An analysis of vowel Productions by a female Brazilian speaker of German: analyzing vowel quality

[Uma análise das realizações vocálicas por uma aprendiz brasileira de alemão: a qualidade vocálica]

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Abstract: In this study, we investigate the development of Standard German vowels, concerning their formants, namely F1, F2 and F3, by a young-adult Brazilian female speaker of German as a third language (L3). The methodology entails an acoustic analysis on Praat. We analyze the vowel sounds regarding their relative formant structure, in order to verify whether (or how) they changed along the evaluated sessions by means of a Monte Carlo analysis. As a result of the analysis, we observe that the speaker uses a formant compensation strategy for the production of her German vowels. According to the *Speech-Learning Model (SLM-(r))*, the speaker altered her formant acoustic cues, i.e. instead of relying on F3 to produce some phonological distinctions in her German vowels, the speaker made use of F2 to account for these distinctions.

Keywords: German vowels; formant structure; acoustic cues; complex dynamic systems

Resumo: Neste estudo, investigamos o processo de desenvolvimento formântico relativo às vogais do alemão padrão (AP), por uma falante nativa brasileira, adulta-jovem, do AP como terceira língua (doravante, L3). Metodologicamente, realizamos uma análise acústica no Praat. Desta forma, analisamos os dados acerca dos três primeiros formantes vocálicos (F1, F2 e F3) de todas as vogais do sistema vocálico do AP, a fim de observar se (ou como) as vogais do AP se modificariam acusticamente ao longo das sessões avaliadas, por meio da verificação de análises de Monte Carlo. Os resultados indicam que a falante se utiliza de uma estratégia de compensação formântica para a produção de suas vogais. Segundo o *Speech-Learning Model (SLM-(r))*, a falante fez uso de outras pistas acústicas, que não as esperadas, a fim de produzir as distinções entre suas vogais, isto é, ela passa a basear a sua produção vocálica na pista referente ao segundo formante (F2) em vez de baseá-la no terceiro formante (F3).

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Palavras-chave: vogais do alemão padrão; estrutura formântica; pistas acústicas; sistemas dinâmicos complexos

Zusammenfassung: In dieser Studie wird der Entwicklungsprozess hinsichtlich aller Vokale im Hochdeutschen als dritte Sprache (L3) von einer jungen-erwachsenen brasilianischen Muttersprachlerin untersucht. Die Methodologie umfasst eine akustische Analyse in Praat. In diesem Sinne werden die Dateien in Bezug auf die drei ersten Formanten (F1, F2 und F3) aller hochdeutschen Vokale analysiert, um herauszufinden, wenn (und wie) sich die Vokale akustisch mittels der Überprüfung der Monte-Carlo Analysen im Laufe der evaluierten Datenerhebungen ändern würden. Die Ergebnisse schlagen vor, dass die Sprecherin eine Formanten-Kompensierung Strategie für ihre Vokalproduktion anwendet. Dem *Speech-Learning Model (SLM-(r))* zufolge benutzte die Sprecherin andere akustische Cues, um phonologische Unterscheidungen in ihren Vokalen auszusprechen, d.h. sie basiert ihre Vokalproduktion auf dem zweiten Formant (F2) anstatt eine Vokalproduktion anhand des dritten Formants (F3).

Schlüsselwörter: hochdeutsche Vokale; Formantenstruktur; akustische Cues; komplexe und dynamische Systemtheorie

Introduction

The production of vowels in Standard German[3] (hereinafter, SG) presents a challenge for Brazilian learners of *DaF (Deutsch als Fremdsprache)*[4] (JUNGES 2012, 2023; JUNGES, ALVES 2019, 2020, 2023). Given the fundamental differences between the phonetic-phonological systems of Standard German and Brazilian Portuguese (hereinafter, BP), achieving intelligibility and comprehensibility is crucial for speakers of both languages (ALVES 2018; ALVES, SANTANA 2020; ALVES, VIEIRA 2023; ALBUQUERQUE 2019; SANTANA 2021; SCHERESCHEWSKY 2021).

In light of Complex Dynamic Systems Theory (CDST – DE BOT, LOWIE, VERSPOOR 2007; LARSEN-FREEMAN, CAMERON 2008; LARSEN-FREEMAN 2015; DE BOT 2017), analyzing the development of an additional language (AL) requires a longitudinal analysis focusing on the learner. Within this paradigm, an individual analysis of vowel production in SG can reveal valuable insights into the learner's trajectory over time.

[3] Stock and Hirschfeld (1996 [2002]: 03), regarding the use of standard German pronunciation, present the following passage: "This form of pronunciation is considered not only cultivated but, above all, makes comprehension possible throughout the entire German-speaking region. For this reason, it has long been standard practice in German as a foreign language classes to focus exclusively on teaching standard pronunciation in relation to German phonetics".
[4] *German as a foreign language*.

A process-oriented linguistic analysis shows that the language system of an AL speaker, particularly its phonetic-phonological subsystem, is continuously subject to restructuring, marked by non-linearity and unpredictability. In this scenario, a salient property of CDST is its longitudinal nature (DE BOT, LOWIE, VERSPOOR 2007), which supports our choice of a longitudinal study (or 'process analysis', cf. LOWIE 2017) over a cross-sectional approach ('product analysis', cf. LOWIE 2017).

In this context, the present study examines the production of all SG vowels through a phonetic experiment, analysing a Brazilian learner in a private teaching context over twelve data collection sessions across one year. Our analysis focuses on her first three vocal formants — F1, F2, and F3 — which are central to defining vowel quality (KENT, READ 2015).

The longitudinal approach adopted here highlights the continuous flow and internal self-organization of language systems. Such systems and subsystems are expected to *vary*, becoming sensitive to particular input patterns within a given time frame and to different patterns in another (DE BOT, LOWIE, VERSPOOR 2007). Within this paradigm, Van Geert (1994) emphasizes development as an iterative process, in which each stage critically depends on the previous one.

Understanding language as a process of temporal development allows us to address the notion of *language variability*. Lowie and Verspoor (2015) argue that variability is a fundamental condition for language development — without it, development does not occur. This process reflects the learner's apparent experimentation with the target language, showing that they are testing new strategies throughout their linguistic trajectory.

In line with CDST, we also adopted the revised version of the *Speech Learning Model (SLM-r)* (FLEGE, BOHN 2021) to investigate the development of vowel categories in the acoustic space over time. The *SLM-r* is a theoretical-methodological framework for investigating how sounds in a new language — such as vowels and consonants — are perceived and produced. Our choice in using this model is justified by its capacity to track the speaker longitudinally while accounting for the variable role of specific acoustic cues (here, F1, F2, and F3) in establishing functional distinctions in the new language.

Considering its psycholinguistic and phonetic contexts, the main objective of this study is to investigate the development of the entire SG vowel system by a Brazilian learner of German through a phonetic experiment conducted over twelve production sessions across one year. To this end, our specific goals are: (i) to examine possible longitudinal variations in the first three formants (F1, F2, F3) involved in the configuration of all SG vowels; and (ii) to discuss, from the perspective of CDST, what the observed variability reveals about the learner's intra-individual linguistic trajectory.

2 Theoretical Framework

2.1 A TSDC

According to CDST (LOWIE, VERSPOOR 2019; YU, LOWIE 2019), language is an adaptive system that combines stability with dynamic change (ELLIS, LARSEN-FREEMAN 2009). Han (2019) further argues that language use is an iterative process of co-adaptation, in which speakers adjust to context and interlocutors to accomplish its semiotic potential. The theory also encompasses epistemological principles that inform scientific thought and theorization. Building on Hulstijn (2020), Hiver, Al-Hoorie, and Evans (2022) describe CDST as a metatheory that provides an ontological framework for understanding language, its use, and its development in dynamic and complex terms.

Research within CDST primarily focuses on studying complex systems through their processes of change. This is often pursued with time-intensive methods, reflecting the dynamic nature of the approach (HIVER, AL-HOORIE, EVANS 2022: 916). According to Ellis and Larsen-Freeman (2009), complex macrobehaviors, dynamic microinteractions, and the emergence of new behavioral patterns are of particular interest. Holland (2006) argues that system components can adapt and learn. Consequently, even systems that appear identical ultimately diverge, as adaptation and development drive them in distinct directions (HIVER 2022).

Finally, the non-linearity and infinitude of dynamic and complex systems make them inherently susceptible to change over time; in other words, their linguistic development has no endpoint (DE BOT 2015). As Hiver (2022) notes, this dynamic change is non-telic, allowing systems to evolve without a fixed or predetermined goal.

2.2 *Speech Learning Model (SLM(-r))*

The *Revised Speech Learning Model (SLM-r)*, proposed by Flege and Bohn (2021), builds on its predecessor, the *Speech Learning Model (SLM)* introduced by Flege (1995). Both versions focus on the acquisition of L2 sounds, namely vowels and consonants (segments).

The basic premises of the *SLM-r* can be summarized as follows (FLEGE, BOHN 2021: 23):

Chart 1: Basic Premises of the *SLM(-r)*

1. *The phonetic categories that are used in word recognition and to define the targets of speech production are based on statistical input distributions.*
2. *L2 learners of any age make use of the same mechanisms and processes to learn L2 speech that children exploit when learning their L1.*
3. *Native versus nonnative differences in L2 production and perception are ubiquitous, not because humans lose the capacity to learn speech at a certain stage of typical neuro-cognitive development, but because applying the mechanisms and processes that functioned "perfectly" in L1 acquisition to the sounds of an L2 do not yield the same results.*

Source: FLEGE AND BOHN (2021: 23)

In addition to its basic premises, Flege and Bohn (2021) outline six main hypotheses of the model: (1) a revised age hypothesis; (2) the relationship between production and perception; (3) category accuracy; *(4) the formation of bilingual phonetic categories*; (5) interactions between L1 and L2; and *(6) the weight of acoustic cues*. This study focuses primarily on *hypotheses (4) and (6)*, as they are most relevant to the data analysis presented here.

Regarding the hypothesis of *bilingual phonetic category formation (4)*, the authors (op. cit.) argue that differences between L1 and L2 learning inevitably emerge because: (1) L1 sounds initially replace L2 sound categories, as L2 sounds are automatically linked to the L1 phonetic inventory; (2) preexisting L1 categories interfere with, and sometimes block, the formation of new categories for L2 sounds; and (3) L2 sound learning is based on input that differs from what monolingual native speakers receive when learning the same sounds.

Building on these explanations, the current model maintains, as previously discussed, that the ability to form L2 phonetic categories remains intact throughout the speaker's lifespan. This applies to new categories for any L2 sound that perceptually differs from the closest L1 sound. However, this process depends on three conditions: (i) the perceived phonetic dissimilarity between an L2 sound and its closest L1 counterpart; (2) the precision with which the closest L1 category is defined; and (3) the quantity and quality of L2 input received.

Regarding the *weight of acoustic cues (6)*, the model suggests that cue weighting in L1 category formation may differ from that in L2. This allows for the emergence of distinct phonetic categories in the L2 phonetic-phonological system, rather than a mere replication of L1 categories. In other words, learning a new language may involve assigning different priorities to L2 cues compared with their weighting in L1. For example, Brazilian learners often prioritize duration when establishing vowel distinctions, whereas in languages such as English and German, vowel quality — reflected in cues like F1, F2, and F3 — plays a more central role than duration (HOLT, LOTTO 2006). Thus, Brazilian learners must adjust their perceptual weighting, shifting cue priorities in order to develop functional vowel categories in these languages.

Combined with Complex Dynamic Systems Theory (CDST), the *Speech Learning Model (SLM-r)* contributes to our phonetic analysis by integrating an acoustic-perceptual microtheory within a broader linguistic framework.

2.3 The German Vowel System

German has 16 vowel sounds, including at least 14 contrasting monophthongs distinguished by height[5], tension, and duration, as well as three diphthongs: /i, ɪ, e, ɛ, ɛː[6], ɑ, a, y, ʏ, ø, œ, u, ʊ, o, ɔ/ - /ə, ɐ/ - /aɪ̯, aʊ̯, ɔɪ̯/. The 14 monophthongs are generally grouped

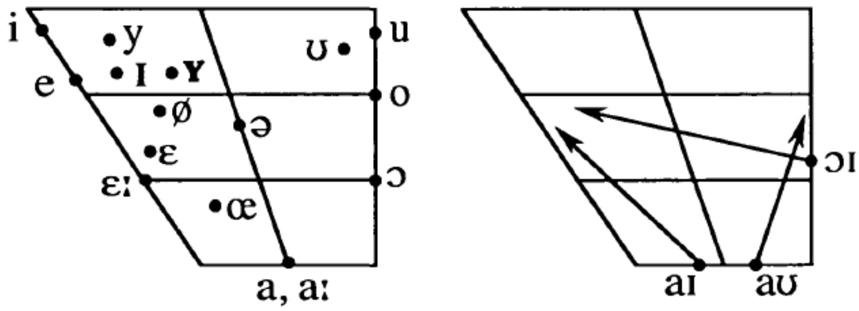
[5] "In the phonetic spectrum of the German language, the vowel groups are frequently referred to as 'closed' and 'open', respectively (VIETOR, BREMER, WÄNGLER, MARTENS, ZWIRNER *et al.*)" (JØRGENSEN 1969: 217).

[6] "A distinctive feature of the German vowel system is that, in addition to the short open vowel [ɛ], there is also the closed vowel [eː] and the long open vowel [ɛː]. This long open [ɛː] is produced with less tongue advancement and a wider mouth opening than the short [eː]. It is, therefore, isolated within the system" (STOCK, HIRSCHFELD 1996 [2002]: 18).

into seven contrasting pairs: /i-ɪ/, /e-ɛ/, /ɑ-a/, /y-ʏ/, /u-ʊ/, /o-ɔ/, /ø-œ/, though phonetic and phonological classifications vary (JØRGENSEN 1969; LINDNER 1969; SENDLMEIER 1981; KOHLER 1990, 1995; RAMERS 1998; STRANGE, BOHN 1998; MEYER 2010; NIMZ 2015; HEERINGA, SCHOORMANN, PETERS 2015; SCHOORMANN, HEERINGA, PETERS 2017; SCHOORMANN 2023).

Below, all German vowels are shown in two charts (monophthongs on the left, diphthongs on the right):

Figure 1: German monophthongs and diphthongs

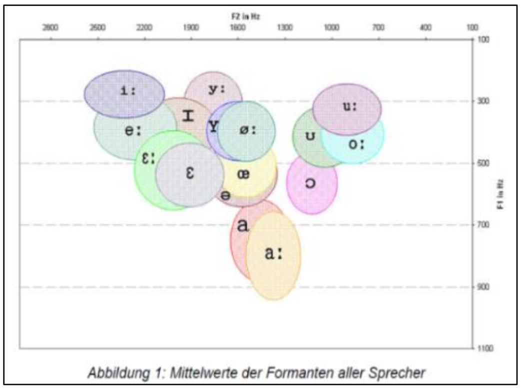


Source: KOHLER (1990: 49)

The vowels in Figure 1 are arranged according to vocal-articulatory order (anterior–central–posterior). Based on a phonetic-acoustic analysis, Sendlmeier and Seebode (2010) describe German vowels in a study conducted between 1998 and 2006 at the Language and Communication Center of the Technical University of Berlin (TU Berlin)[7], with 127 native SG speakers (69 men, 58 women) aged 20–30. The acoustic area defined for these vowels is shown in Figure 2, and separately for female and male speakers in Figure 3.

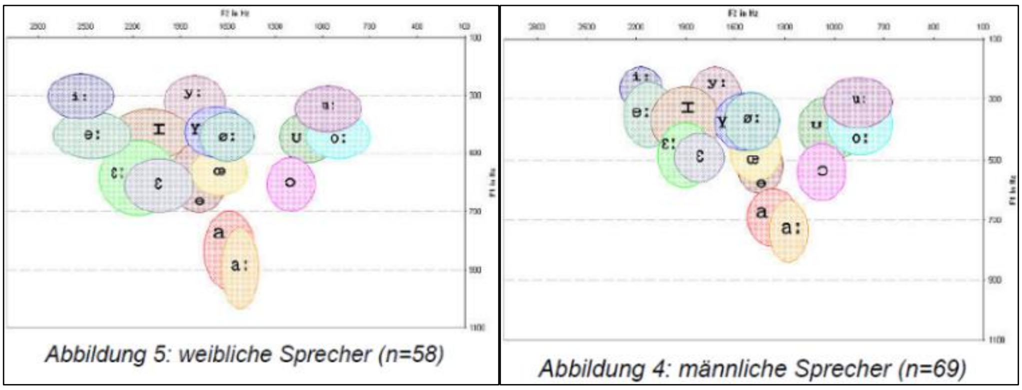
[7] Original name of the university center: *"TU Berlin, Institut für Sprache und Kommunikation"*.

Figure 2: (*Abb.* 1, original) - Acoustic space of German vowels (F1 and F2)



Source: SENDLMEIER, SEEBODE (2010: 03)

Figure 3: (*Abb.* 4, 5, original) - Acoustic distribution (F1 x F2) of German vowels for female and male speakers, respectively



Fonte: SENDLMEIER, SEEBODE (2010: 03)

Figures 2 and 3 show that the formant values of vowels produced by women are more widely dispersed across the acoustic space than those of men. Female data range from 200 Hz to 2800 Hz, while male data range from 250 Hz to 2100 Hz, indicating greater dispersion in the female vowel spectrum.

In addition to the formant values reported by Sendlmeier and Seebode (2010), Strange et al. (2004: 1801) present Table 1, which shows the average values of the first three formants and absolute duration (ms) of Northern German vowels. The data were produced by four native speakers in hVp/hVb syllables within carrier phrases.

Table 1 (*TABLE IV*, original): Average values of formant frequencies and durations in North German (NG). Rate of difference between the long and short vowels = 1.9[8].

Vowels	F1 (Hz)	F2 (Hz)	F3 (Hz)	Duration (ms)
iː	317	1943	2971	84
ɪ	428	1784	2462	54
eː	382	2008	2697	97
ɛ	597	1738	2471	65
yː	306	1590	2061	84
ʏ	406	1348	2104	63
øː	409	1345	2051	99
œ	551	1364	2231	74
uː	344	710	2002	84
ʊ	441	836	2398	60
oː	427	727	2454	100
ɔ	610	966	2414	60
ɑː	713	1173	2438	115
a	713	1227	2395	64

Source: STRANGE *et al.* (2004: 1801)

This table shows the values of the first three vowel formants (F1/F2/F3) for each monophthong in Standard German (AP), as well as the absolute duration (in ms) produced by native speakers from Northern Germany. These rates will be useful for discussing our participant's production data, as they will help determine whether her productions align with Standard German.

[8] In the table, Strange *et al.* (2004) did not include the vowel [ɛː] in the inventory of Northern German, although we can observe it in the vowel chart of monolingual and trilingual speakers presented by Schoorman, Heeringa, and Peters (2017: 07).

3 Method

3.1 Longitudinal Study

Within CDST, the development of an additional language is viewed through the lens of *ergodicity*, which entails two scenarios. The first is a hypothetical case in which the linguistic process remains stable over time, with every measurement showing the same mean and variance. This would require a homogeneous population in which all participants follow identical dynamic patterns without individual differences (HANNAN 1970, as cited in YU; LOWIE 2019). Since such ergodic groups do not exist in reality, the second scenario frames language development as a *process* marked by extensive individual differences and dynamic interactions among many factors. Consequently, ergodicity cannot be applied to groups (LOWIE, VERSPOOR 2019).

As noted, the CDST views language change as shaped by dynamic entities that influence development differently over time. Consequently, no two individuals develop language in the same way, as development is non-linear, with phases of high variability often accompanied by rapid growth (LOWIE, VERSPOOR 2019). According to this view, research should focus on tracing the behavior and interactions of system components rather than generalizing across groups.

Based on these principles, we conducted a longitudinal study with twelve data collections over one year, tracking the vowel development of a female participant (German learner at CEFR[9] level A2–B1). A basic–intermediate learner was chosen because this proficiency level was regarded as more likely to exhibit noticeable changes over the year, making it possible to observe dynamic shifts in her vowel system.

The participant in the longitudinal study was a learner of German as a third language (L3), residing in Passo Fundo, a city in southern Brazil. Further details are provided in Section 3.2.

[9] Common European Framework of Reference for Languages (CEFR).

3.2 Language Background Questionnaire

Before the recordings, the participant completed a registration form with personal information and a language history questionnaire for bilingual or trilingual speakers. Both instruments followed the model used in Pereyron's dissertation (2017), based on Scholl and Finger[10] (2013). This provided details about the participant's linguistic background, including the age at which she began learning German, when she started using it actively, and the contexts of her learning (home, informal settings, or formal instruction).

3.3 *Corpus*

The instrument used in this study followed the model of Strange and Bohn (1998) in their acoustic-perceptual study of vowel dynamics and coarticulation in German. In their design, nonsense words (logatoms) were embedded in carrier sentences such as *"Ich habe /dVt/ gesagt"* ("I said dVt") (ibid., p. 490). Their logatom set included: *diet, ditt, deht, dett, däht, daht, datt, düht, dütt, döht, dött, duht, dutt, doht, dott*, with the vowels /iː, ɪ, eː, ɛ, ɛː[11], ɑː, a[12], yː, ʏ, øː, œ, uː, ʊ, oː, ɔ/.

In our study, however, we used the syllable structure hVt (voiceless glottal fricative [h], target vowel V, voiceless alveolar stop [t]) instead of dVt (voiced alveolar stop [d], vowel V, voiceless alveolar stop [t]). This phonetic-articulatory context ensures that the vowel, as the syllable nucleus, is minimally influenced by adjacent consonants in both articulation and acoustics. As Jørgensen (1969: 228) observes, "[h] has almost no influence on the following vowel". In technical terms, the vowel's central spectral information (its "target") remains relatively unaffected by coarticulation, since [h] is produced primarily at the glottal source (F0) without supraglottal articulations that could alter the acoustic space. For this reason, we adopted the hVt syllable, as in previous

[10] The Language History Questionnaire in Portuguese was designed for adult bilinguals with diverse linguistic experiences and proficiency levels, aiming to select participants for research on bilingualism.
[11] According to Strange and Bohn (1998: 503, fn. 1), the vowel /ɛ/ is considered a hypercorrect form for speakers of Northern German. The authors retained it in their corpus as an alternative response to the perception stimuli.
[12] Although descriptions of the German phonetic system by Kohler (1995, 1999), Rues et al. (2009), and Stock and Hirschfeld (1996 [2002]) standardized the transcription [aː, a] for both long/tense and short/lax low vowels, we retained the transcription used by Strange and Bohn (1998). Their system employs distinct symbols to differentiate the two vowels and serves as the basis for their acoustic analysis.

studies on German vowels and dialects (e.g., BOHN 2004; BOHN, POLKA 2001; HEERINGA, SCHOORMANN, PETERS 2015; POLKA, BOHN 1996, 2003, 2011; STRANGE, BOHN 1998; STRANGE ET AL. 2004; SCHOORMANN, HEERINGA, PETERS 2017).

Thus, we obtained the following list of AP logatoms (seven vowel contrast pairs: long vs. short): *hiet, hitt, heht, hett, häht, haht, hatt, hüht, hütt, höht, hött, huht, hutt, hoht, hott*, with the corresponding tense and lax vowels: /i, ɪ, e, ɛ, ɛː, ɑ, a, y, ʏ, ø, œ, u, ʊ, o, ɔ/. Each logatom was repeated five times, embedded in the carrier sentence *"Sage x heute"* (“Say x today”), resulting in 75 tokens (15 logatoms × 5 repetitions). In each slide, we included a real German word above the logatom sentence to guide vowel production. The real word contained the same stressed vowel as the target vowel in the nonsense word presented below. These real words, in the same vowel order as above, are: *sie; Tisch; geht; nett; Väter; das; haben; Schüler; Mütter; hören; Töchter; Stuhl; Mutter; wo; doch*.[13] Below is an example of a randomized[14] slide in which the word *haben* (meaning “to have” in German) contains the same long low vowel [aː] as the logatom *haht*.

Figure 4: Examples of *slides*[15] presented to the participant in the longitudinal study

Source: Authors’ own elaboration (2025)

In the same PowerPoint presentation, we first included a slide with instructions to be followed during the recordings. We also reiterate that we considered the grapho-phonemic relationships in the corpus for the analysis of both acoustic and graphemic data.

For audio recording, the participant used a mobile app on her iPhone (iOS 10.0) to record the sentences at home. The files, saved in .wav format, were then extracted and

[13] These words mean, respectively, *she* or *they*; *table, ‘goes’ (verb to go); cool; fathers; this; to have; student(-s); mothers; to hear; daughters; chair; mother; where; sure/of course*.
[14] The randomization of the AP words and sentences presented to the participant was carried out using the list randomization tool available for free at https://www.random.org/lists/
[15] The slide colors “green” and “blue” signaled slide transitions, helping the participant identify the items and reducing sample loss of AP vowels.

analyzed with the *Praat*[16] speech analysis software (BOERSMA, WEENINK 2020; version 6.1.09).

3.4 Brazilian speaker

According to the Language History Questionnaire for bilingual research (SCHOLL, FINGER 2013), the Brazilian female participant was 24 years old and enrolled at university at the time of the recording.

Regarding her linguistic background, the participant's first language (L1) is Brazilian Portuguese (BP), her second (L2) is English, and her third (L3) is Standard German. Portuguese was acquired at home and at school. English was learned in school and language courses from the age of 6 years 11 months, with fluency attained at 14. German (L3) was introduced only at age[17] 21.

For her self-assessed proficiency in additional languages, the participant used a 1–6 scale (1 = very low; 6 = proficient). In English, she rated herself 6 (proficient) in reading and listening, and 4 (good) in writing and speaking. In German, she rated herself 2 (low) across all skills: reading, writing, listening, and speaking.

3.5 Recording Schedule

Data were collected through monthly recordings[18], spaced three weeks apart, from July 2020 to May 2021. At the participant's request, and in line with COVID-19 health precautions, the recordings were conducted remotely. Each recording was sent asynchronously via WhatsApp in .wav format.

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[16] The Praat program can be downloaded for free from the website http://www.fon.hum.uva.nl/praat/.

[17] In line with CDST, all languages of an individual are interconnected and mutually influential. However, given the scope of this study, we focus exclusively on the development of Standard German. Future research will examine the simultaneous development of all the learner's languages.

[18] In this context, it should be noted that the Covid-19 pandemic prevented access to the university and the acoustic booth, and all recordings were conducted in accordance with the safety standards in place during the pandemic.

3.6 Analytical Procedures

3.6.1 Acoustic Analysis of the Data

The acoustic analysis in this study followed the methodological procedures of Strange and Bohn (1998), Junges (2012, 2023), De los Santos (2017), Pereyron (2017), and Schoormann, Heeringa, and Peters (2017). This section outlines the programs, tools, and methods adopted from these works. These include: *Praat* (BOERSMA, WEENINK 2020; an acoustic speech analysis program), *LPC*[19] (Linear Predictive Coding), *Microsoft Excel* (used to track rising and falling peaks in the longitudinal study and examine correlations between variables over time), and the open-source software *R*, used to generate vowel mean data.

Our focus on German vowels is justified by the laboratory setting of the research. The approach follows the phonetic-methodological framework of Xu (2010), which provides strong support for laboratory-based studies. Xu (2010) defends laboratory research by dispelling myths about recorded speech and highlighting its advantages over spontaneous data. According to Xu (2010: 332)[20], "no matter how unnatural the examined speech samples may be, the real objective is always to understand the kind of speech that occurs outside the lab", much like how chemistry and physics rely on test tubes, which are not the actual objects of study, but tools to understand natural phenomena.

In this laboratory context, the recorded stimuli were transferred to Praat (version 6.1.09), developed by Boersma and Weenink at the Phonetic Sciences Laboratory, University of Amsterdam. The stimuli were manually segmented using both waveform and spectrogram displays in Praat. No scripts were used in the measurement process, aligning our methodology with Pereyron (2017).

[19] *Linear Predictive Coding* (LPC) is a class of methods used to obtain a spectrum. It predicts nearby values from a linear combination of weighted samples (KENT, READ 2015: 491). LPC enables visualization of formant frequency traces overlaid on the spectrogram and calculation of formant frequency, amplitude, and bandwidth at specific points in the utterance (BARBOSA, MADUREIRA 2015: 157). Lima Júnior (2016: 153) defines LPC as "a predictive algorithm that decomposes the acoustic signal by estimating the resonances generated in the vocal tract."

[20] Xu's (2010) article is central to our methodology, serving both as a theoretical foundation and as guidance for the recordings conducted.

Based on this analysis, we manually segmented[21] the vowels in Praat by marking the first and second regular pulses of the waveform corresponding to the target vowel and the darker regions of the spectrogram. The vowel's steady state and formant frequencies were then determined using the LPC method. As Pereyron (2017: 91) notes, "the central portion of the vowel corresponds to its most stable region and should not be heavily influenced by the coarticulation of adjacent sounds." Similarly, Clark and Yallop (1995) define the steady state as the interval when the tongue, lips, and jaw reach a stable configuration, often referred to as the "target configuration". Following this approach, we adjusted the final portion of each segmented vowel in Praat's textgrids to remove residual voicing, ensuring that the segment did not extend beyond the final zero-crossing of the waveform, visible in the fading of spectrogram bands over time[22].

Based on this process, we measured F1, F2, and F3 using Praat. The formant frequency values were then plotted using the tools available on the *Visible Vowels*[23] website (HEERINGA, VAN DE VELDE 2018, 2023).

3.6.2 Monte Carlo Analyses

To carry out the Monte Carlo analyses, we identified significant performance peaks using the PopTools[24] add-on (free) in Microsoft Excel, entering the data into spreadsheets based on Van Dijk, Verspoor, and Lowie (2011). The procedure followed the methodological steps described by Schereschewsky (2021) and Junges (2023). Identifying significant performance peaks aims to detect "sudden jumps" in the system, which, due to their high variability, can indicate destabilization and the emergence of a new pattern in the learner's linguistic system.

In Excel, we displayed the maximum (for rising peaks) or minimum (for falling peaks) distances between moving averages, calculated with differences of two to six

[21] "Segmentation: the delineation of successive sound segments in a speech signal. Typically, segmentation yields units such as phonemes, allophones, or some other phonetic segment" (KENT, READ 2015: 494).
[22] According to Pereyron (2017: 91), "neglecting this step can alter the formant values of rounded vowels produced by male speakers, since the software may identify only one formant instead of two in the low-frequency range. As a result, a vowel such as [uː] may display an F1 value of 500 Hz rather than the expected 300 Hz reported in the literature."
[23] Access via the website: https://www.visiblevowels.org/#load_file
[24] In order to use *PopTools*, we had to install a Windows 10 virtual machine using *VirtualBox (version 6.1)* by Oracle VW, as it was not possible to run PopTools on standard Microsoft Excel without it.

points ("2-step difference" to "6-step difference"). The greatest distance among these moving averages was used as the empirical criterion to identify the most significant performance peak.

In the final stage, following Yu and Lowie (2019), we ran Monte Carlo simulations with 10,000 replications to identify rising or falling peaks. This procedure enabled the detection of abrupt increases or decreases in the moving average values of formants and vowel durations across two sampling rounds. As in Schereschewsky (2021), we applied Monte Carlo simulations to estimate the likelihood of rising peaks (≥) in the investigated vowels[25].

Based on this statistical process, we conducted 180 Monte Carlo simulations related to the participant's vowel data: 45 simulations for the mean values of F1, F2, and F3 (15 vowels per formant); 45 simulations for Standard Deviation (SD) values for F1, F2, and F3 (15 vowels per formant); 45 simulations for minimum values of $F1^{min}$, $F2^{min}$, and $F3^{min}$ (15 vowels per formant); 45 simulations for maximum values of $F1^{max}$, $F2^{max}$, and $F3^{max}$ (15 vowels per formant).

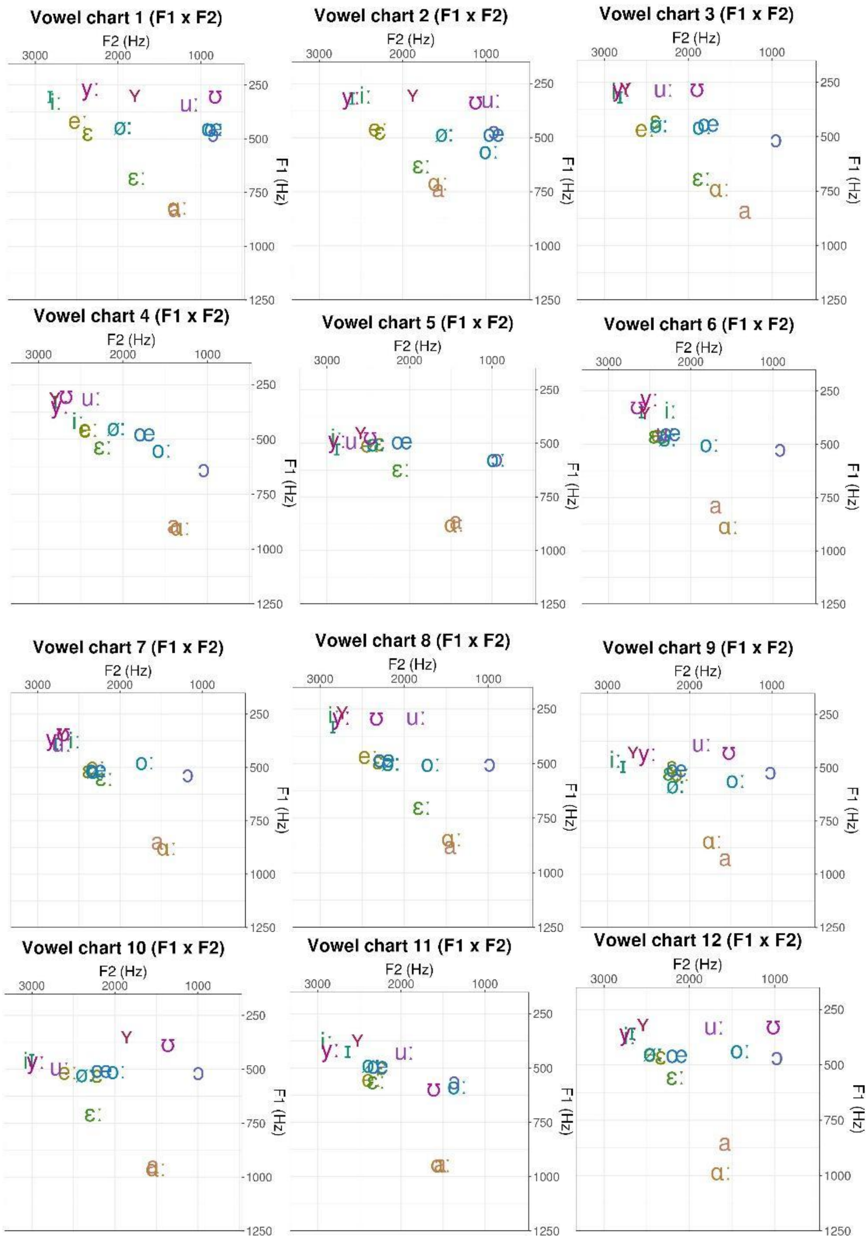
4 Description and Analysis of the Data

4.1 Description of the speaker's individual trajectory

In this subsection, we examine the acoustic spaces across twelve data collection sessions (Recordings 1–12), focusing on average vowel values along the F1 and F2 axes. The vowel charts below display the results for each session.

[25] Overall, the Monte Carlo simulation allowed us to determine whether the variability observed in longitudinal performance reflected random fluctuation or the natural instability of the system, or whether it was triggered by the acquisition of a new pattern.

Figure 5: Two-Dimensional Acoustic Spaces (F1 x F2), Mean Graphs[26], Collections 1-12



Source: Authors' own elaboration (2025)

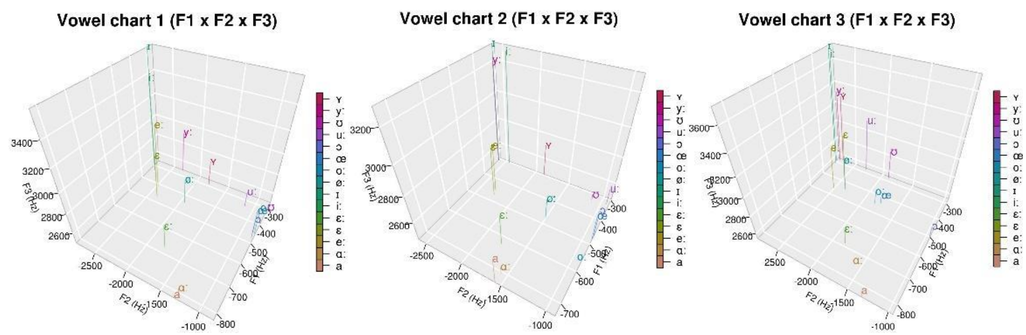
The graphs above depict the F1–F2 acoustic space of a Brazilian speaker's realizations of Standard German vowels. Across sessions, the speaker's vowel productions shift within the acoustic space. These shifts do not fully align with the native

[26] For higher image quality, all acoustic spaces (plots) can be viewed and downloaded via the link **Informante brasileira** (hold Ctrl + click on 'Plotagens'). On the page, two folders are available: one containing the two-dimensional plots for the F1 and F2 axes, and the other with three-dimensional plots for the F1, F2, and F3 axes.

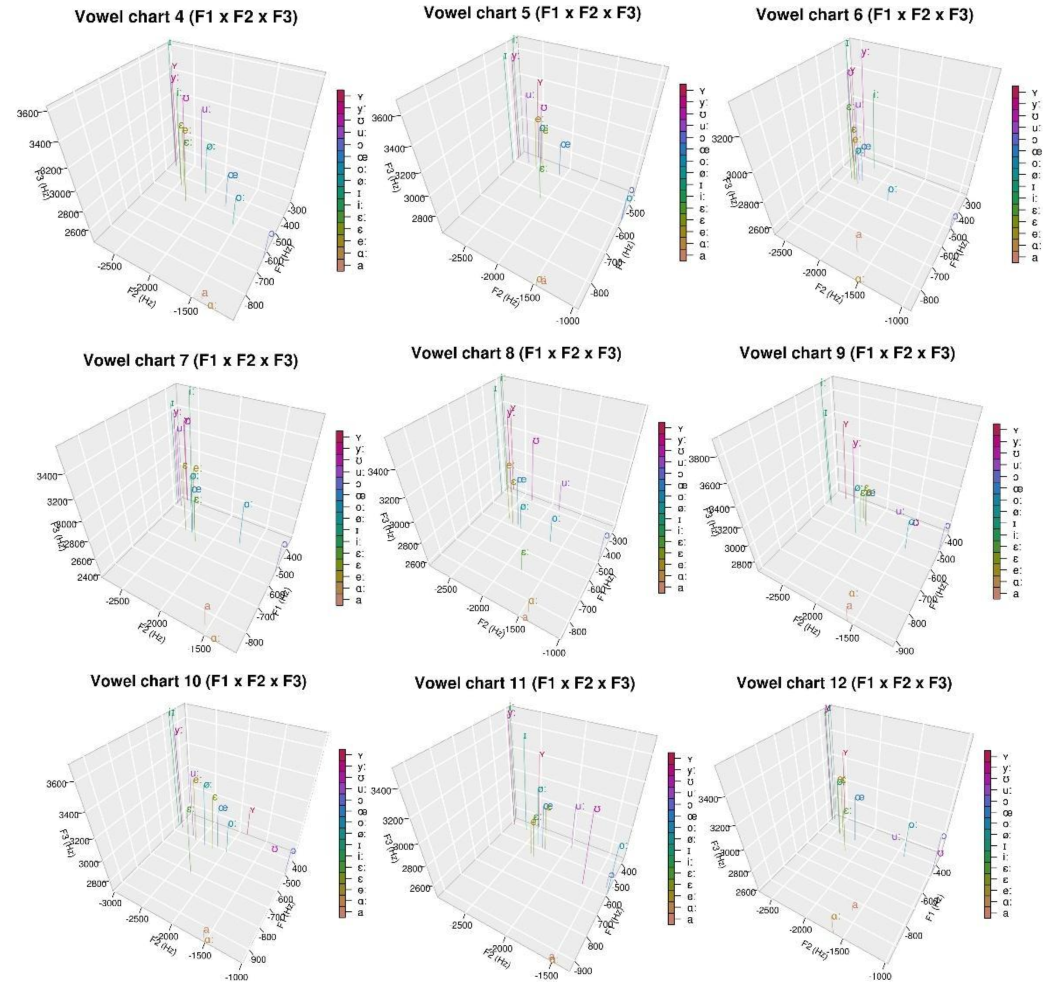
pattern described in the theoretical framework, but they indicate emerging strategies to readapt the vowel system and preserve distinctions between functional language categories — an issue to be explored in the next sections.

In addition to the two-dimensional (F1–F2) graphs, we present three-dimensional graphs incorporating the average F1, F2, and F3 values for the speaker's productions of Standard German vowels, starting with Figure 6.

Figure 6: Three-Dimensional Acoustic Spaces (F1 x F2 x F3), Mean Graphs[27], Collections 1–12



[27] Access to the graphs is available through the same link **Informante brasileira**, by clicking on the folder 'F1xF2xF3' (2 Mean Graphs).



Source: Authors' own elaboration (2025)

These graphs display the acoustic configuration of the vowels, with the Y- and X-axes representing the first and second formant frequencies (F1 and F2) and the Z-axis representing the third formant (F3). The third formant typically shows much higher frequencies than the second. As in the previous F1–F2 graphs, the speaker's productions reveal acoustic variability across sessions, reflected in the F3 dispersion plots.

4.2 Analysis of the speaker's individual trajectory

Based on the empirical data, we identified significant variability peaks over time by applying Monte Carlo simulations. These statistical tests highlight abrupt changes, either increases (rising peaks) or decreases (falling peaks), in the learner's developmental trajectory.

According to the principles of CDST, significant peaks signal system destabilization, a moment of “chaos”, indicating a high degree of variability across different stages of data collection. This variability suggests system reorganization, characteristic of emerging linguistic patterns (Verspoor, Lowie, & De Bot, 2021).

We analyzed the formant data (F1, F2, F3) for each vowel produced by the speaker, applying Monte Carlo simulations.

4.2.1 First Formant (F1)

Table 2 presents the significant peaks in F1 values, extracted from moving averages for each vowel (rows) and statistical measure (columns). The legend is as follows: each point (e.g., Point 2) marks a moving average between two collection sessions (e.g., Sessions 1 and 2) where a significant peak occurred for a given vowel. The first point indicates the base of the peak, and the second its apex. Blank cells indicate vowels without significant values for any measure. Blue cells represent vowels with no significance across the four statistical measures, while yellow cells highlight vowels that displayed significant peaks. The arrows ↗ and ↘ denote rising and falling peaks in the dynamic trajectories of the vowels, respectively.

Table 2: Statistically significant rising ↗ and falling ↘ peaks in F1 values across data collection sessions

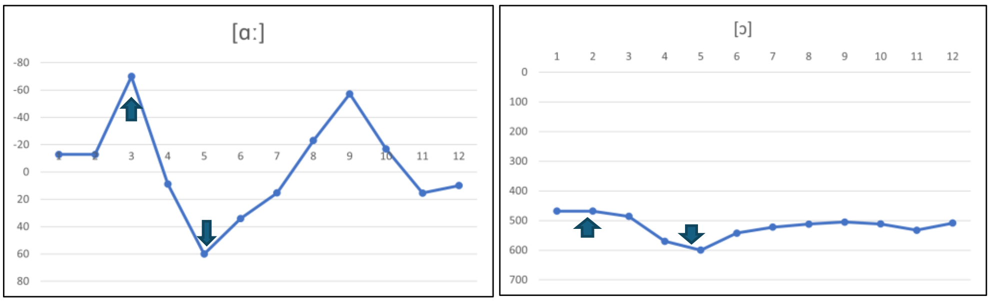
↗↘	Médias	*Pontos*	DP	*Pontos*	MÍN	*Pontos*	MÁX	*Pontos*
[iː]								
[ɪ]					↗	2 e 5		
[yː]								
[ʏ]								
[eː]								
[øː]								
[ɛ]								
[ɛː]							↘	2 e 5
[œ]								
[a]							↘	4 e 8
[ɑː]	↗	3 e 5						
[ɔ]	↗	2 e 5						
[oː]								
[uː]			↗↘	3 e 6/6 e 9			↗	4 e 6
[ʊ]								

Source: Authors’ own elaboration (2025)

In Table 2, we see the peaks related to the mean, SD, and minimum and maximum[28] values of F1 for each analyzed vowel (a total of 15 vowels).

We identified a total of eight (8) peaks - five rising ↗ and three falling ↘: The vowel [ɑː] exhibited a rising peak ↗ between Points 3 (Sessions 2 and 3) and 5 (Sessions 4 and 5), with a *p*-value of 0.04. The vowel [ɔ] showed a rising peak ↗ between Points 2 (Sessions 1 and 2) and 5 (Sessions 4 and 5), with a *p*-value of 0.03. Below, we display the moving average graphs for F1 mean values. The lines on the left represent inverted F1 values (Hz), based on the vertical axis of the vowel space, while the top columns indicate the moving average point numbers. In these graphs, an upward arrow ⬆ below the point indicates the base of the peak, and a downward arrow ⬇ above it marks the *peak's apex* - used consistently throughout the peak analysis in this article.

Figure 7: Rising peaks ↗ in F1 mean values for the vowels [ɑː] and [ɔ]



Source: Authors' own elaboration (2025)

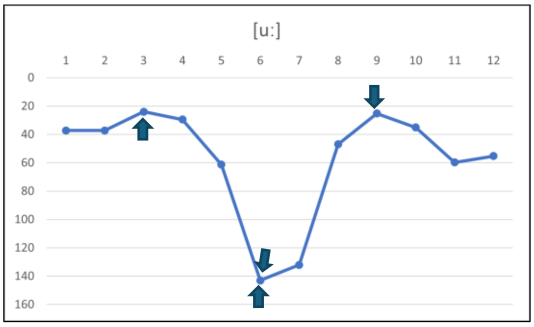
From these F1 mean value graphs, we observe significant peaks at Points 3 and 5 for both vowels. Since each point represents a moving average across two collection sessions, the inferential variations occurred between Sessions 2 - 3 and 4 - 5, respectively.

Next, we identify significant rising ↗ and falling ↘ peaks in the SD F1 values, observed only for the high back long vowel [uː]: The rising peak ↗ occurred between Points 3 (Sessions 2 and 3) and 6 (Sessions 5 and 6), with a *p*-value of 0.02. The falling

[28] Due to page limitations in this study, the minimum and maximum values were presented in *Tables 2*, *3*, and *4*, corresponding to the first three formants (F1, F2, F3) of the speaker's vowels; however, although these analyses were conducted, they were not included in the text.

peak ↘ appeared between Points 6 (Sessions 5 and 6) and 9 (Sessions 8 and 9), with a *p*-value of 0.03.

Figure 8: Rising ↗ and falling ↘ peaks in F1 Standard Deviation (SD) values for the vowel [u:]



Source: Authors' own elaboration (2025)

In this graph, we observe the progression from the initial peak to the central peak and, subsequently, to the final one, with Point 6 functioning both as the apex for the rising peak ↗ between Points 3 and 6 and as the base for the falling ↘ peak between Points 6 and 9.

4.2.2 Second Formant (F2)

Table 3 presents the statistically significant peaks in F2 values, derived from moving averages for each vowel (rows) and statistical measure (columns).

Table 3: Statistically significant rising ↗ and falling ↘ peaks in F2 values across data collection sessions

↗ ↘	Médias	*Pontos*	DP	*Pontos*	MÍN	*Pontos*	MÁX	*Pontos*
[i:]								
[ɪ]								
[y:]							↗	2 e 5
[ʏ]	↗	2 e 4			↗	2 e 4	↗	2 e 5
[e:]								
[ø:]	↗	3 e 6					↗	8 e 11
[ɛ]								
[ɛ:]								
[œ]	↗	2 e 7	↗	2 e 5	↗	5 e 7	↗	2 e 4
[a]					↗	3 e 7		
[ɑ:]			↘	3 e 8				
[ɔ]								
[o:]							↗	2 e 4
[u:]	↗	2 e 5						
[ʊ]	↗	2 e 7						

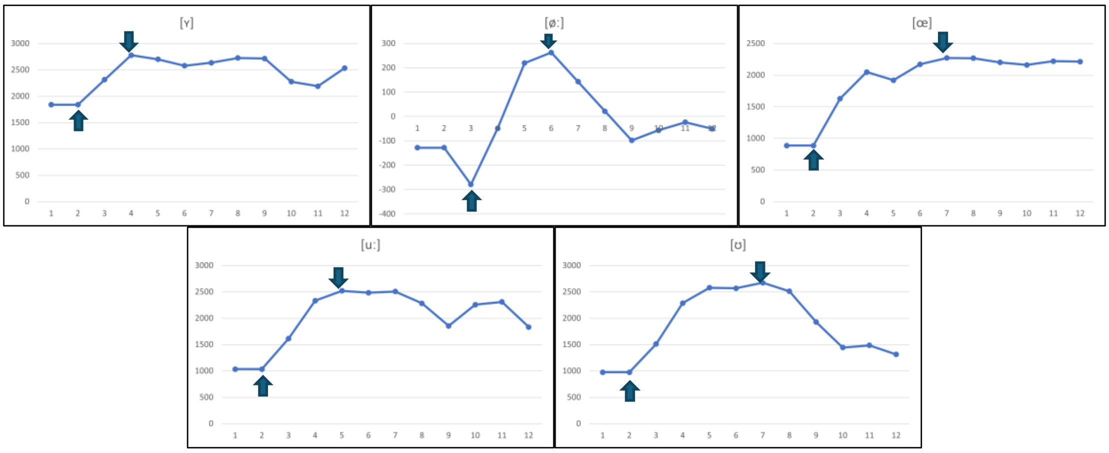
Source: Authors' own elaboration (2025)

In Table 3, we observe peaks corresponding to the mean and SD values of F2 for each of the 15 vowels analyzed, totaling fifteen (15) statistically significant peaks. We begin with the mean values.

Five vowels showed significant rising peaks ↗ in their mean F2 values: [ʏ], [øː], [œ] (three front vowels), and [uː], [ʊ] (two back vowels). The vowel [ʏ] presented a rising peak ↗ between Points 2 (Sessions 1 and 2) and 4 (Sessions 3 and 4), *p* = 0.02. [øː] showed a rising peak ↗ between Points 3 (Sessions 2 and 3) and 6 (Sessions 5 and 6), *p* = 0.00. [œ] had a peak a rising peak ↗ between Points 2 (Sessions 1 and 2) and 7 (Sessions 6 and 7), *p* = 0.05. [uː] presented a rising peak ↗ between Points 2 (Sessions 1 and 2) and 5 (Sessions 4 and 5), *p* = 0.04. [ʊ] also showed a rising peak ↗ between Points 2 (Sessions 1 and 2) and 7 (Sessions 6 and 7), *p* = 0.04.

These rising peaks ↗ are shown in the next moving average graphs below.

Figure 9: Rising peaks ↗ in mean F2 values for vowels [ʏ], [øː], [œ], [uː], and [ʊ]



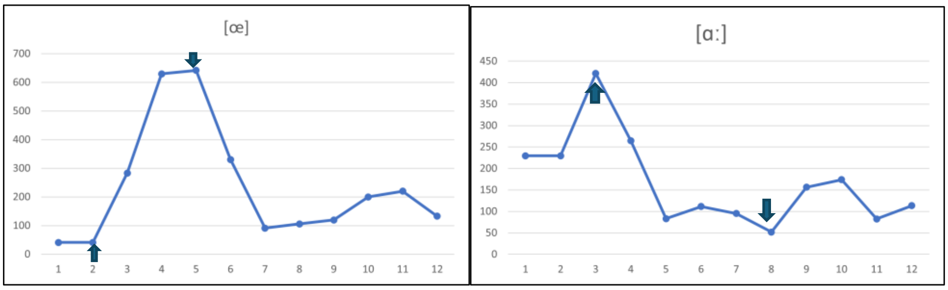
Source: Authors' own elaboration (2025)

Because peaks result from differences between two points — each derived from a moving average across sessions — rising peaks indicate a shift toward higher F2 values. This shift suggests production in more fronted positions within the vowel space. Notably, three of these vowels ([ʏ], [øː], [œ]) are front rounded vowels. This pattern may represent a compensatory strategy: faced with difficulties attaining native-like F3 values, learners may rely on F2 modification to signal vowel distinctions, a pattern supported by studies on acoustic cue trade-offs.

All the observed peaks begin early in the data collection process (Sessions 1-5), and with the exception of [œ] and [ʊ], the apex also occurs within the first six sessions. This suggests that for this learner, changes in F2 occurred early - possibly compensating for limited F3 control. These findings support the idea that F2 may play an important role in the initial developmental phase of vowel learning, helping the learner establish contrasts in the different vowel systems.

Regarding SD values, only two vowels exhibited statistically significant peaks: [œ] showed a rising peak ➚ between Points 2 (Sessions 1 and 2) and 5 (Sessions 4 and 5), $p = 0.00$. [ɑː] displayed a falling peak ➘ between Points 3 (Sessions 2 and 3) and 8 (Sessions 7 and 8), $p = 0.01$.

Figure 10: Rising ➚ and falling ➘ peaks in F2 Standard Deviation (SD) values for vowels [œ] and [ɑː]



Source: Authors' own elaboration (2025)

4.2.3 Third Formant (F3)

Table 4 presents the significant F3 peaks, derived from moving averages for each vowel (rows) and each statistical measure (columns).

Table 4: Statistically significant rising ↗ and falling ↘ peaks in F3 values across data collection sessions

↗↘	Médias	*Pontos*	DP	*Pontos*	MÍN	*Pontos*	MÁX	*Pontos*
[iː]								
[ɪ]								
[yː]								
[ʏ]	↗	2 e 5	↗	5 e 10				
[eː]								
[øː]								
[ɛ]							↗	2 e 4
[ɛː]					↗	8 e 10		
[œ]								
[a]								
[ɑː]								
[ɔ]								
[oː]					↗	6 e 10		
[uː]								
[ʊ]	↗	2 e 7			↘	8 e 10		

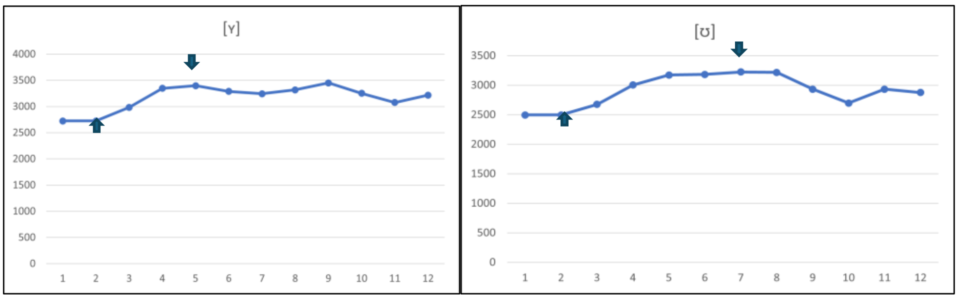
Source: Authors' own elaboration (2025)

This table reveals seven (7) significant peaks for the mean, SD, and minimum/maximum values of F3 across 15 vowels. We'll begin with the mean values.

Only two rounded vowels showed statistically significant rising peaks in their mean F3 values: [ʏ] exhibited a rising peak ↗ between Points 2 (Sessions 1 and 2) and 5 (Sessions 4 and 5), $p = 0.05$. [ʊ] displayed a rising peak ↗ between Points 2 (Sessions 1 and 2) and 7 (Sessions 6 and 7), $p = 0.01$.

Next, we will look at the moving mean graphs, in relation to the development trajectory concerning both vowels.

Figure 11: Rising peaks ↗ in mean F3 values for vowels [ʏ] and [ʊ]

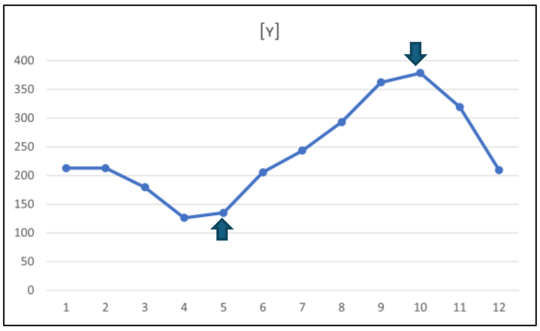


Source: Authors' own elaboration (2025)

Both peaks have their bases in Session 2, indicating that changes in F3 began early. However, as previously discussed, the learner made more pronounced changes in F2 than F3 at this stage, possibly because she had more difficulty controlling F3. This suggests a compensatory strategy using F2 to handle contrasts that would typically rely more on F3.

Additionally, the vowel [ʏ] exhibited another significant rising peak ↗ in its SD values between Points 5 (Sessions 4 and 5) and 10 (Sessions 9 and 10), $p = 0.04$.

Figure 12: Rising peak ↗ in F3 Standard Deviation (SD) values for vowel [ʏ]



Source: Authors' own elaboration (2025)

The peak above results from a moving average across Points 5 and 10, covering Sessions 4–5 and 9–10. It indicates increased individual variation in the learner's production of [ʏ] over time.

5 Final considerations

The vowels produced by the learner of Standard German as an additional language occupy an acoustic space characterized by high variability. Rather than fixed positions, they fluctuate within a viable range for forming vowel categories, regardless of alignment with native acoustic standards. Each vowel nonetheless represents a functional category (FLEGE, 1995; FLEGE, BOHN 2021).

Regarding formants (F1, F2, F3), and in line with our first goal, we conclude that F2 showed the most statistically significant peaks, with nine of fifteen vowels varying in F2. In contrast, five vowels varied significantly in F1 and F3. Most F2 changes occurred early (Sessions 1–5), predominantly in rounded vowels, suggesting that the learner used F2 as a compensatory acoustic cue, particularly to convey lip rounding (HOLT, LOTTO 2006; LEHET, HOLT 2016).

Thus, the learner likely relied on alternative acoustic cues, specifically by adjusting the front–back (X-axis) dimension, to distinguish between rounded and unrounded vowels. The vowels that showed the most significant peaks were: Front vowels: [yː], [ʏ], [øː], [œ]; Low vowels: [a], [ɑː]; Back vowels: [oː], [uː], [ʊ]. This suggests the learner actively worked to preserve functional vowel distinctions, even when the strategies used diverged from native norms.

From a CDST perspective, this case represents an individual developmental process not generalizable to all learners (LOWIE, VERSPOOR 2015). It reflects interindividual linguistic variability, particularly in the formant dimensions of German vowels (VERSPOOR, LOWIE, DE BOT 2021).

Regarding the second goal, variability reveals that the learner employed different strategies to build functional vowel contrasts. Although the learner's system does not fully match native acoustic norms, it is clearly developing, with a strong drive to maintain functional category distinctions. This is central to CDST, which emphasizes process-oriented analysis over outcome-based evaluation (LOWIE 2017). Rather than focusing on whether the learner has achieved the native standard, what matters here is how the learner progresses and which strategies are adopted to preserve the system's distinctiveness and functionality.

In summary, this study contributes to both theoretical and empirical linguistic research. Theoretically, it highlights how variability can foster new learning even when results diverge from native norms. Empirically, it offers descriptive insights into learning German as an additional language, demonstrating emerging system strategies and the developmental trajectory of a Brazilian learner.

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Data availability statement

The data supporting this research can be obtained by consulting the author.