DEVELOPMENT OF BRAZILIAN PORTUGUESE VOWELS BY AN ARGENTINEAN LEARNER: A LONGITUDINAL CASE STUDY USING BAYESIAN GAMMS

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This study investigated the impact of explicit instruction on the pronunciation of Brazilian Portuguese (BP) mid vowels by an Argentinean learner (L1 Spanish, L2 English, L3 BP) over the course of one year. The participant took part in 24 biweekly data collection sessions. Between sessions 10 and 15, instruction focused on the pronunciation of the vowels /e–ɛ/ and /o–ɔ/. To assess instructional effects, we compared the participant's BP vowel productions with their Spanish baseline productions using Mahalanobis distances that captured F1, F2, and duration values. Developmental trajectories were analyzed using Bayesian generalized additive mixed models (GAMMs). Results showed that vowel development was not uniform, with the back mid vowels /o–ɔ/ showing most changes, particularly after the instruction period. These findings highlight the potential of pronunciation instruction to influence L3 phonological development.

INTRODUCTION

The acquisition of Brazilian Portuguese (BP) by L1 Spanish speakers is a challenging task. BP has seven stressed vowels (/i/, /e/, /ɛ/, /a/, /ɔ/, /o/, /u/), while Spanish has only five (/i/, /e/, /a/, /o/, /u/). As a result, perceiving and producing minimal pairs such as *peso* (/e/, noun, "weight") versus *peso* (/ɛ/, verb, "I weigh") or *avô* (/o/, "grandfather") versus *avó* (/ɔ/, "grandmother") is difficult for these learners regardless of their proficiency (Pereyron, 2017). In this context, explicit pronunciation instruction (Atar, 2018; Stratton, 2025) may support learners' phonological development.

This study adopts the principles of Complex Dynamic Systems Theory (CDST; De Bot, 2017; De Bot et al., 2007; Larsen-Freeman & Cameron, 2008; among others) to conceptualize language development. From a CDST perspective, language evolves nonlinearly because it comprises multiple interacting components. Consequently, language systems are emergent, self-organizing, and adaptable. Being open systems, they are sensitive to a range of internal and external factors that learners must negotiate throughout development. Variability in the learner's output is therefore a key property of development (Verspoor et al., 2021). Higher variability is expected when the learner is introduced to a nonnative contrast, but this variability should decrease over time as the learner finally integrates that nonnative contrast into their phonology. In other words, development is gradual rather than categorical, and variability in the output signals learning as the system accommodates new information and reorganizes accordingly. CDST thus takes the individual as the primary unit of analysis (De Bot, 2015) and employs a process-oriented approach (Lowie, 2017), analyzing longitudinal data across multiple datapoints to highlight nonlinearity and variability.

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Given these CDST principles, explicit instruction is expected to destabilize the learner's system by raising awareness and providing opportunities to perceive and produce new, nonnative sounds. Because all elements in a complex system are interconnected, the emergence of new vowel categories should affect the entire vowel space. As these categories develop, shifts across all vowel classes are expected due to the adaptive nature of the system (Flege, 1995; Flege & Bohn, 2021).

In light of this, the present study investigates the impact of explicit instruction on the development of BP mid vowels by an Argentinean learner (L1 Spanish, L2 English, L3 BP), looking into this learner's BP mid vowels over one year. This participant had been residing in Brazil for more than three years and made use of BP in his home and work environments, which justified his interest in learning BP pronunciation. The participant completed 24 biweekly data-collection sessions. Following an A-X-A design (Hiver & Al-Hoorie, 2020), in which "X" denotes instruction, explicit pronunciation instruction on BP vowels was provided between the fifth and eighth months (sessions 10–15). This design allowed us to examine how the learner's developing L3 vowel system adapted to instruction.

Besides discussing the effects of explicit pronunciation instruction, in this paper we also aim to discuss the effectiveness of Bayesian generalized additive mixed models (GAMMs) to analyze F1, F2 and duration measures. This approach is expected to capture both individual variation and nonlinear change over time. We also compared the learner's BP vowel productions across all sessions to their baseline production of Spanish vowels using Mahalanobis distances calculated from F1, F2, and duration. These distances were then modeled with a GAMM to trace multidimensional change over time.

The use of Bayesian GAMMs and Mahalanobis distances in L2 vowel development research is relatively recent. Lima Jr. and Alves (2025), focusing on F1 and F2, argued that this methodology is well suited to capture nonlinear development and variability in CDST-oriented studies. The present study advances this approach by including duration as an additional dimension and incorporating it into the Mahalanobis calculations. It also advances this methodology by considering the learner's L1, baseline productions of /e/ and /o/. By modeling these distances with a Bayesian GAMM, we aim to demonstrate how these three dimensions adapt over time, particularly following explicit instruction.

Research Questions

This study addresses the following research questions:

1. What developmental changes occur in the learner's vowel system following explicit pronunciation instruction?
2. How do Mahalanobis distances and Bayesian GAMMs capture the learner's developmental changes over time?

Because the study is grounded in CDST, the first question does not seek a binary outcome regarding instructional effectiveness. We assume that instruction will influence the system (regardless of whether the resulting patterns are target-like) by prompting reorganization and development. Our goal is to describe these changes and the learner's developmental trajectory rather than to determine whether the target forms were achieved.

The second question concerns the analytical approach. Given that Mahalanobis distances and Bayesian GAMMs are emerging tools in L2 research, we examine their capacity to model changes in the learner's BP vowel system.

METHOD

Participant

The participant, a 36-year-old male from Buenos Aires, Argentina, was an L1 speaker of River Plate Spanish. Data collection began in October 2018. At that time, the participant had an A2 proficiency level in English, which he began studying as a teenager but interrupted before reaching adulthood. He resumed his English studies at a private language course and was enrolled in an A2-level group at the time data collection began. After six months, he discontinued the course. At the time of data collection, he had limited exposure to English and did not use the language productively. His opportunities to use Spanish (his L1) were also limited, being largely confined to telephone interactions with family members in Argentina. As reported by the participant, over 95% of his interactions occurred in BP.

BP was the participant's L3. His first contact with BP was in 2010, when he moved to Rio de Janeiro to pursue his PhD studies. After one year, he returned to Buenos Aires, where he lived from 2011 until February 2015, when he moved to Porto Alegre, Brazil. At the time of data collection, he had been working as a professor at a public university in Porto Alegre for 3 years and 7 months. In 2015, he achieved the "highly advanced" level (the highest grade) on the Celpe-Bras exam, Brazil's official BP proficiency test administered by the Ministry of Education. In future studies, we intend to investigate the interaction of the learner's three language systems.

Explicit Pronunciation Instruction

From data collection sessions 10 to 15, the participant attended 12 weekly, one-on-one pronunciation instruction sessions. Each session lasted 90 minutes and was conducted by the second author at the participant's residence. All classes adopted a communicative approach to pronunciation teaching (Celce-Murcia et al., 2010). The adoption of Celce-Murcia et al.'s (2010) framework was particularly important, as this proposal ensures opportunities for explicit pronunciation instruction in its initial pedagogical component (Description and Analysis). Following Lima Jr. and Alves (2019), the implementation of the framework was guided by a task-based methodology, with the aim of contextualizing the pronunciation features addressed.

During the classes, the pronunciation textbook *Curtindo os Sons do Brasil* (Alves et al., 2017) was used as the primary instructional material. The textbook covers various consonantal and vowel aspects of BP pronunciation that are challenging for L1 Spanish learners. Although our study specifically focused on vowels, the instruction covered the first twelve units of the textbook. Given our focus on vowels, we altered the order of the units, beginning with those targeting vowels. After completing the three vowel-focused units, we proceeded with the remaining material, incorporating regular review activities. At the start of each class, we included a warm-up activity that focused on the perception and production of vowels, ensuring consistent exposure to BP mid-vowels throughout the 12 sessions.

It is important to note that, during data collection sessions 1–9 (pre-instruction) and 16–24 (post-instruction), the participant did not receive any form of language instruction, either in BP or in any other language. Thus, the only instruction provided in this study comprised the 12 pronunciation sessions conducted between sessions 10 and 15, as described above.

Data Collection Instruments and Sessions

In each data collection session, the participant provided data in three languages: Spanish, English, and BP. In this study, only the instruments for Spanish and BP are described. Both tasks involved sentence reading, following protocols previously used in studies on BP acquisition by L1 Spanish speakers (Pereyron, 2017). The Spanish instrument included 30 target words (six per vowel), each repeated three times, yielding 90 analyzable tokens. It also included 15 distractor words, totaling 105 words. The BP instrument contained 42 target words (six per vowel), with three repetitions per word type, resulting in 126 tokens per session. It also included 20 distractor words, totaling 146 words. In both instruments, all tokens were presented in the carrier sentence *Diga* ____ ("Say ___"). In both instruments, each target vowel was elicited in three disyllabic and three trisyllabic words. In addition, the phonetic environment of the target vowels was controlled, with both preceding and following segments being preferably voiceless plosives or fricatives. No sonorants were employed in preceding and following contexts.

Data collection began in October 2018 and ended in September 2019. For each task, the same set of two-word sentences (which can be regarded as a methodological limitation, as repetitions in each session may lead to learning effects) were displayed in random order on PowerPoint slides. The participant's productions were recorded with Audacity, conducted by the second author every two weeks at the participant's residence. To avoid cross-linguistic influence, data collection for each language occurred at different times of day. Conversations between the participant and the second author were in the task's target language.

Data Analysis

Acoustic analyses of F1, F2, and absolute duration values were performed using Praat (version 6.1.16; Boersma & Weenink, 2019). These values were manually extracted using the Linear Predictive Coding (LPC) algorithm in Praat. Formant frequencies were obtained by manually selecting the central position of the steady-state vowel.

Following the acoustic analyses, all vowels were plotted using the PhonR package in R. Bayesian GAMMs were run to model F1, F2, and duration values individually over time. Mahalanobis distances were then calculated for the participant's front mid vowels (combining F1, F2, and duration as a single construct) in relation to the centroid of /e/ in Spanish, using data from the participant's first Spanish data collection session. The same process was applied to the back mid vowels. Finally, a Bayesian GAMM was fit to the Mahalanobis distances to model changes over time between the BP vowels and the L1 Spanish baselines.

Generalized additive models (GAMs) are well suited for longitudinal studies characterized by dynamic trajectories because, unlike traditional linear models, they model smooth curves rather than straight lines. This flexibility makes them more capable of capturing nonlinear changes over time. As a type of regression model, GAMs can incorporate random effects. In

this study, the words, which were the same across all data collection sessions, were included as random effects, resulting in a GAMM.

A Bayesian version of the model offers additional analytical advantages. First, Bayesian inference estimates the probability of the working hypothesis given the data, rather than the probability of the data given the null hypothesis, as is typical in frequentist approaches. Second, it allows the inclusion of prior distributions informed by theoretical expectations or previous findings. Third, it yields full posterior distributions rather than single-point estimates, enabling the examination of credible intervals, which have more intuitive interpretations than frequentist confidence intervals.

To assess the distance between the vowels in each pair, we calculated their Mahalanobis distances relative to the participant's Spanish /e/ and /o/. Unlike geometric distance measures (e.g., Euclidean distances), Mahalanobis distances can incorporate any number of parameters regardless of their original scale, due to a normalization step in its computation. It can, for example, accommodate F1 and F2 (in Hertz but on different ranges of the scale) and duration (in milliseconds) simultaneously. Moreover, it considers how each data point relates to the baseline distribution's centroid: points that lie outside the baseline distribution receive larger distance values even if their geometric distance equals that of points located near the center of the baseline distribution. This procedure results in one distance value per data point relative to the centroid of the participant's baseline Spanish /e/ or /o/, computed jointly over F1, F2, and duration.

As an example, Figure 1 shows the distances of all /e/ and /ɛ/ in BP (red and blue, respectively) produced by the participant in comparison to his Spanish /e/, plotted in black according to its mean F1 and F2 values.

RESULTS

Descriptive Data

Figure 2 displays the vowel production data across all 24 data collection sessions.

With respect to F1 and F2 values (Figure 2), initial analysis shows that the productions of /e/ and /ɛ/ overlap into a single category, as both vowels are assimilated into one (cf. Flege, 1995; Flege & Bohn, 2021). For the back mid vowels, while two distinct categories are not clearly established, some productions of /ɔ/ are positioned lower in the acoustic space, indicating the potential emergence of this vowel as a new category. This will be further illustrated in Figure 3, which shows the mean values of each BP vowel category across all data collection sessions.

Figure 1

Illustration of Mahalanobis Distances of the Front Mid Vowels /e/ and /ɛ/ in BP Produced Across the 24 Data Collection Sessions in Relation to Participant's Spanish /e/ (in Black)

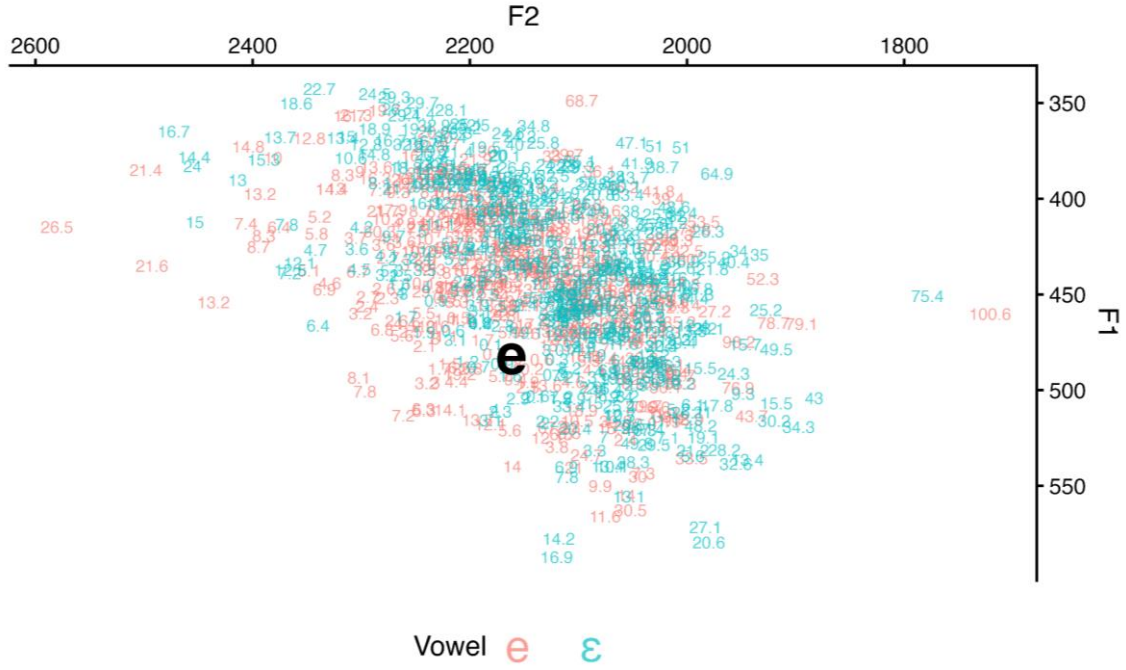


Figure 2

Plot of F1 and F2 Raw Values for all BP Vowel Across the 24 Data Collection Sessions

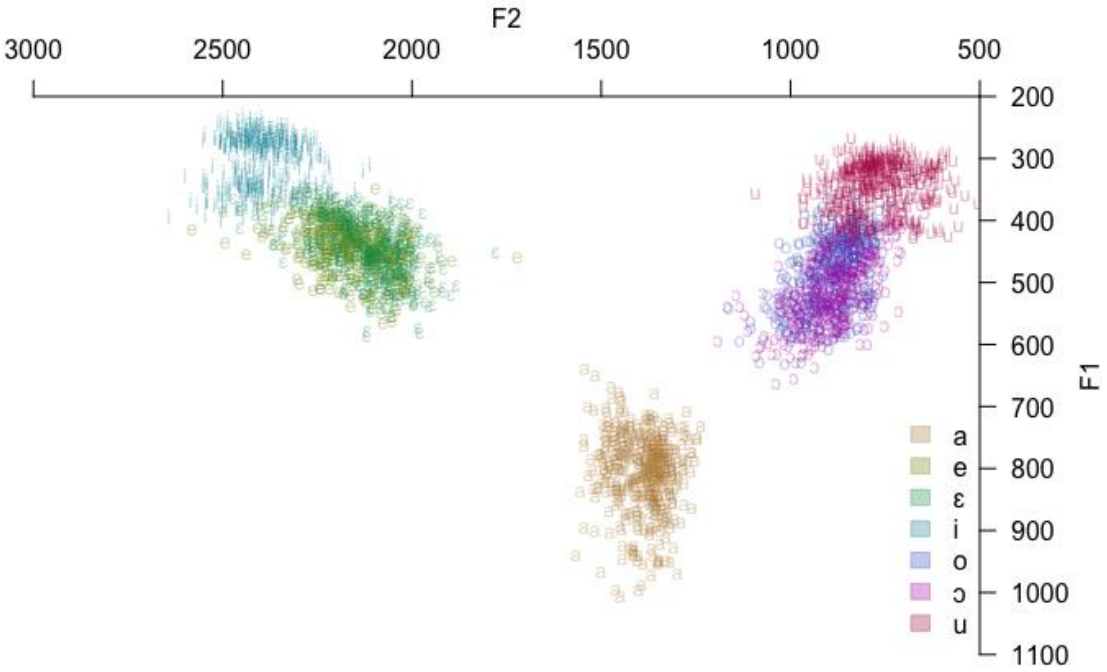


Figure 3
Plot of mean values for each vowel category across the 24 data collection sessions

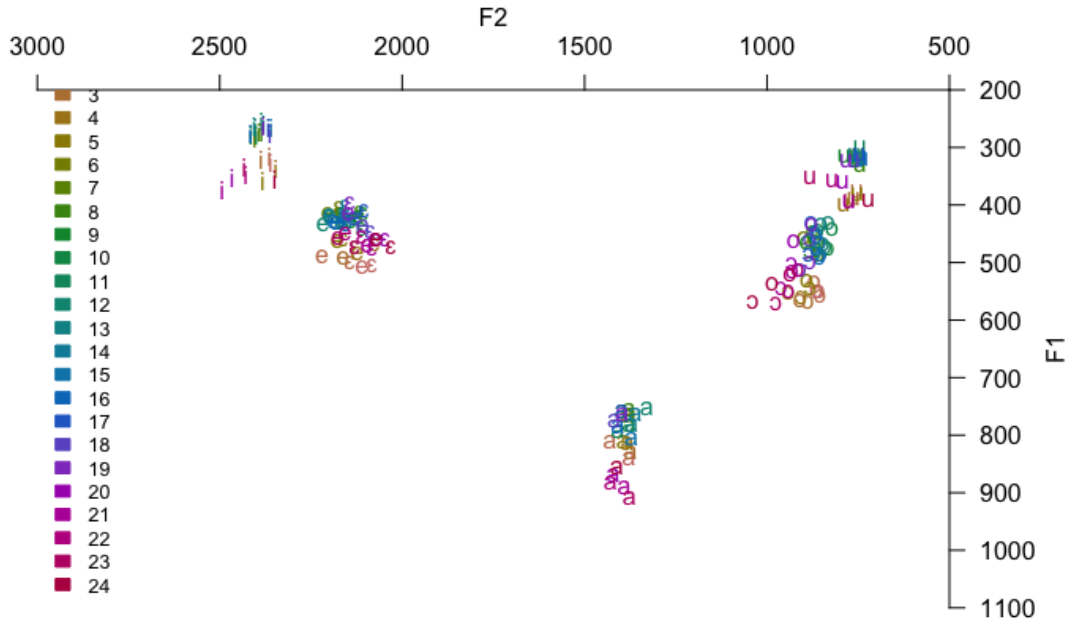


Figure 3 illustrates that in the initial data collection session, the mid vowels had comparable F1 mean values (/e/: 487 Hz (*SD* = 34); /ɛ/: 481 Hz (*SD* = 39); /o/: 546 Hz (*SD* = 28); /ɔ/: 556 Hz (*SD* = 27)). These values closely align with those reported for monolingual speakers of Buenos Aires Argentinean Spanish (/e/: 457 Hz (*SD*: 18 Hz); /o/: 539 Hz (*SD*: 19 Hz); Pereyron, 2017).

From the sixth data collection session onward, the learner's BP vowels showed a raising trend (lower F1 values), with /e/ at 434 Hz (*SD* = 34), /ɛ/ at 431 Hz (*SD* = 45), /o/ at 464 Hz (*SD* = 50), and /ɔ/ at 500 Hz (*SD* = 55). This shift caused the mid vowels to align more closely with the F1 values of the high-mid /e/ and /o/ in monolingual Porto Alegre BP speakers (/e/: 405 Hz (*SD* = 17); /o/: 424 Hz (*SD* = 16); Pereyron, 2017). Initially, the learner's productions of /e/ and /o/ mirrored his L1, but by data collection sessions 6–8, these vowels shifted to higher positions, resembling BP mid vowels. This created an acoustic gap, suggesting that the learner's BP vowel system was adapting and preparing for the later emergence of /ɛ/ and /ɔ/. This gap indicates that the learner's system was "primed" for these vowels to emerge in subsequent time points, characterizing an intermediate developmental step by which the learner goes through before contrasting the mid-high and mid-low vowels in his production.

It is important to note that the entire vowel system adapts to changes in the mid vowels. As the mid vowels raise, the high vowels /i/ and /u/ also raise. Without this adjustment, the mid and high vowel categories would be too close in the acoustic space, risking their merger. Additionally, /a/ was also raised to avoid an oversized acoustic gap in the system. In other words, the vowel system adjusts all categories to accommodate changes in the mid vowels, reflecting its adaptive, complex, and dynamic nature.

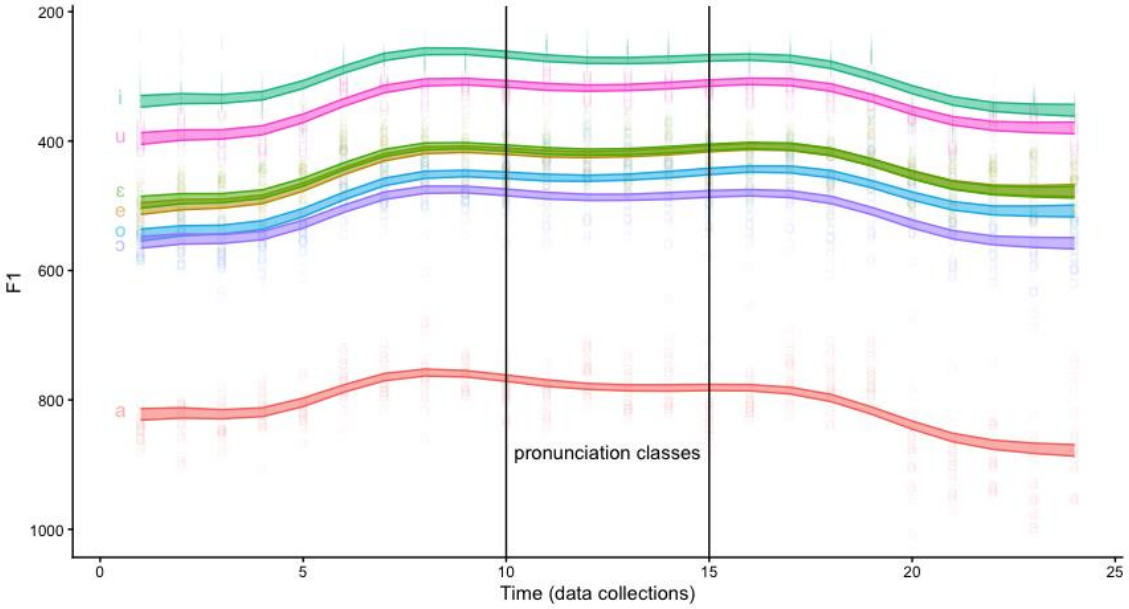
Figure 3 also suggests that in the final data collection sessions, a new category for /ɔ/ begins to emerge. Although the two categories of /o/ and /ɔ/ are not fully distinct, the productions in

the later data collection sessions show a tendency to differentiate the back mid vowels, but not the front ones.

Bayesian GAMMs of F1, F2 and Duration Values

Bayesian GAMMs were fitted individually for F1, F2, and duration values in a similar manner. To capture the nonlinear trajectory of F1, F2, and duration values over time, first we constructed a cubic B-spline basis (degree = 3) with 8 knots placed at the quantiles of the data collection sessions, generating the smooth function to be used in the model. The model was specified using the brms package for R as a Gaussian likelihood with F1 as the outcome, the spline basis matrix as the population-level predictor, and by-vowel random effects allowing both intercepts and slopes over time to vary across the vowels. Weakly informative priors were placed on all parameters, based on values found in the descriptive analyses. The posterior predictive means and 95% credible intervals were extracted and used for the plots that follow. As can be seen, the models effectively captured the developmental trends in the data. Figure 4 displays the Bayesian GAMM fit for F1 values.

Figure 4
Bayesian GAMM of F1 Values



The Bayesian GAMM model demonstrated that changes in the mid vowels were reflected across the entire developing system, as both low and high vowels exhibited a similar raising trend between data collection sessions 6 and 8. Figure 4 also indicates the period of explicit pronunciation instruction, during which F1 values for all vowels showed a mostly stable pattern. Following the instruction, between data collection sessions 18 and 20, all vowel categories lowered. The front mid vowels /e/ and /ɛ/ exhibited a similar pattern of descent, while /ɔ/ showed a more pronounced drop than /o/, explaining the early emergence of a new category for /ɔ/ in the final data collection sessions. As the mid vowels lowered, the high /i/ and /u/ vowels, as well as the low /a/ vowel, also lowered, approximating the original values observed in the first data collection session. Figure 5 shows the results of the Bayesian GAMM fit for F2, and Figure 6 presents the results for duration values.

Figure 5
Bayesian GAMM of F2 Values

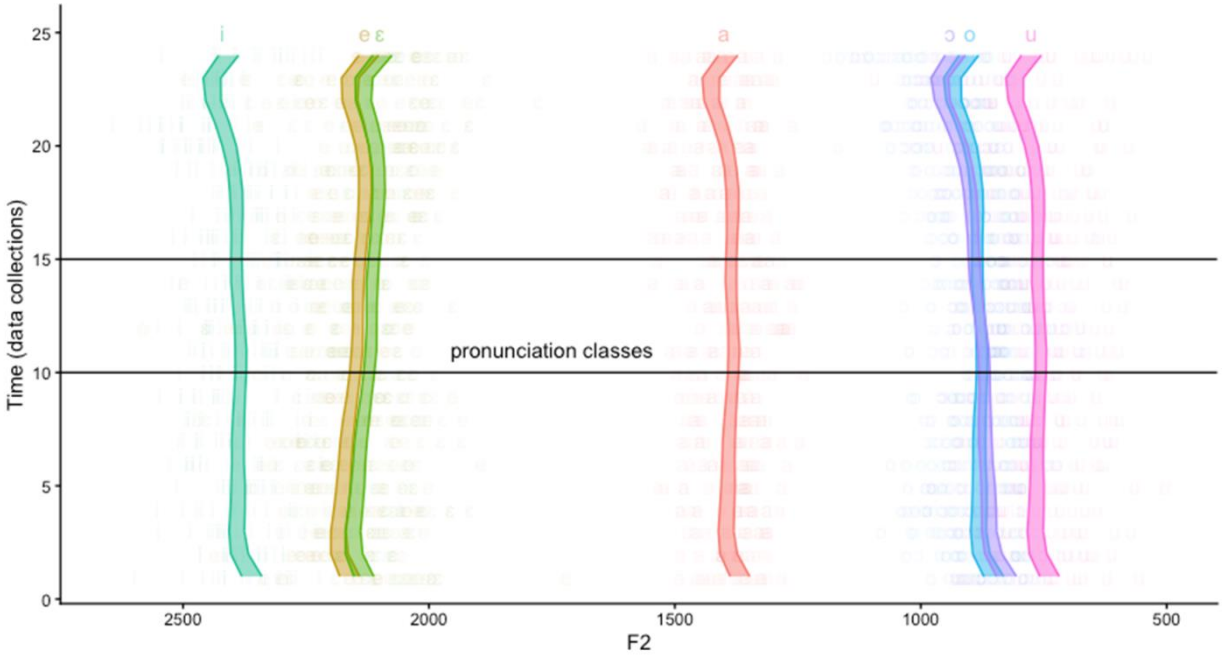
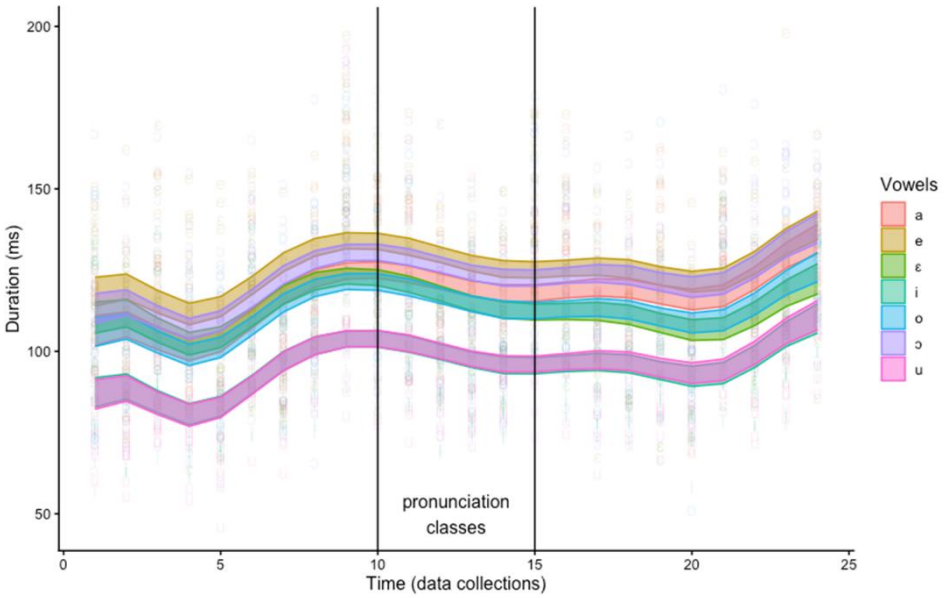


Figure 5 suggests that F2 values are not a primary acoustic cue for the learner in distinguishing mid vowel categories. F2 values show minimal changes over time, and the /o–ɔ/ distinction appears to merge across sessions, especially during explicit instruction. It is important to note that the patterns also reveal a reversal with /o/ fronter than /ɔ/ before instruction, but then /o/ backer than /ɔ/ after the instructional period, which suggests the beginning stages of a developmental change over time. Despite these minor changes, F1 seems to play a more decisive role than F2 in distinguishing vowel categories in BP, consistent with data from native BP speakers (Alves et al., 2020).

Regarding duration, the learner appears to be experimenting with this cue throughout the 24 sessions. Vowels in the BP dialect of Porto Alegre tend to be longer than those in River Plate Spanish (Pereyron, 2017). Since /ɛ/ and /ɔ/ are generally longer than /e/ and /o/ (Pereyron, 2017), the learner may be using duration to differentiate these categories, even though duration is considered a secondary cue in L1 BP perception (e.g., Alves et al., 2020). The model in Figure 6 shows that vowel duration increased between data collection sessions 5 and 8, coinciding with the raising of vowels in the learner's system. As vowel raising would be expected to result in shorter durations (given that /ɛ/ and /ɔ/ are generally longer than /e/ and /o/ in BP, as previously noted), the observed increase in vowel duration may reflect a compensatory strategy associated with vowel raising. This possibility will be further investigated in future studies.

Figure 6
Bayesian GAMM of Vowel Duration



Mahalanobis Distances

Finally, the Mahalanobis distances between the participant's BP /e–ɛ/ and his Spanish /e/ as well as the distances between his BP /o–ɔ/ and his Spanish /o/ were used to fit Bayesian GAMMs with the same structure described for the F1, F2 and duration models. The Mahalanobis distances between the participant's BP /e–ɛ/ and his Spanish /e/, shown in Figure 7, indicate that both BP vowels moved away from the Spanish baseline (i.e., increased their distances) between data collection sessions 5 and 10. Their distances then decreased slightly during the pronunciation lessons. After the lessons, however, the two vowels began to separate from each other, with the participant's BP /e/ moving farther away from his Spanish /e/. Although these patterns do not reflect the emergence of distinct categories for BP /e/ and /ɛ/, they reveal the dynamic and nonlinear trajectories characteristic of L2 phonological development, suggesting that explicit pronunciation instruction led the participant to try out new forms and patterns in time.

For the back vowels, Figure 8 shows that both BP vowels increased their distances from the participant's Spanish /o/ prior to the pronunciation lessons, which then led to a separation between them, with BP /o/ moving farther from the Spanish baseline. These patterns likewise illustrate the dynamic, nonlinear nature of his L2 vowel development over time, with the period of explicit instruction appearing to perturb the system, even if not yet in a direction consistent with the formation of separate L2 phonetic categories.

Figure 7

Posterior Distribution of the Bayesian GAMM Predicting Mahalanobis Distances Between BP /e–ɛ/ and the Participant's Spanish /e/ Over Time

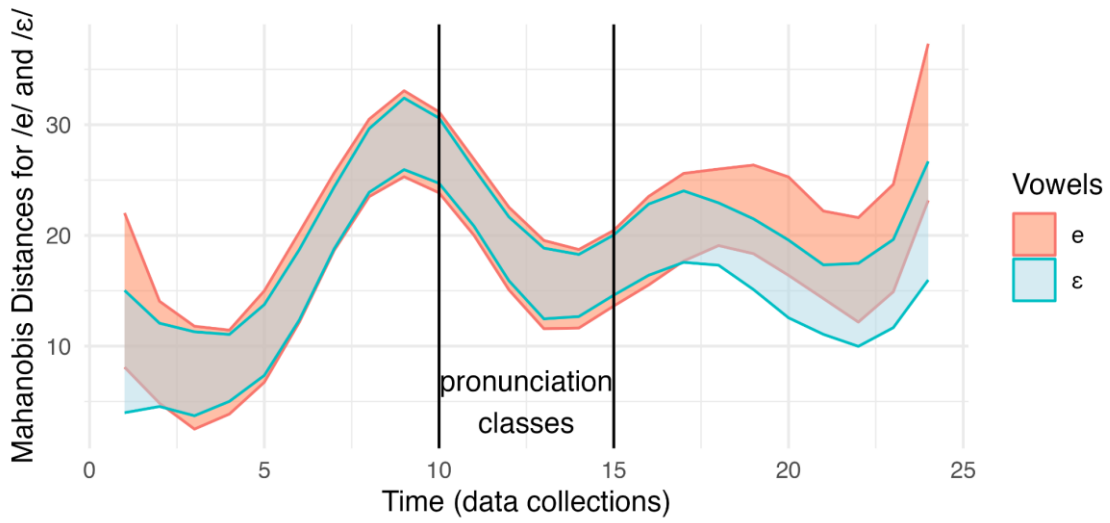
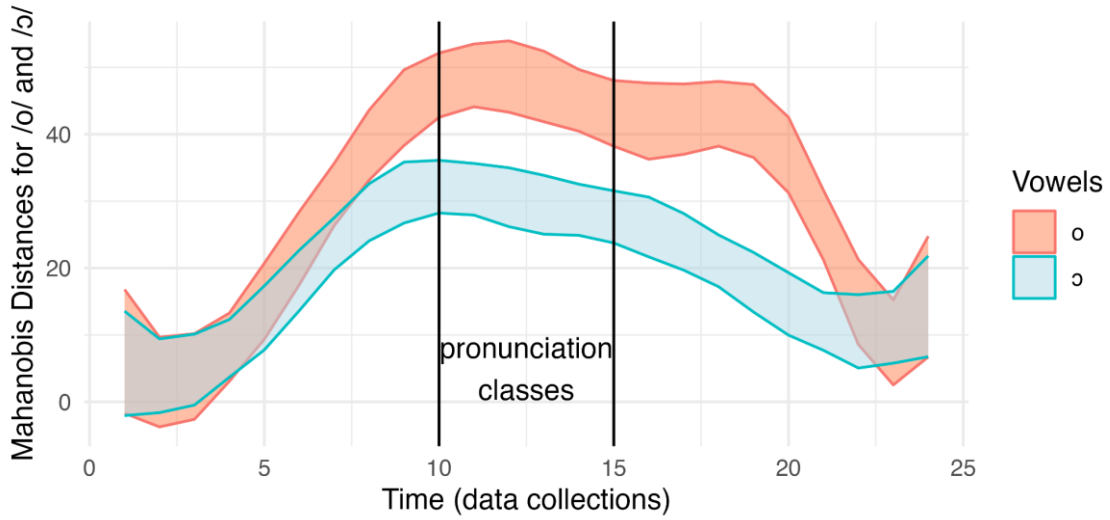


Figure 8

Posterior Distribution of the Bayesian GAMM Predicting Mahalanobis Distances Between BP /o–ɔ/ and the Participant's Spanish /o/ Over Time



DISCUSSION

In this process-oriented study, we investigated the development of the BP mid vowels /e–ɛ/ and /o–ɔ/ by an Argentinean learner who received explicit pronunciation instruction in BP.

Regarding the first research question (*What developmental changes occur in the learner's vowel system following explicit pronunciation instruction?*), it can be concluded that the learner's attempt to form new vowel categories for /ɛ/ and /ɔ/ involved interactions among all vowels in the system. Developmental changes began before explicit instruction and continued afterward, emphasizing the dynamic nature of the process. Pronunciation instruction had an impact on the dynamic trajectory, but was not the only factor at play, given that

developmental movements also occurred before and after instruction; and its influence is not a linear route towards standard L1 forms. The earlier emergence of /ɔ/ compared to /ɛ/ may be influenced not only by instruction itself, but also by visual cues, such as lip rounding, which help distinguish /o/ and /ɔ/.

Although the /ɛ/ category does not fully emerge, the hybrid /e–ɛ/ category is not static. The raising observed in the sixth data collection session, followed by further adaptations, indicates the system was creating an acoustic gap for /ɛ/ to emerge. This is particularly relevant within CDST, which emphasizes the developmental process and the strategies learners use, rather than the final acquisition outcome.

As for the second research question (*How do Mahalanobis distances and Bayesian GAMMs capture the learner's developmental changes over time?*), the Bayesian GAMM proved to be an appropriate model for capturing the dynamic, nonlinear trajectories of vowel development. The Mahalanobis distances were also suitable for this purpose, particularly because they incorporate the three primary acoustic cues for vowel production (F1, F2, and duration), thus providing a more integrated and informative measure of change over time.

Future studies will explore the interactions between BP vowels and the learner's Spanish (L1) and English (L2) to highlight the interconnection between language systems. Overall, this study demonstrates the nonlinear development of the learner's vowel system and confirms the role of explicit instruction in promoting variability (regardless of whether these new patterns approach target forms) and nonlinear trajectories over a relatively short period.

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