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Neural network-based measure of consonant lenition in Parkinson's Disease

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This study investigated the effects of Parkinson's disease (PD) and various linguistic factors on the degree of lenition in Spanish stops. Lenition was estimated from posterior probabilities calculated by recurrent neural networks trained to recognize sonorant and continuant phonological features. Firstly, individuals with PD exhibited a higher degree of lenition in their voiceless stops compared to healthy controls, suggesting that PD significantly impacts the articulatory control of stops, resulting in more pronounced lenition. Secondly, lenition was significantly more advanced for dental stops than bilabial stops, further suggesting that the muscles controlling tongue tip movement are more affected than those involved in lip movement among PD patients. These findings are consistent with previous literature. Importantly, the results highlight the sensitivity of Phonet in quantifying lenition in this group of PD patients.

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1. INTRODUCTION

Parkinson’s disease (PD), first described in 1817 (Parkinson, 1817), is now the second most common progressive neurodegenerative disorder after Alzheimer’s disease (Schapira, 1999; Nussbaum & Ellis, 2003), with a higher prevalence among men than women starting at the age of 50 (Rocca, 2016). The Global Burden of Disease 2016 study (Dorsey et al., 2018) estimated that the number of PD patients has more than doubled from 2.5 million in 1990 to 6.1 million in 2016 due to longer life expectancy, extended duration of the disease, and changes in environmental and social risk factors (Rocca, 2016). If this estimate is accurate and the trend continues, the number of PD patients will reach 12 million by 2050 (Rocca, 2016; Dorsey et al., 2018). In the USA, it is estimated that approximately 1.5 million people have PD, with about 40,000 new cases diagnosed every year, resulting in an estimated total annual fiscal burden of approximately $23 billion (Krauss & Jankovic, 1996; Tapper, 1997). In addition, COVID-19 has had a significant impact on PD patients, exacerbating motor and non-motor symptoms (Cartella et al., 2021). Furthermore, a few cases of parkinsonism following COVID-19 infection have been reported, suggesting that the SARS-CoV-2 virus can gain access to the CNS, affecting midbrain structures and leading to neurologic signs and symptoms (Cohen et al., 2020; Méndez-Guerrero et al., 2020; Faber et al., 2020).

Parkinson's disease is characterized by a gradual decline in dopaminergic neurons, primarily located in the substantia nigra pars compacta. It is prevalent in around 1–2% of individuals aged 60 years and above (Marsden, 1994). The progressive decline in dopaminergic function leads to various motor and non-motor challenges for individuals with PD. In addition to prominent symptoms like muscle stiffness, tremors, slowed movement, and balance issues, many patients also experience a distinct speech alteration known as hypokinetic dysarthria. Research suggests that around 70% of PD patients exhibit dysarthria (Hartelius & Svensson, 1994), characterized by a reduction in voice strength and difficulty initiating speech. Dysarthria can manifest at any point in the disease's progression and typically worsens as the condition advances, leading to a gradual decline in communication abilities (Ho et al., 1998; Mutch et al., 1986).

Hypokinetic dysarthria involves a spectrum of speech impairments affecting various aspects of speech production, such as breathing, phonation, articulation, and prosody (Skodda, 2009). These impairments can manifest individually or in combination. A common feature is hypophonia, characterized by reduced voice volume and decay, resulting in quieter and less distinct speech (Ho, Iansek, & Bradshaw, 2001). Additionally, dysphonia may occur, presenting as a breathy, hoarse, or harsh voice quality, further complicating speech clarity (Baumgartner, Sapir, & Ramig, 2001). Hypokinetic articulation refers to difficulties in forming precise consonant and vowel sounds due to restricted articulatory movements. Lastly, dysprosodia involves abnormalities in voice pitch inflections, leading to monotone or hurried speech patterns, along with dysfluency, hesitancy, or speech patterns resembling stuttering (Forrest, Weismer, & Turner, 1989). Together, these characteristics underscore the complexity and challenges of hypokinetic dysarthria in individuals with Parkinson's disease.

Previous research on speech kinematics in PD suggests a reduction in articulator displacement compared to healthy older adults (Caligiuri, 1988; Hirose et al., 1981, 1982). Investigations into movement initiation challenges at the laryngeal level have focused on the voice onset time (VOT) of stops produced by individuals with PD. However, the findings have been inconsistent. Some studies have noted longer VOT durations in PD (Forrest, Weismer, & Turner, 1989; Novotný, Rusz, Cmejla, & Ruzicka, 2014), while others have observed no significant changes or even shorter VOT (Fischer & Goberman, 2010; Ravizza, 2003). These conflicting results may stem from differences in speaking rate (Volaitis & Miller, 1992). Attempts to use the VOT ratio, a measure unaffected by rate, have not fully resolved the contradictory findings (Fischer & Goberman, 2010; Novotný et al., 2014). Rather than further examining VOT, this study shifts focus to explore alternative dimensions of consonant imprecision, particularly the weakening observed in stop consonants.

Consonant weakening, or lenition, is a common phonological phenomenon in natural languages. For example, in most, if not all, dialects of Spanish, the voiced stops /b, d, g/ typically transform into voiced fricatives [β, ð, ɣ] in certain contexts, such as between vowels and following vowels. However, they retain their stop quality [b, d, g] after pauses, nasal sounds, and for /d/, after /l/. This phenomenon, known as spirantization, is part of a broader process called lenition, which involves the weakening of consonants. While it was previously believed that this weakening led to the production of fricatives (e.g., Harris, 1969; Navarro Tomás, 1977; Lozano, 1979; Mascaró, 1984), recent studies propose that these sounds are closer to approximants [β̞, ð̞, ɣ̞] (e.g., Martínez Celdrán, 1991; Romero, 1995), indicating a more nuanced and gradual distribution influenced by factors like vowel quality, stress, and speaking pace. Additionally, in some Spanish dialects, voiceless stops also undergo lenition, transitioning into voiced sounds.

Using a deep neural network method known as 'Phonet,' this research seeks to measure the extent of lenition in voiced and voiceless stop consonants produced by both Parkinson's disease (PD) patients and healthy control subjects who are native Spanish speakers.

A. PHONET

Phonet, introduced by Vásquez-Correa et al. (2019) is a bi-directional recurrent neural network model, trained to discern input phones and assign them to various phonological categories determined by phonological features (such as sonorant, and continuant). This semi-automatic tool requires a segmentally aligned acoustic corpus, employing forced alignment. The data fed into Phonet comprises log energy distributed across triangular Mel filters. This data is calculated from 25-ms windowed frames of each 0.5-second segment of the input signal (for more information, refer to Vásquez-Correa et al., 2019). Post-training, the model can compute posterior probabilities for the phonological features of target segments. It has proven highly accurate in measuring the extent of lenition in Spanish (Tang et al., 2023; Wayland et al., 2023a; Wayland et al., 2022), in intoxicated speech (Wayland et al., 2023 b, c), and in modeling the speech impairments of patients diagnosed with Parkinson's disease (Vásquez-Correa et al., 2019;). Phonet offers flexibility for customization with different sets of phonological features and acoustic representations. In this particular investigation, our attention is directed towards evaluating the probability of the phonological features [continuant] and [sonorant] to gauge the degree of lenition. The structure and training methodology of Phonet is described in Vásquez-Correa et al. (2019), with further information on model training for the current study provided by Tang et al. (2023). In brief, the model was trained on a corpus of Argentinian Spanish. Altogether, 23 phonological classes of Spanish including sonorant and continuant were trained by a bank of 23 Phonet networks and 26 phonemes by one network. The model was highly accurate in detecting different phonological classes, with unweighted average recall (UAR) ranging from 94% to 98%. UAR for sonorant and continuant features were 97% and 96%, respectively. The model showed varying accuracy for individual phoneme detection, from 42% for /spn/ to 96% for /f/.

2. THIS STUDY

This study extends the Phonet model to investigate the degree of lenition of Spanish stops among PD patients and normal control subjects, both of whom are native speakers of Colombian Spanish.

A. METHODS

I. MATERIALS

The speech data under examination was taken from the PC-GITA corpus (Orozco-Arroyave et al., 2014). The corpus contains speech recordings of native Colombian Spanish speakers. The speakers consist of 50 patients with PD and their respective healthy controls, matched by age and gender. The demographic data of the subjects are shown in Table 1. It provides a summary of the age, gender, Unified Parkinson's Disease Rating Scale (UPRDS) (Stebbing and Goetz, 1998), the speech component of UPRDS (UPDRS-Speech), Hoehn & Yard scale (H&Y) (Hoehn and Yahr, 1967) and time after the PD diagnosis of the patients, and the age and gender of the healthy controls.

Table 1. Demographic data of subjects included in the study. Age, Gender, UPDRS, UPDRS-Speech, H&Y, and time after the PD diagnosis of the patients. PD: Parkinson's Disease, HC: Healthy Controls.

Group	Age (year)	Male/ Female	UPDRS	UPDRS-speech	H&Y	Time after PD diagnosis (years)
PD	61.02 ± 9.44	25/25	37.66 ±18.32	1.34 ± 0.82	2.19 ± 0.66	11.24 ± 9.93
HC	60.98 ± 9.46	25/25	N/A	N/A	N/A	N/A

The target consonants for this study were intervocalic Colombian Spanish stops /b, d, g, p, t, k/ produced in 10 sentences by the 50 PD patients and the 50 HCs in a sentence repetition task and syllable-initial /p, t, k/ from a rapid repetition of syllables /pa, ta, ka/ (diadochokinetic evaluation) task (see Orozco-Arroyave et al., 2014, for details). The sentences were not specifically designed to elicit the target stop consonants. The stimuli were forced-aligned using the Montreal Force Aligner (version 2.0) (McAuliffe et al., 2017).

The distribution of the target consonants across the two speaker groups is shown in Tables 2 and 3 below.

Table 2. Token distribution from the sentence production task

Group	/b/	/d/	/g/	/p/	/t/	/k/
PD	42	52	19	51	33	46
HC	53	51	20	49	36	45

Table 3. Token distribution from the rapid syllable repetition task.

Group	/p/	/t/	/k/
PD	473	481	477
HC	423	448	445

II. STATISTICAL ANALYSES

The sonorant and continuant posterior probabilities generated by the Phonet model served as dependent variables in the linear mixed-effects regression models. For the /b, d, g, p, t, k/ data set from the sentence production task, the models' fixed variables were Group (PD or HC), voicing (voiced or voiceless), stop position (word-initial or word-medial), place of articulation (bilabial, dental, or velar), syllable stress (unstressed or stressed), and preceding and following vowel height (close, mid, open). Group and Place of Articulation or POA were the fixed variables in the model for the /p, t, k/ data set from the rapid syllable repetition task.

Deviation coding was used for the categorical variables group, word position, syllable stress and voicing while forward difference coding was used for the place of articulation (bilabial > dental > velar) and preceding and following vowel height (close > mid > open). The analyses were conducted using the *lmer* function from the *lme4* package (Bates et al., 2015) in R (R Core Team, 2022). For each data set, two models were performed, one for each dependent variable (continuant posterior probability and sonorant posterior probability). Each model also included interactions between Group and the other factors. After evaluating multiple model structures through maximum likelihood estimation, the best-fit model structure for each dependent variable was determined. The formulae for the model for the two data sets (sentence production and rapid syllable repetition) are as follows:

DEPENDENT VARIABLES ~ Group + stress + voicing + place + position + preceding_vowel + following_vowel + group:stress + group:voicing + group:place + group:preceding_vowel + group:following_vowel + group:position + (1|Speaker) + (1|Word)

DEPENDENT VARIABLES ~ Group + Place: Group + Place + (1 | Speaker).

Specifically, the models for the /b, d, g, p, t, k/ data set assess the seven main effects: Group, Stress, Voicing, Place of articulation, Position (word-initial or word-medial), Preceding vowel, and Following vowel, along with six interaction terms with Group (e.g., Group x Voicing, Group x Place of articulation, Group x Preceding vowel, Group x Following vowel, and Group x Position). Additionally, we include Speaker and Word as random intercepts. The models for the /p, t, k/ data set evaluate the main effects of Group and Place of articulation and their interaction, with Speaker as a random intercept. Post-hoc comparisons of the interaction terms were conducted using the *emmeans* package, employing Tukey's HSD method for p-value adjustment (Lenth et al., 2021). The results of the best-fit model for each dependent variable will be reported in the following section.

B. RESULTS

I. SENTENCE PRODUCTION

Figure 1 visualizes the mean continuant posterior probability for voiced and voiceless stops (right panel) in word-initial and word-medial positions (left panel) for the PD and the HC subjects from the sentence production task. The results of the linear mixed-effects regression model revealed significant main effects of Voicing [$\beta = -0.343$, $t = -12.144$; $p < 0.001$] with voiced stops being significantly more lenited than voiceless stops. The main effect of the Group was non-significant, and neither were the interactions.

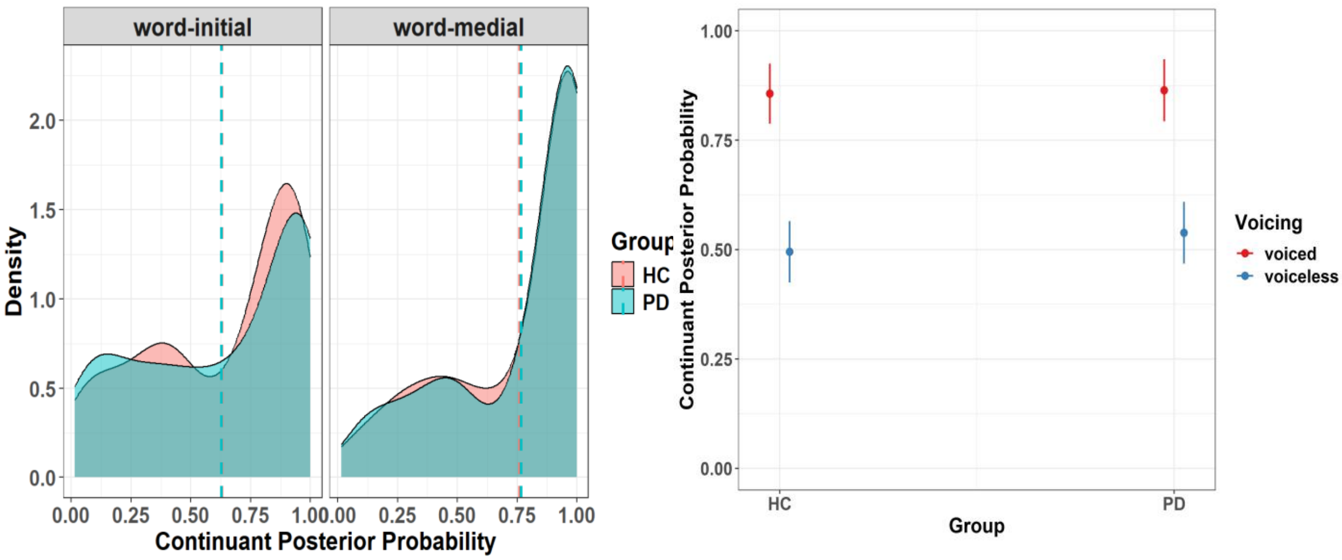

Figure 1. Mean continuant posterior probabilities Combian Spanish voiced and voiceless stops in word-initial and word-medial positions produced by PD patients and healthy control subjects.

Figure 2 shows the mean sonorant posterior probability for voiced and voiceless stops (right panel) in word-initial and word-medial positions (left panel) for the PD and the HC subjects from the sentence production task.

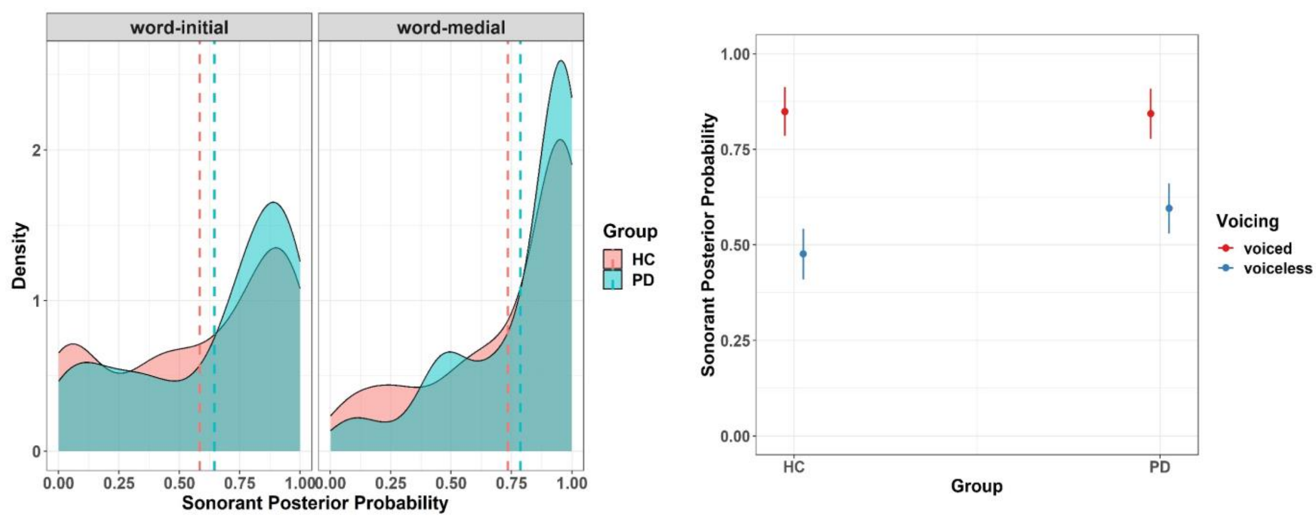

Figure 2. Mean sonorant posterior probabilities of Colombian Spanish voiced and voiceless stops in word-initial and word-medial positions produced by PD patients and healthy control subjects.

The results of the linear mixed-effects regression model revealed significant main effects of Voicing [β = -0.311, t = -9.053; p < 0.001] as well as a significant Group x Voicing interaction [β = 0.132, t = 2.665; p = 0.008]. The main effect of Voicing indicates that the sonorant posterior probability is significantly higher for the voiced than voiceless stops. Additionally, post-hoc pairwise comparisons revealed that the sonorant posterior probabilities for the voiceless stops are significantly higher for the PD patients than for the HC subjects [β = -0.119, t = -2.952; p = 0.030].

II. RAPID SYLLABLE REPETITION

Figure 3 shows the continuant posterior probabilities for the PD patients and the HC subjects for bilabial, dental, and velar voiceless stops from the rapid syllable repetition task.

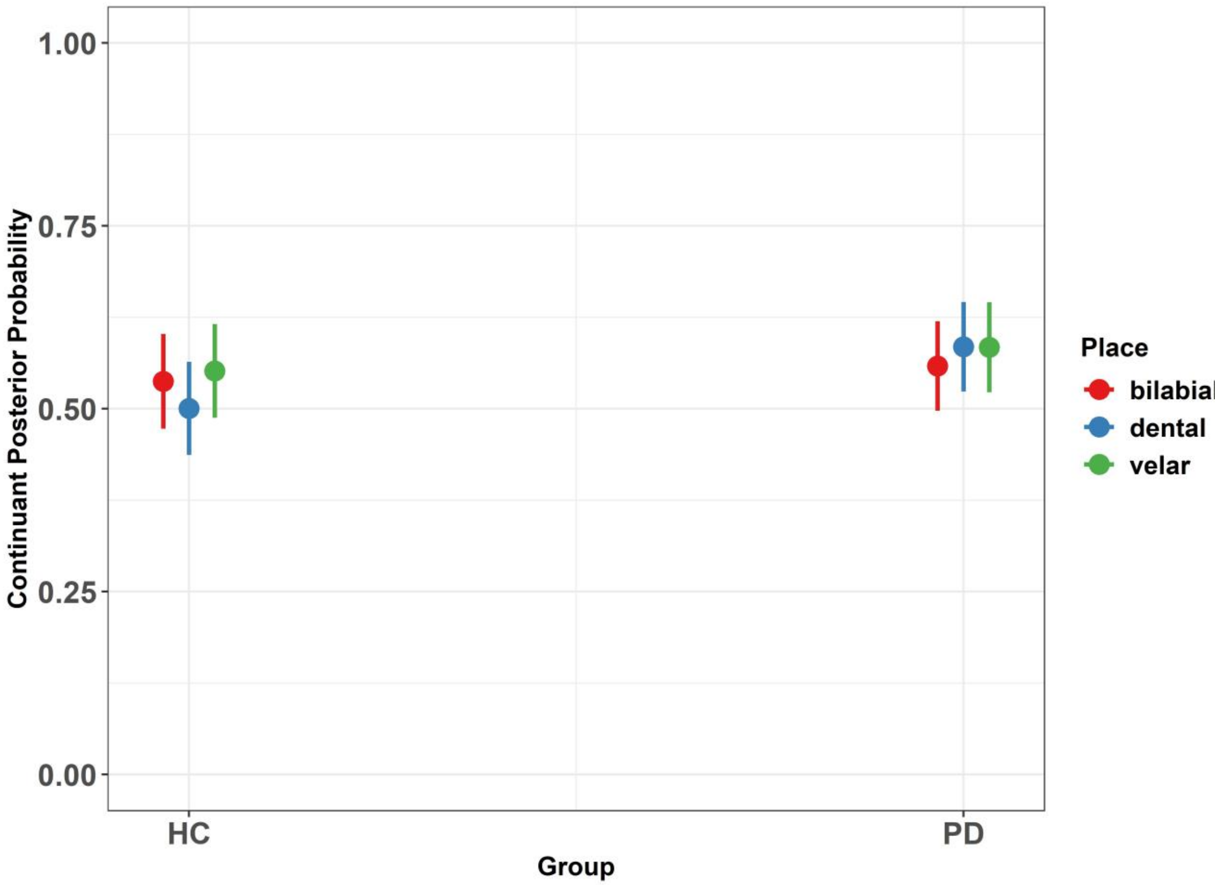

Figure 3. Mean continuant posterior probability for /p, t, k/ produced by PD and HC subjects from the rapid syllable repletion task.

The results of the linear mixed-effects model revealed a significant main effect of Group [β = 0.079, t = 2.663, p = 0.009], indicating that continuant posterior probabilities were higher for PD patients than for HC subjects. There was also a significant Group x POA interaction [β = -0.063, t = -2.262 p = 0.024]. This interaction stems from the lack of difference between bilabial stops across groups, while dental stops produced by PD patients have a significantly higher continuant posterior probability than dental stops produced by healthy controls [β = -0.117, t = -3.485 p = 0.008].

Figure 4 shows the sonorant posterior probabilities for the PD patients and the HC subjects for bilabial, dental, and velar voiceless stops from the rapid syllable repetition task.

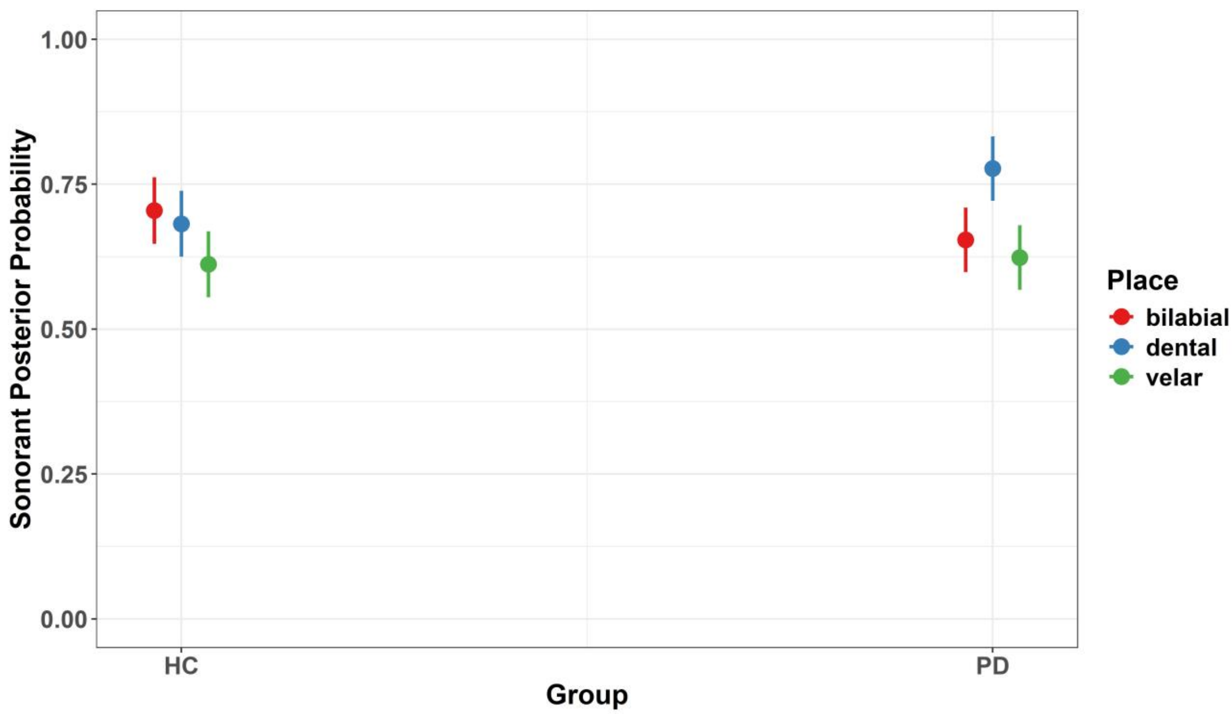

Figure 4. Mean sonorant posterior probability for /p, t, k/ produced by PD and HC subjects from the rapid syllable repletion task.

This model showed no significant difference between HC and PD subjects on sonorant posterior probability. However, there were effects of place of articulation (POA), with bilabial stops [β = -0.050, t = -3.510 $p < 0.001$] and velar stops [β = 0.112, t = 7.957 $p < 0.001$] both having a significantly lower sonorant posterior probability than dental stops. In addition, Group x POA interactions were also significant for bilabial vs. dental and dental vs. velar comparisons [β = -0.053, t = -3.734, $p < 0.001$; β = 0.113, t =8.030, $p < 0.001$, respectively]. Post-hoc pairwise comparisons indicated that for healthy controls, both bilabial and dental stops had a higher sonorant posterior probability than velar stops [β =0.093, t =4.543, $p < 0.001$; β = 0.070, t =3.460, p = 0.007, respectively]. For PD patients, dental stops had a higher posterior probability than bilabial [β = -0.123, t = 7.679, $p < 0.001$] or velar stops [β =0.154, t =7.87, $p < 0.001$]. Additionally, dental stops produced by PD patients had a significantly higher posterior probability than dental stops produced by HC patients [β =-0.113, t =-3.095, p = 0.028].

3. DISCUSSION AND CONCLUSION

This study explores the gradient phonetic variations in the lenition of Spanish voiced and voiceless stops among native speakers of Colombian Spanish diagnosed with Parkinson's Disease using a deep neural network, Phonet. Unlike direct quantitative acoustic-based methods, Phonet is trained to calculate the posterior probabilities of phonological features relevant to lenition, specifically continuant and sonorant, from acoustic data. Phonet's posterior probabilities allow for a gradient analysis of phonological features, complementing traditional acoustic measures (Tang et al., 2023). Additionally, Phonet has proven effective in assessing the extent of lenition (Wayland et al., 2023).

The target consonants for the study are intervocalic voiced /b, d, g / and voiceless stops /p, t, k/ from a sentence production task and syllable-initial voiceless /p, t, k/ from a rapid syllable repetition task. As expected, the results of the regression model for the /b, d, g, p, t, k/ from the sentence production task revealed that voiced stops are more lenited than voiceless stops (higher continuant and sonorant posterior probabilities). Additionally, based on the sonorant posterior probability, voiceless stops produced by PD were significantly more lenited than those produced by HC participants. These results suggest that for both PD and HC, voiced stops are more lenited than voiceless stops. However, PD patients exhibited more approximant-like production (higher sonorant posterior probability) of voiceless stops than HC subjects.

The regression model for the voiceless stops /p, t, k/ from the rapid syllable repetition task revealed additional differences between PD patients and HC participants. Overall, PD patients exhibited a significantly higher continuant posterior probability than HC subjects, suggesting a more advanced degree of lenition among the former than the latter group. This finding is consistent with that of Chenausky, MacAuslan & Goldhor (2011), who suggested that the speech of patients with PD is more spirantized than that of normal controls and that spirantization is not affected by deep brain stimulation. More importantly, this result aligns with the findings of Godino-Llorente et al. (2017), who examined the same data set as ours using acoustic kinetic biomarkers (the velocity and acceleration of the amplitude envelope of the signal). Specifically, their results indicated that the voiceless stops produced by PD patients are produced with less articulatory effort and exhibit a clear tendency toward the pattern expected of voiced stops. In addition, passive voicing was observed during the stops, suggesting that airflow was not completely interrupted (Godino-Llorente et al., 2017).

Additionally, we found that while the two groups did not differ in their continuant posterior probability for the bilabial /p/, the dental /t/ produced by PD patients exhibited a significantly higher continuant posterior probability than that of HC participants. This result suggests that the muscles controlling tongue tip movement are more affected than those involved in lip movement among PD patients. Similarly, the regression model for the sonorant posterior probability is consistent with this finding. Specifically, the sonorant posterior probabilities for /t/ were significantly higher for PD patients than for HC participants. Furthermore, the sonorant posterior probabilities for /t/ were greater than for both /p/ and /k/ among PD patients, further suggesting that the muscles controlling tongue tip movement are more adversely affected than those controlling tongue back movement.

In summary, Phonet is a sensitive measure of lenition. In addition to lenition patterns consistent with traditional acoustic metrics of lenition, Phonet revealed nuanced patterns including stronger effects of PD on the tongue tip than on the tongue back or lips.

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