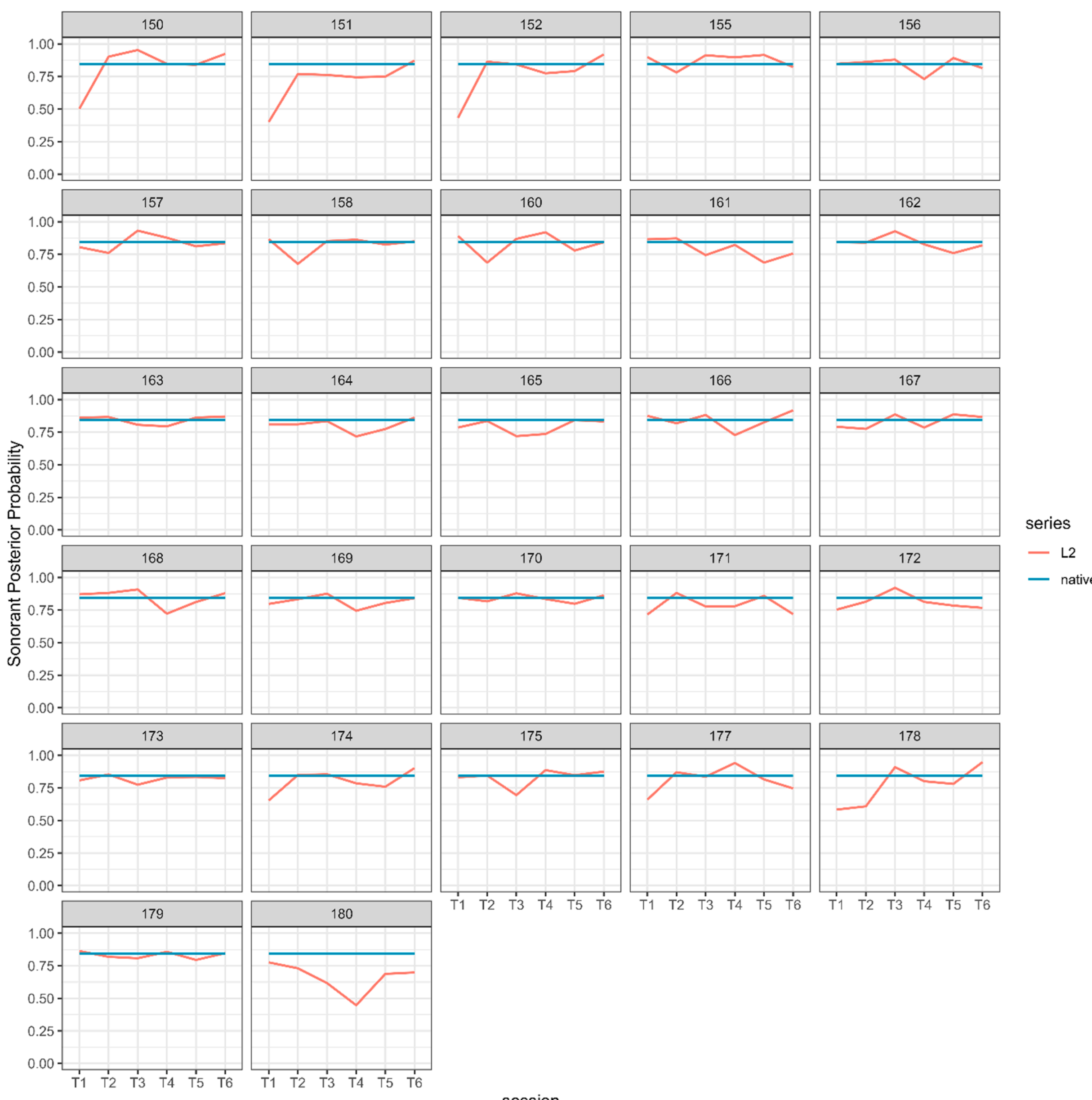

Fig. 4. Individual trajectories for sonorant posterior probability for native (blue), and L2 (red) speakers.

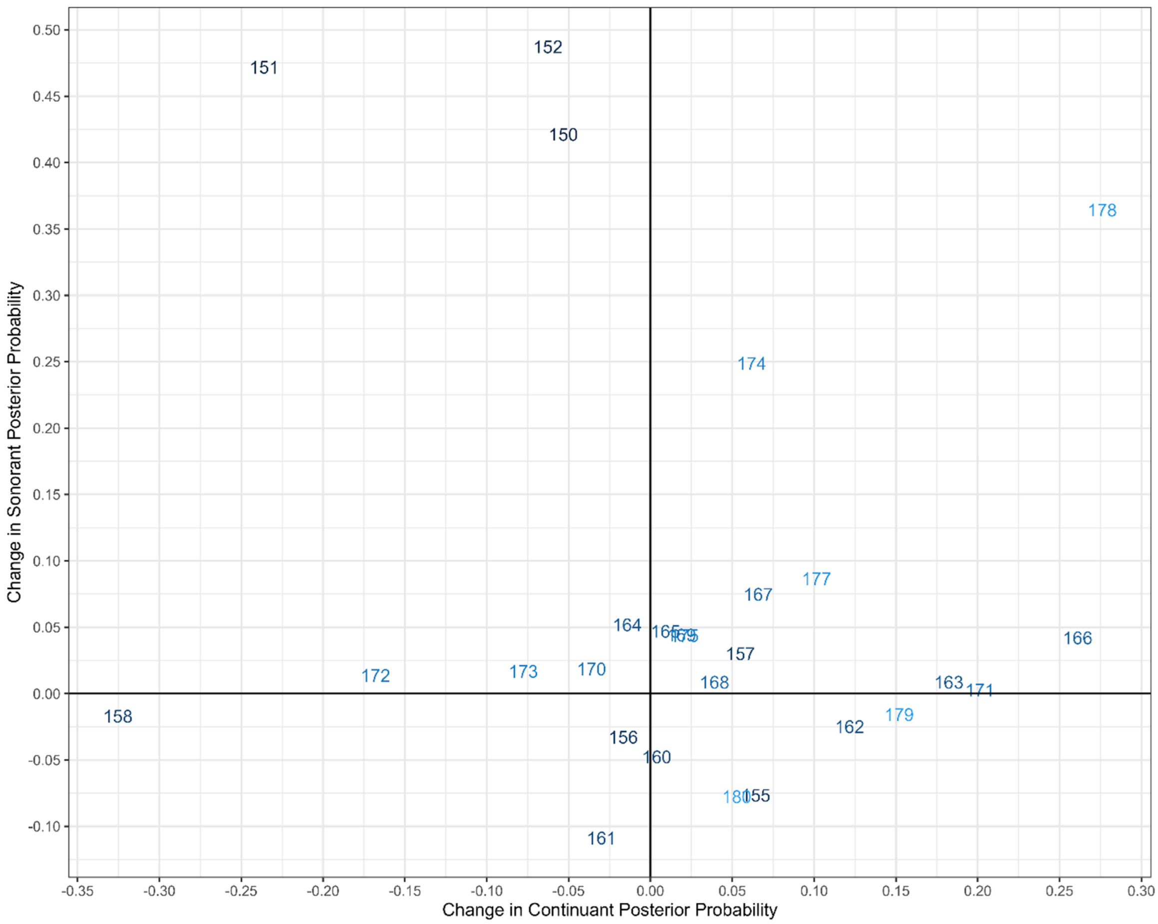

Fig. 5. Individual trajectories on posterior probabilities for continuant and sonorant features for L2 speakers.

speakers, voicing accounted for 18.7 % of the variation in continuant posterior probability and 21.1 % in sonorant posterior probability, underscoring its central role in Spanish phonology. Stress also emerged as a secondary factor, contributing modestly to variability (1.6 % for continuant and 1.8 % for sonorant probabilities), as did place of articulation (0.1 % for continuant and 0.2 % for sonorant probabilities). Other factors, such as word position and vowel context, had minimal or negligible effects on native productions.

Non-native speakers also relied heavily on voicing, which explained 3.5 % of the variation in continuant posterior probability and 21.4 % in sonorant posterior probability. Stress played a comparable role for learners, contributing 1.1 % for continuant and 1.7 % for sonorant probabilities, as did place (0.1 % for continuant and 1.9 % for sonorant probabilities). Unlike natives, learners exhibited sensitivity to additional contextual factors, including preceding vowel height (1.6 % for continuant and 4.5 % for sonorant), session (2 % for sonorant), and vowel environment. Testing sessions (times of testing) further influenced learner production, reflecting fluctuation in developmental progress over the period of the study-abroad program. These results suggest a broad alignment with native phonological tendencies among the learners. In addition, their sensitivity to other factors, including word position, indicates that learners' productions are shaped by other contextual variables as they work toward approximating native-like patterns during immersion.

The results also indicated a preference for fricative-like realizations over approximant-like forms among the learners, as evidenced by the greater number of positive trajectories for continuant posterior probabilities (12 positive trajectories) compared to sonorant posterior probabilities (8 positive trajectories). In addition, two learners (160 and 168) exhibited positive trajectories for continuant probabilities, associated with fricatives, but flat trajectories for sonorant probabilities, associated with approximants. This trend suggests that learners often rely on intermediate fricative-like forms that are [+continuant, –sonorant], rather than progressing directly to native-like approximants. While this finding may initially appear counterintuitive—given that approximants are articulatorily more permissive than fricatives—it may reflect learners' reliance on perceptual accessibility and acoustic stability. Fricatives, with their turbulent airflow and sharper acoustic profile, offer more robust cues for learners to perceive and monitor in their own production. Approximants, by contrast, lack strong acoustic salience and require fine control to maintain voicing without generating turbulence, which poses a subtler motor and perceptual challenge. Prior studies using auditory or scalar acoustic measures (e.g., intensity trough depth) may have underestimated the prevalence of such intermediate fricative-like forms, classifying them instead as approximants (Face and Menke, 2009). Our use of probabilistic feature modeling reveals these gradient realizations with greater granularity, showing that learners do not always progress in a categorical manner from stops to approximants. Instead, fricative-like realizations may serve as stable, perceptible waypoints that facilitate the gradual acquisition of more native-like approximant targets.

Cross-linguistic differences further complicate the acquisition of approximants. While English shares the interdental fricative [ð] with Spanish, it lacks labial ([β]) and velar ([ɣ]) fricatives as well as all lenited approximant variants ([β̞], [ð̞], [ɣ̞]). Consequently, learners often rely on fricative-like forms as intermediate steps, reducing articulatory complexity while approximating target forms. This strategy aligns with prior research (Face and Menke, 2009; González-Bueno, 1995), which suggests that learners simplify complex articulatory targets during the early stages of acquisition. Cognitive factors may also play a role in learners' preference for fricative-like forms. Producing approximants requires overriding entrenched L1 articulatory habits, which demands substantial motor coordination and cognitive effort (Nagle, 2017). When faced with a high cognitive load, learners may default to fricative-like realizations. Although less native-like, these forms offer a more accessible and stable intermediate step toward mastering the production of approximants.

It is also important to consider factors that may have influenced the initial values of learners' productions, especially for continuants. An important caveat in interpreting learner trajectories is that some L2 participants may have begun with already elevated continuant posterior probabilities. This could reflect transfer from English, where aspirated stops ([pʰ], [tʰ], [kʰ]) produce a turbulent burst that may resemble frication. Because the Phonet model was trained on Argentinian Spanish, where such aspiration is not present—these features may have been misclassified as indicative of the [+continuant] feature. As a result, some learners may appear to show flat or even negative development in continuant probabilities, not due to lack of learning but due to high starting values or model overestimation. Future work could address this by comparing learners' pretest values against native baselines and testing Phonet's response to aspirated L1 segments.

Individual variability emerged as a key finding, potentially influenced by sociolinguistic factors. While these factors were not directly measured in this study, their plausibility is supported by known differences in learners' placements contexts. As noted in Section 3.4, most Mexico-based participants were placed in universities, while those in Spain were often assigned to schools. These institutional differences may have shaped the amount and type of interaction learners had with native speakers. Learners with more opportunities for informal, conversational contact are more likely to develop approximant-like realizations, whereas those in more formal or non-native-dominant contexts may reinforce fricative-like patterns. This interpretation aligns with prior work emphasizing the role of social networks and interaction quality in shaping L2 phonological outcomes (Díaz-Campos, 2006; Collentine and Freed, 2004).

Nagle (2017) highlighted substantial variability in learners' pronunciation trajectories, emphasizing the impact of motivation and individual effort on phonological acquisition. Similarly, Alvord and Christiansen (2012) demonstrated that cultural integration, prior instruction, and interaction with native speakers significantly shape learners' ability to produce lenited forms. In this study, learners who aligned more closely with native patterns likely benefited from richer, more frequent interactions with native speakers, underscoring the importance of sociolinguistic and cognitive influences. The variability observed in our results—with some learners showing rapid progress while others plateaued or regressed—likely reflects differences in these factors.

These results underscore that while immersion may support gains in global proficiency and communicative competence, it does not consistently promote the acquisition of gradient, low-salience phonetic features such as approximant-like realizations—features that are often less critical for intelligibility but informative for understanding L2 phonological development. The variability observed among learners highlights the need for more targeted support within study-abroad programs. Rich, informal interaction with native speakers may foster the perceptual sensitivity and articulatory control needed for approximant-like realizations. At the same time, pedagogical practices might benefit from explicitly addressing the cognitive and motor demands posed by such segments, providing learners with structured opportunities to transition from fricative-like to approximant-like forms. Consistent with Lord (2010), our findings suggest that study-abroad programs may be most effective when authentic input is paired with tailored instructional guidance, helping learners move beyond surface-level imitation toward deeper phonological integration.

Beyond lenition, this study contributes to our understanding of L2 acquisition during immersion by illustrating how learners may vary in their trajectories of acquiring gradient phonetic features, even under similar learning conditions. While the LANGSNAP database does not provide direct measures of input quality, social interaction, or individual learner traits, the observed variability is consistent with prior work emphasizing the importance of these factors in L2 phonological development (Alvord and Christiansen, 2012; Nagle, 2017). This pattern underscores the value of longitudinal designs and nuanced phonetic analysis in identifying the kinds of phonological patterns that may be more or less amenable to acquisition in immersive contexts.

6. Conclusion

This study investigated the acquisition of lenition in Spanish voiced stops (/b, d, g/) among native English speakers during a study-abroad program, focusing on individual differences and influencing factors. While learners aligned with native speakers in recognizing voicing as the primary cue for lenition, they diverged in their productions, favoring fricative-like over approximant-like realizations.

The variability in learners' trajectories highlights the role of individual differences in L2 phonological development and suggests that immersive experiences alone may not suffice to promote acquisition of gradient, low-salience features like approximants. To address these challenges, instructional strategies should explicitly target the articulatory demands of approximants and offer structured practice with less salient cues. By combining authentic input with tailored pedagogical support, language programs can better support learners in developing more native-like phonological patterns.

While this study did not directly assess learners' input quality, social interactions, or instructional contexts, the observed variability is consistent with prior research suggesting that such factors can shape phonological outcomes. These findings contribute to our understanding of the conditions under which late L2 learners approximate native-like realizations and underscore the value of longitudinal, feature-based analyses in SLA research.

This study demonstrates the value of applying probabilistic phonological feature modeling to L2 speech. By leveraging Phonet's frame-level posterior probabilities for articulatorily relevant features, we captured subphonemic gradience in learner speech that traditional transcription or acoustic scalar measures might obscure. Specifically, our analysis revealed a preference for fricative-like ([+continuant, –sonorant]) forms as intermediate waypoints—challenging prior assumptions that learners move categorically from stops to approximants. These findings show how feature-based deep learning models can uncover patterns of phonological development that reflect not just categorical change, but graded, dynamic shifts over time. This approach offers a scalable, interpretable framework for capturing L2 speech variation, and may complement traditional acoustic and categorical methods in future work on speech modeling and phonological acquisition.

CRediT authorship contribution statement

Ratree Wayland: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rachel Meyer:** Writing – review & editing, Writing – original draft, Visualization, Resources, Formal analysis, Data curation. **Sophia Vellozzi:** Validation, Software. **Kevin Tang:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ratree Wayland and Kevin Tang report financial support was provided by National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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