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ESTUDIOS

Anticipatory coarticulation of the Spanish alveolar fricative /s/ in adults with apraxia versus dysarthria

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ENG **Abstract:** This acoustic study compares anticipatory coarticulation characteristics of the Spanish alveolar sibilant fricative /s/ when in utterance-initial position followed by a vowel in adults with dysarthria and apraxia of speech. Three groups of participants (28 individuals with no speech disorder, 20 with dysarthria, and 8 with apraxia of speech) produced 12 monosyllabic words that included the five vowel sounds of Central-Peninsular Spanish. The acoustic measurements compared within and between groups were frequency of the spectral intensity peak ($Freq_{Mid}$) in different zones of fricative execution, magnitude of the change in frequency of the spectral intensity peak (ΔFreq) in the end zone compared to the average of the initial and middle zones, first three spectral moments, and the difference in spectral center of gravity between the middle and end zones ($Diff_{M-E}$ CoG). Several of these measures were able to differentiate between dysarthric and healthy speech, especially when /s/ was followed by an unrounded vowel, and the same occurred for apraxia, but this time when the adjacent vowel was rounded. While both disorders showed similar spectral patterns, the two motor speech disorders differed in terms of the measures $Freq_{Mid}$ and $Diff_{M-E}$ CoG. Possible explanations for these differences are here discussed within the framework of motor control models.

Keywords: acoustic analysis; anticipatory coarticulation; apraxia of speech; differential diagnostic; dysarthria; fricative.

ES Coarticulación anticipatoria de la fricativa alveolar /s/ del español en adultos con apraxia versus disartria

ES **Resumen:** El estudio analiza acústicamente las características de la coarticulación anticipatoria en la fricativa sibilante alveolar cuando aparece en posición inicial de palabra seguida de vocal comparando las producciones generadas por 28 personas sin patología del habla con 20 personas con disartria y 8 personas con apraxia del habla. Los participantes repiten 12 palabras monosilábicas que incluyen las cinco vocales del español centropeninsular. Se toman distintas medidas acústicas con el fin de comprobar si existen diferencias o no entre los distintos trastornos frente a normalidad y entre sí en los trastornos del habla. Las características acústicas analizadas son la frecuencia del pico de intensidad espectral en la banda de los 3-5 KHz ($Freq_{Mid}$) en tres zonas de ejecución de la fricativa (inicial, media y final), la magnitud del cambio en la frecuencia del pico de intensidad espectral (ΔFreq) en la zona final respecto del promedio de las zonas inicial y media, los tres primeros momentos espectrales (centro de gravedad, desviación estándar y asimetría) en la zona final y la diferencia del centro de gravedad entre la zona media y final (DiffM-F CoG). Los resultados muestran que varias de las medidas distinguen disartria de habla sana, especialmente cuando la /s/ va seguida de vocal no redondeada, y del mismo modo sucede para apraxia, pero cuando la vocal adyacente es redondeada. Aunque ambas patologías presentan patrones similares se distinguen entre sí en $Freq_{Mid}$ y DiffM-F CoG. Se intenta explicar estas diferencias dentro del marco los modelos de control motor.

Palabras clave: análisis acústico; coarticulación anticipatoria; apraxia del habla; diagnóstico diferencial; disartria; fricativa

Sumary: Introduction. Methodology. Statistical Analysis. Results. Discussion. Acknowledgements. Declaration of Interest. References.

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Introduction

Apraxia of speech (AoS) and dysarthria are motor speech disorders that can arise after a brain injury and whose clinical symptoms reflect alterations in different motor processes. While AoS seems to be linked to abnormal phonetic-motor planning, dysarthria is more related to problems in motor programming and/or execution of movement (McNeil et al., 2009). Data arising from motor control models suggest the impaired functioning of the feedforward control system as the underlying cause of AoS, and that of the feedback control system as the underlying cause of dysarthria. While the feedforward control system is responsible for generating motor plans, sequencing and synchronizing movements, the affected system in dysarthria has the role of monitoring and correcting movements in real-time through auditory and somatosensory comparison processes between actual and planned movements (Chen & Watson, 2017; Ghosh et al., 2010; Perkell, 2012; Mass et al., 2015). Notwithstanding, both disorders frequently lead to errors in the production of consonants such as the voiceless alveolar sibilant fricative /s/. As this sound is among the most complex to articulate, the fricative /s/ is attractive for the analysis of motor disorders (Haley et al., 2000; Kim et al., 2010). Hence one of the speech contexts often used to compare different motor disorders is coarticulation. When the articulation of a particular sound is affected by that of a later-occurring sound, this is known as anticipatory coarticulation. This form is probably the most interesting for this type of study (D'Alessandro et al., 2019; Hertrich & Ackerman, 1999; Katz, 2000). However, coarticulation varies according to the degree of articulatory constraint which is, in turn, marked by the extent of tongue involvement in constriction during sound production and by the manner of articulation. While the vowel /i/, like the fricative /s/, is highly resistant to coarticulation, this is not the case for /u/. Thus, anticipatory coarticulation of the vowel over the consonant in sequences such as /si/ or /su/ requires both anticipatory cognitive planning and good motor control of the lingual system so that the tongue tip and body are able to independently move. Demands on the tongue tip will be greater for /si/, as the degrees of freedom of this articulator are subject to intra-articulator mechanical and temporal coordination constraints, whereas for /su/, this is not the case, as the vowel is pronounced with the posterior dorsum of the tongue. Nevertheless, in this latter sequence, there is also inter-articulator coordination due to vowel labialization, which is reflected anticipatorily in the fricative (Forrest et al., 1988; Hough & Klich, 1998; Kelso & Tuller, 1984; Lubker & Gay; 1982; Recasens & Rodríguez, 2016; Solé & Ohala, 2010; Zharkova et al., 2012).

In this context, it could be that anticipatory coarticulation is impaired in AoS, as this disorder involves problems in inter- and intra-articulator planning and sequencing. However, anticipatory coarticulation could also be impaired in dysarthria, because of the neuromuscular alteration that affects somato-acoustic feedback, along with difficulties in the execution of programmed motor commands. Accordingly, analyzing anticipatory coarticulation could reveal, in a differential manner, the difficulties present in both disorders (Reetz & Jongman, 2020; Whalen, 1990; Zharkova et al., 2012).

For the study of dysarthria and AoS, several spectral acoustic measures have been employed such as spectral peak frequency (Freq), magnitude of change in spectral peak frequency (ΔFreq), and spectral moments (center of gravity-CoG, standard deviation-SD, and skewness) (Haley, 2002; Kim, 2017; Koenig et al., 2013; Tjaden & Turner, 1997). These measures reflect the effects of both segmental linguistic variables (e.g., adjacent vowel) and sociophonetic variables (e.g., speaker sex) (Manuel, 1999).

Spectral peak frequency (Freq)

This variable measures the highest amplitude frequency appearing in a selected frequency band or in the entire frequency spectrum. It identifies the position of lingual placement and the effects of adjacent vowels. In Spanish (Leonese variant), the spectral peak frequency of the fricative /s/ when in initial position in a monosyllabic word is 3 515 – 6 317 Hz, while in English it is slightly higher, in the range 4 336 –6 900 Hz (Barreiro, 1995; Jongman et al., 2000). During sound production in both Spanish (Leonese variant) and English, tongue and jaw displacements determine a lower spectral peak frequency in the mid-range of the spectrum ($Freq_{Mid}$), which is between 3.5 - 5 kHz when the fricative is followed by a rounded rather than an unrounded vowel (Barreiro, 1995; Iskarous et al., 2011; Shadle & Mair, 1996; Shadle & Scully, 1995; Yeni-Komshian & Soli, 1981). Further, the magnitude of spectral peak change (ΔFreq) relates peak frequencies of different areas of the sound, reflecting changes in articulatory form, mainly of the lips, because of the adjacent vowel sound. Thus, in English, the ΔFreq at the end of the fricative is higher if the vowel is rounded (Iskarous et al., 2011; Jongman et al., 2000; Koenig et al., 2013; Munson, 2004). The same is true for the fricative in Argentinean Spanish (Borzone de Manrique & Massone, 1981). Research into the effects of the socio-phonetic factor speaker sex conducted in English-speaking populations has shown that in both adolescents and adults, spectral peak frequency in the center of the fricative is higher in females than males (Koenig et al., 2013). As far as we know, no similar study has examined this issue in speakers of Central-Peninsular Spanish.

It should also be mentioned that in the field of motor speech disorders, few studies in Spanish have examined the presence or absence of variations in spectral peak frequency. While we were unable to find any contributions in the field of dysarthria, some such studies exist in English and these have examined the impacts of AoS, or in the case of earlier work, of non-fluent aphasia. In these reports, lower spectral peaks, less sharp spectra and a greater range of dispersion are described for apraxia compared to healthy speech (Wambaugh et al., 1995; Harmes et al., 1984).

Spectral Moments

Knowing the spectral center of gravity (CoG) allows for determining the frequency that corresponds to the mean of frequencies weighted by their amplitudes. This provides information about the location of the articulatory point and presence or absence of lip rounding. In contrast, the spectral standard deviation (SD) represents the distance of frequencies in the spectrum from the mean, and provides information about lip rounding through the degree of dispersion of the spectrum. Similarly, the spectral skewness records in which part of the frequency spectrum energy accumulates relative to the mean, offering the possibility to determine the articulatory point and the presence or absence of lip rounding. In healthy male speakers of Spanish these variables are typically: CoG = 4 827 – 5 911 Hz, SD = 1 552 – 2 353 Hz, and skewness = 0.25 – 1.85, with variations in all of these depending on the adjacent vowel (Cicres, 2011). In English, the rounding effect is observed more clearly in the center of the fricative independently of speaker age such that CoG is higher, SD lower, and skewness more negative when the adjacent vowel is unrounded (Jongman et al., 2000; Koenig et al., 2013; Nittrouer et al., 1989). In addition, CoG and SD are higher and skewness is more negative in females. This higher CoG is attributed to more anterior and narrower constrictions, as well as differences in the degree of lip retraction along with wider vocalic spaces, despite smaller articulatory spaces (Avery & Liss, 1996; Flipsen et al., 1999; Fox & Nissen, 2005; Fuchs & Toda, 2010; Jongman et al., 2000; Yeni-Komshian & Soli, 1981).

In contrast, scarce data are available for the study of spectral moments in the production of fricatives by speakers with AoS, with or without aphasia. Moreover, results obtained for the only measured moment, CoG, have been contradictory in terms of their values compared to those of healthy speakers (Haley, 2002; Harmes et al., 1984; Katz et al., 2006). These studies have also shown that individuals with AoS show a greater variability in CoG for repeated sound productions, and in some cases, delays in the onset of spectral change towards the fricative or its minimal modification during its production, as compared to healthy speakers (Haley, 2002). In the case of dysarthria due to both cerebral palsy and a neurodegenerative disease such as amyotrophic lateral sclerosis (ALS), it has been found that CoG is lower and SD higher than in healthy speakers (Buder et al., 1996; Hernandez et al., 2019). However, other studies have detected similar values of these variables in healthy speakers and those with neurodegenerative diseases such as Parkinson's disease and multiple sclerosis (Kim, 2017; Lam & Tjaden, 2016; Tjaden, 2003). When examining the effect of the adjacent vowel on the fricative, Martel-Suavageau et al. (2021) observed the same pattern of a lower CoG and higher SD in Parkinson's disease and healthy speech in the context of a rounded vowel, while skewness showed the opposite trend and was more positive. Lastly, acoustic differences related to speaker sex have not been extensively explored. In fact, there are no available data on sex-specific differences in spectral moments for AoS. For dysarthria, among the literature reports available, only one study (Tjaden & Turner, 1997) has examined the impacts of speaker sex indicating that females with ALS dysarthria show a lower CoG and higher skewness than healthy females, while no differences emerge for CoG yet skewness is lower in males.

The present study sought to examine possible differences in intra-syllabic anticipatory coarticulation of the Spanish (Central-Peninsular variant) sibilant alveolar fricative /s/ embedded in different vowel contexts in adults with dysarthria or AoS and healthy speakers through objective acoustic measures and easily-reproducible speech tasks. In the light of what is already known, the specific questions addressed here were whether:

(1) Individuals with AoS show scarce differences in acoustic measures according to vowel rounding.
(2) Compared to dysarthric and healthy speakers, individuals with AoS show greater differences in the context of a rounded vowel.
(3) Compared to apraxic and healthy speakers, individuals with dysarthria show greater differences in acoustic measures in an unrounded vowel context.
(4) Compared to males, females generally show a higher Freq and CoG, lower SD, and more negative skewness in an unrounded than rounded vowel context.

This type of information is important to generate automated analysis methods facilitating a differential diagnosis of dysarthria and AoS with the ultimate goal of defining optimal clinical rehabilitation procedures for each speech disorder.

Methodology

Participants

Three study groups were established: dysarthria (20 individuals), AoS (8 individuals), and control (28 healthy individuals) (Table 1). All participants were adults, mostly native speakers of Madrid Spanish

(> 80%, henceforth Central-Peninsular Spanish) who lacked any organic auditory or vocal pathology. Participation was voluntary and unpaid. Each participant gave their informed consent before the study outset. Candidates for the speech disorder groups were independently selected according to inclusion-exclusion diagnostic criteria applied by a speech-language pathologist from the State Center for Acquired Brain Injury and the Pita López Foundation, both located in Madrid, Spain. Subjects for the healthy control group were selected through a non-probabilistic sampling method (snowball sampling) to ensure homogeneity.

The study protocol was approved by the Deontological Committee of the official organization where it was conducted. Data protection was ensured in accordance with current European legislation.

Table 1. Descriptive data: N, mean age, and sex. Dysarthria classification and underlying etiology

	N	**Mean age (age range) years**	**Sex male: female**
Control	28	42.6 (21-71)	19:9
Apraxia	8	41.5 (30-61)	4:4
Dysarthria	20	41.8 (21-72)	14:6
*** Dysarthria type**	**N**	**Etiology**	**N**
Spastic	15	Head trauma	10
Ataxic	2	Stroke	10
Flaccid	1	Tumor	3
Mixed	2	Other (encephalopathy, toxoplasmosis)	5

* According to the classification system of Darley, Aronson & Brown (1969)

Materials

The materials used were 12 real monosyllabic Spanish words that began with the voiceless alveolar fricative sound /s/ with the structure sV(C). No carrier phrase was used to pronounce the words, so the fricative /s/ was both in word-initial and utterance-initial position. An equal number of rounded and unrounded vowels were included. The word list was: *sal, sus, se, sor, sin, su, ser, son, si, sur, sed, sol*.

Task

The task used forms part of a broader protocol. Participants produced one word at a time until completing the series of 12 words after a practice run using similar stimuli (i.e., san, so). The order of word presentation in which rounded and unrounded vowels were alternated was the same for all participants.

Recording, segmentation, and labeling

The speech sample was recorded in an isolated room (ambient noise > 30 dB signal to noise ratio) using Audacity 2.2.2 software with a Shure SM48 microphone and a Focusrite Scarlett 2i2 USB audio interface for sound digitization. Praat software (Boersma & Weenink, 2020) was used for segmentation, applying objective criteria of change in acoustic energy in the 3 500 Hz – 8 500 Hz region determined through linear predictive coding (LPC)-autocorrelation and discrete Fourier transform (DFT) analysis in the case of the fricative, and the presence of glottal pulses and vowel formants in the spectrogram for vowels. Once the segment was established, it was labeled with the TextGrid function of that program (for more details see Melle et al., 2023). In total, 672 samples were collected at a sampling frequency of 44 100 Hz and quantization of 16 bits. 10% of the segmentations were subjected to inter- and intra-rater agreement analysis to determine the reliability of the cuts. Thus, three judges collaborated to determine agreement, and one of these judges assessed intra-rater agreement after a 3-month gap between segmentations. An *ad hoc* Praat script was used to calculate the temporal difference between the segment boundary determined by two independent judges, and this difference was recorded as a proportion relative to total segment duration. The mean of these measurements, represented as a value between 0 and 1, was subtracted from 1, yielding a percentage of agreement. In both inter- and intra-rater comparisons, percentage agreement was higher than 94%.

Acoustic analysis

Using the software package Praat 6.1.16 (Boersma & Weenink, 2020), an *ad hoc* script was employed to apply successive Hamming windowing of 3.125 ms every 1 ms for 25 ms over the initial, middle and end zones of the fricative. The acoustic measurements taken were:

(1) Frequency of the spectral intensity peak ($Freq_{Mid}$) in the middle frequency band. This allows us to determine the frequency of the fricative spectrum that exhibits the highest wave amplitude in a specific region of spectral frequencies calculated using the method employed by Koenig et al. (2013). This calculation was modified by applying the fast Fourier transform (FFT) with a bandpass filter of 3 000 – 5 000 Hz and a smoothing of 100 Hz in each of the successive windows of each zone, to adjust it to

the fricative sounds of Spanish, with Freq_{Mid} in a lower frequency band, and to the greater age of the sample of this study compared to that of Koenig et al. (2013). From the spectrum calculated in each window, the frequency of the spectral peak with the highest amplitude or intensity was extracted, and the average spectral peak frequency was determined for the analyzed fricative zone: initial, middle and end.

(2) Magnitude of change in the spectral intensity peak frequency (ΔFreq) in the middle frequency band. This indicates the variation in the intensity peak frequency that exists over the course of the fricative's execution time. As the average of this frequency is compared between the initial and middle zones against the average of the end zone of the fricative, Koenig et al. (2013) consider it is not affected by speaker sex and thus helps determine the effect of anticipatory lip rounding. Thus, the equation of these authors was adapted for this study in its middle frequency band to 3 000 – 5 000 Hz:

$$\Delta F = \frac{FreqMid\ (initial) + FreqMid\ (middle)}{2} - FreqMid\ (end)$$

Freq_{Mid} is the average of the spectral intensity peak frequencies in the middle frequency band for each of the analyzed execution zones of the fricative.

(1) Three spectral moments: CoG, SD, and skewness calculated in the last 25 ms of the fricative following the procedure used in Melle et al. (2023).

(2) Magnitude of the $\text{CoG}_{\text{middle-end}}$ difference ($\text{Diff}_{\text{M-E}}$ CoG). This enables the determination of the change in CoG from the position of full realization (middle) to the position of greater coarticulation (end). It was calculated by subtracting the average CoG value obtained in the middle zone from the study of Melle et al. (2023) from the average CoG value obtained in the final zone of the fricative using the following equation:

$$Diff_{M\text{–}E}\, CoG = CoG_M - CoG_E$$

Statistical Analysis

All statistical calculations were performed with R (R Core Team, 2020) using the packages *WRS2* (Mair & Wilcox, 2020) and *ggstatsplot* (Patil, 2021). As the samples violated the assumptions of normality (determined using Lilliefors' Kolmogorov-Smirnov test) and homogeneity of variances (determined using the Fligner-Killeen test), and also had extreme data points, especially in the pathological groups, robust methods of analysis were employed in the descriptive and inferential statistics to obtain results that more accurately reflected the behavior of our pathological groups. Thus, for the descriptive part, trimmed means at 5% and absolute standard deviation were calculated, while for the inferential part, a heteroscedastic one-way ANOVA with trimmed means at 5% and a bootstrap resampling method of 5000 was used to identify group differences. In addition, Yuen's test with 5000 bootstraps was used to detect differences by vowel rounding and sex, and for pairwise comparisons between groups. False discovery rate control was applied in all inferential analyses. Effect size was also estimated using the explanatory effect size measure (ξ) for ANOVA, and Algina-Keselman-Penfield's robust standardized difference (δR^{AKP}) for Yuen's test.

Results

Descriptive data stratified by group, vowel rounding, and sex are presented in Table 2. Tables 3 and 4 summarize the results of the different inferential analyses.

Table 2. Descriptive results of the spectral measures of coarticulation: trimmed mean α (and median absolute deviation) according to group, vowel rounding and sex of speaker.

	n	Freq_{Mid} I (Hz)	Freq_{Mid} M (Hz)	Freq_{Mid} E (Hz)	ΔFreq (Hz)	CoG (Hz)	SD (Hz)	Skewness	$\text{Diff}_{\text{M-E}}$ CoG (Hz)
Control	336	3 990 (535)	4 288 (420)	4 004 (368)	131 (305)	2 787 (923)	1 613 (551)	1.83 (1.12)	2 910 (1 038)
Unrounded	168	4 255 (333)	4 524 (180)	4 154 (240)	224 (303)	3 026 (921)	1 623 (615)	1.83 (1.15)	3 102 (1 091)
Rounded	168	3 731 (282)	4 043 (389)	3 848 (305)	39 (255)	2 549 (895)	1 606 (514)	1.84 (1.08)	2 725 (1 050)
Female	108	4 105 (484)	4 421 (317)	3 945 (361)	296 (304)	3 027 (1 145)	1 757 (606)	1.59 (1.12)	3 406 (1 262)
Male	228	3 938 (514)	4 225 (450)	4 031 (348)	54 (295)	2 683 (854)	1 54 (493)	1.95 (1.06)	2 704 (938)
Apraxia	96	4 020 (412)	4 211 (393)	3 981 (307)	128 (221)	3 433 (923)	1 913 (476)	1.23 (0.85)	2 521 (994)
Unrounded	48	4 242 (411)	4 416 (255)	4 110 (244)	205 (337)	3 455 (798)	1 824 (519)	1.38 (0.85)	2 718 (1 076)
Rounded	48	3 807 (310)	4 009 (251)	3 855 (214)	61 (193)	3 418 (1 067)	2 007 (440)	1.10 (0.66)	2 296 (1 141)
Female	48	4 071 (381)	4 246 (379)	3 973 (311)	175 (235)	3 619 (1 139)	2 075 (690)	1.29 (0.97)	2 677 (1 622)
Male	48	3 971 (408)	4 175 (288)	3 990 (311)	92 (221)	3 276 (778)	1 769 (370)	1.18 (0.66)	2 362 (920)
Dysarthria	240	3 970 (369)	4 124 (416)	3 988 (318)	58 (287)	3 366 (1 358)	1 766 (503)	1.42 (1.16)	1 741 (1 773)

	n	Freq$_{Mid}$ I (Hz)	Freq$_{Mid}$ M (Hz)	Freq$_{Mid}$ E (Hz)	ΔFreq (Hz)	CoG (Hz)	SD (Hz)	Skew ness	Diff$_{M-E}$ CoG (Hz)
Unrounded	120	4 074 (407)	4 226 (422)	4 001 (287)	130 (310)	3 545 (1 352)	1 668 (455)	1.41 (1.09)	1 673 (1 672)
Rounded	120	3 869 (298)	4 022 (399)	3 976 (332)	-22 (274)	3 187 (1 283)	1 866 (443)	1.42 (1.26)	1 809 (1 854)
Female	84	4 078 (377)	4 128 (428)	3 942 (277)	138 (306)	3 285 (1 458)	1 732 (611)	1.75 (1.41)	1 474 (1 779)
Male	156	3 916 (355)	4 123 (401)	4 013 (311)	12 (282)	3 412 (1 279)	1 783 (399)	1.27 (1.11)	1 887 (1 854)

FreqMid: frequency of the spectral intensity peak, I (initial), M (middle), F (end); ΔFreq: magnitude of the change in the frequency of the spectral intensity peak; CoG: center of gravity; SD: standard deviation; DiffM-E CoG: differences in the center of gravity between the middle and the end zones; n (number of observations)Table 3. Results of spectral measures of coarticulation according to group, vowel rounding and sex of the speaker.

Table 3. Results of spectral measures of coarticulation according to group, vowel rounding and sex of the speaker.

Factor	Group			Vowel rounding			Sex		
Measurement	$F_{Trimmed\ means}$	p	Effect size ξ	t_{Yuen}	p	δ_{R}^{AKP}	t_{Yuen}	p	δ_{R}^{AKP}
Freq$_{Mid}$ Initial	0.60	.55	0.10	14.88	.001^{a}	1.07	4.81	.001^{a}	-0.40
Freq$_{Mid}$ Middle	12.11	.001^{a}	0.22	14.05	.001^{a}	1.14	3.17	.001^{a}	-0.27
Freq$_{Mid}$ End	0.27	.76	0.09	8.62	.001^{a}	0.72	2.82	.001^{a}	0.23
ΔFreq	4.68	.01^{c}	0.16	7.37	.001^{a}	0.55	7.13	.001^{a}	-0.62
CoG	30.30	·001^{a}	0.34	4.57	.001^{a}	0.36	2.64	.001^{a}	-0.24
SD	14.04	.001^{a}	0.29	2.00	.05	-0.15	3.34	.001^{a}	-0.32
Skewness	14.99	.001^{a}	0.26	0.35	.73	0.03	0.65	.52	0.05
Diff$_{M-E}$ CoG	40.06	.001^{a}	0.41	1.85	.06	0.14	1.60	.11	-0.16

One-way robust ANOVA, 5% trimmed mean (in group comparisons). Yuen's test for 5% trimmed mean (in comparisons by vowel rounding and sex of speaker). Level of significance: a) $p < .001$***; b) $p < .01$**; c) $p < 0.05$*. FreqMid: frequency of the spectral intensity peak; ΔFreq: magnitude of change in frequency of the spectral intensity peak; CoG: center of gravity; SD: standard deviation; DiffM–F CoG: differences in the center of gravity between the middle and end zones.

For each of the analyzed measures, below we describe the effects of vowel rounding and sex on fricative production. These effects are first analyzed separately within each group, and we then conclude with comparisons between groups.

Frequency of the spectral intensity peak (Freq$_{Mid}$)

In all the analyzed zones, a significant effect of vowel rounding was observed in that higher Freq$_{Mid}$ values were obtained when the vowel subsequent to the fricative /s/ was unrounded. Most difference was observed for the initial zone, and least for the end zone (Table 3). This occurred separately in each group. Thus, while Freq$_{Mid}$ in the control group showed most differences according to vowel rounding, the dysarthria group showed least differences, including no significant differences in the end zone (Table 4a).

Table 4. Results of pairwise comparisons between groups, vowel contexts and sex.

a)	Freq$_{Mid}$ Initial			Freq$_{Mid}$ Middle			Freq$_{Mid}$ End			ΔFreq		
	T	**U**	**R**	**T**	**U**	**R**	**T**	**U**	**R**	**T**	**U**	**R**
C vs D t_{Yuen}(p)	0.61 (.54)	4.19 (.001^{a})	3.74 (.001^{a})	4.93 (.001^{a})	7.62 (.001^{a})	0.47 (.80)	0.58 (.84)	4.74 (.001^{a})	3.39 (.01^{b})	2.90 (.01^{b})	2.64 (.03^{c})	1.75 (.12)
δ_{R}^{AKP}	0.05	0.52	-0.43	0.40	1.21	0.05	0.05	0.63	-0.39	0.24	0.31	0.22
C vs A t_{Yuen}(p)	0.63 (.54)	0.22 (.83)	1.60 (.17)	1.81 (.07)	2.20 (003^{c})	0.71 (.80)	0.64 (.84)	0.99 (.33)	0.17 (.86)	0.08 (.94)	0.37 (.71)	0.59 (.55)
δ_{R}^{AKP}	-0.07	0.04	-0.24	0.19	0.43	0.09	0.07	0.18	-0.02	-0.00	0.06	-0.08
A vs D t_{Yuen}(p)	1.07 (.54)	2.65 (001^{b})	1.26 (.21)	1.97 (.07)	3.40 (.001^{a})	0.25 (.80)	0.20 (.84)	2.23 (.04^{c})	2.63 (.01^{b})	2.13 (.05^{c})	1.47 (.22)	20.2 (.12)
δ_{R}^{AKP}	0.13	0.45	-0.22	0.24	0.61	-0.05	-0.02	0.38	-0.48	0.26	0.25	0.39
	C	**D**	**A**	**C**	**D**	**A**	**C**	**D**	**A**	**C**	**D**	**A**
U vs R t_{Yuen}(p)	14.25 (.001^{a})	4.73 (.001^{a})	6.47 (.001^{a})	13.59 (.001^{a})	4.30 (.001^{a})	7.11 (.001^{a})	9.69 (.001^{a})	0.65 (.52)	4.63 (.001^{a})	5.79 (.001^{a})	3.97 (.001^{a})	2.69 (.001^{a})
δ_{R}^{AKP}	1.52	0.56	1.17	1.95	0.56	1.32	1.26	0.09	0.89	0.60	0.53	0.47
F vs M t_{Yuen}(p)	3.27 (.001^{a})	3.34 (.001^{a})	1.24 (.22)	4.36 (.001^{a})	0.11 (.92)	0.98 (.33)	2.24 (.03^{c})	1.76 (.08)	0.28 (.78)	7.30 (.001^{a})	3.04 (.001^{a})	1.50 (.14)
δ_{R}^{AKP}	-0.39	-0.48	-0.26	-0.48	-0.02	-0.21	0.26	0.24	0.06	-0.86	-0.42	-0.38

Yuen's test for 5% trimmed mean. Total: total comparison; U: unrounded vowel; R: rounded vowel; C: Control; D: dysarthria; A: apraxia; F: female; M: male. Level of significance: a) p < .001***; b) p < .01**; c) p < 0.05*

b)	**Center of gravity**											
	T	**U**	**R**	**T**	**U**	**R**	**T**	**U**	**R**	**T**	**U**	**R**
C vs D t_{Yuen}(p)	6.31 (.001^a)	4.00 (.001^a)	5.07 (.001^a)	3.38 (.001^a)	0.70 (.49)	4.26 (.001^a)	3.46 (.001^a)	2.51 (.02^c)	2.37 (.03^c)	8.93 (.001^a)	7.67 (.001^a)	5.02 (.001^a)
δ_R^{AKP}	-0.64	-0.57	-0.74	-0.28	-0.07	-0.55	0.32	0.33	0.30	1.00	1.22	0.81
C vs A t_{Yuen}(p)	6.03 (.001^a)	2.88 (.01^b)	5.64 (.001^a)	4.98 (.001^a)	2.28 (.08)	4.84 (.001^a)	5.24 (.001^a)	2.71 (.02^c)	4.69 (.001^a)	2.86 (.01^b)	2.08 (.04^c)	2.12 (.05^c)
δ_R^{AKP}	-0.71	-0.47	-1.02	-0.55	-0.33	-0.84	0.46	0.35	0.54	0.33	0.33	0.38
A vs D t_{Yuen}(p)	0.54 (.59)	0.53 (.60)	1.32 (.19)	0.54 (.59)	1.80 (.11)	1.58 (.12)	1.40 (.16)	0.16 (.87)	1.80 (.07)	4.73 (.001^a)	4.57 (.001^a)	2.02 (.05^c)
δ_R^{AKP}	0.07	-0.10	0.24	0.07	0.30	0.27	-0.21	-0.03	-0.40	0.66	0.93	0.39
	C	**D**	**A**	**C**	**D**	**A**	**C**	**D**	**A**	**C**	**D**	**A**
U vs R t_{Yuen}(p)	4.93 (.001^a)	2.35 (.02^c)	0.19 (.85)	0.29 (.77)	3.00 (.001^a)	1.73 (.09)	0.04 (.97)	0.07 (.95)	1.59 (.11)	2.97 (.001^a)	0.60 (.55)	1.74 (.09)
δ_R^{AKP}	0.53	0.30	0.04	0.03	-0.41	0.35	-0.00	-0.00	0.30	0.32	-0.08	0.38
F vs M t_{Yuen}(p)	2.89 (.001^a)	0.76 (.45)	1.80 (.08)	3.11 (.001^a)	0.64 (.52)	2.99 (.001^a)	2.28 (.02^c)	2.10 (.04^c)	0.67 (.51)	4.82 (.001^a)	1.79 (.08)	1.26 (.21)
δ_R^{AKP}	-0.42	0.11	-0.43	-0.43	0.11	-0.79	0.28	-0.36	-0.16	-0.67	0.23	-0.34

Yuen's test for 5% trimmed mean. Total: total comparison; U: unrounded vowel; R: rounded vowel; C: Control; D: dysarthria; A: apraxia;

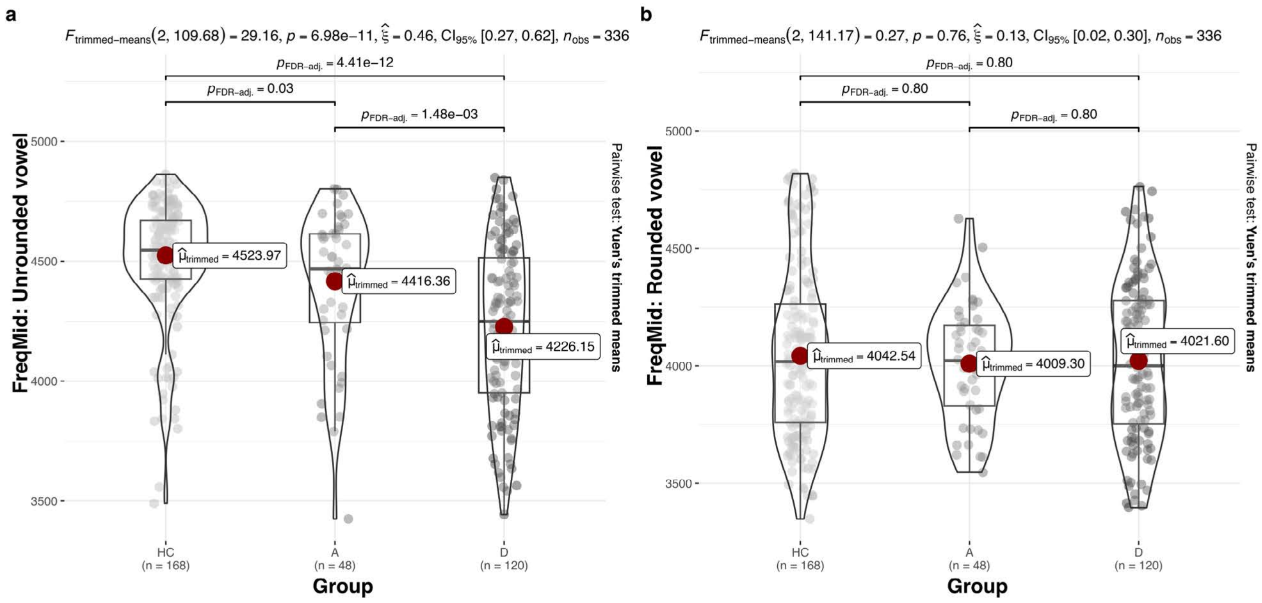

Figure 1. Differences in $Freq_{Mid}$ Middle between the groups according to vowel rounding context

Similarly, an effect of sex was observed in all zones. In this case, females returned higher values of $Freq_{Mid}$ in the initial and middle zones, and lower values in the end zone. These differences were more pronounced in the initial zone and less marked in the end zone (Table 3). In all zones, both sexes showed significantly higher $Freq_{Mid}$ in an unrounded vowel context (males: initial zone t_{Yuen} $(_{377.44})$ = 11.10, $p < .001$; middle zone t_{Yuen} $(_{386.73})$ = 9.52, $p < .001$; end zone t_{Yuen} $(_{359.7})$ = 6.72, $p < .001$; females: initial zone t_{Yuen} $(_{213.88})$ = 10.95, $p < .001$; middle zone t_{Yuen} $(_{208.56})$ = 11.61, $p < .001$; end zone t_{Yuen} $(_{204.97})$ = 5.40, $p < .001$). When each group was separately considered, it emerged that $Freq_{Mid}$ for females in the control group was significantly higher in both vowel contexts in the initial and middle zones compared to males (initial zone: unrounded t_{Yuen} $(_{117.05})$ = 3.37, $p < .001$, rounded t_{Yuen} $(_{82.65})$ = 2.89, $p < .004$; middle zone: unrounded t_{Yuen} $(_{152})$ = 6.60, $p < .001$; rounded t_{Yuen} $(_{100.98})$ = 2.84, $p < .005$). In the end zone, however, this pattern was reversed such that $Freq_{Mid}$ was higher for males than females, but only significantly so in an unrounded vowel context (unrounded: t_{Yuen} $(_{71.85})$ = 3.27, $p < .001$; rounded: t_{Yuen} $(_{101.72})$ = 0.30, p = 0.76). Among the pathological groups, while the dysarthria group only showed significant $Freq_{Mid}$ differences, these only appeared in the initial zone for both vowel contexts, with females showing the higher values (unrounded: t_{Yuen} $(_{67.03})$ = 5.13, $p < .001$; rounded: t_{Yuen} $(_{141.87})$ = 2.50, p = 0-30).

When we analyzed $Freq_{Mid}$ differences by group, although significance was only reached in the middle zone (Table 3), more discrepancies were detected through pairwise comparisons. Thus while, overall, the dysarthria group featured lower $Freq_{Mid}$ than the control group in all three zones, in the initial and end zones, higher $Freq_{Mid}$ values were observed when the vowel adjacent to the fricative was rounded and lower values when the vowel was unrounded than in the control group. Conversely, in the middle zone, although there was a Freq_{Mid} difference in an unrounded vowel context with higher values recorded in the control group, the dysarthria and control groups did not differ in a rounded vowel context (Table 4a). Hence, the largest Freq_{Mid} difference was noted for unrounded vowels in all three zones, with higher values observed in the control group (Figure 1). In contrast, the AoS group only showed a significantly lower Freq_{Mid} than the control group in the middle zone when the fricative was followed by an unrounded vowel. When comparing the pathological groups, Freq_{Mid} values were significantly higher in the AoS group in all three zones in an unrounded vowel context of the fricative. Further, Freq_{Mid} values in the AoS compared to the dysarthria group were significantly lower in the end zone when the adjacent vowel was rounded (Table 4a).

Magnitude of the spectral intensity peak frequency change (ΔFreq)

Overall, our results indicate that ΔFreq was significantly higher when the fricative was followed by an unrounded vowel. Additionally, ΔFreq values in the control group varied significantly according to the vowel accompanying the fricative such that very high values were recorded for unrounded vowels and small values for rounded vowels (Table 4a). The dysarthria group showed a lower average rise for the rounded vowel context, resulting in negative ΔFreq values (Table 2). Hence, ΔFreq in this group was the lowest of the three in both vowel contexts.

When stratified by sex, the dysarthria and control groups showed significant differences between males and females. In both cases, females showed a higher ΔFreq, and this difference was more pronounced in the control group (Table 4a). Further, differences between males and females were present regardless of the vowel context, with a greater difference in the case of an unrounded vowel context (control: unrounded $t_{Yuen}\ (_{98.21}) = 7.09$, $p < .001$; rounded $t_{Yuen}\ (_{102.85}) = 4.11$, $p < .001$; dysarthria: unrounded $t_{Yuen}\ (_{56.95}) = 2.58$, $p < .01$; rounded $t_{Yuen}\ (_{100.19}) = 2.30$, $p < .02$). When we compared ΔFreq data between groups, both the control and AoS groups differed significantly from the dysarthria group. This difference was noted between the control and dysarthria groups in an unrounded vowel context of the fricative, with higher values detected in the control group, while the AoS and dysarthria did so in a rounded vowel context, although only close to significance, with higher values detected in AoS (Table 4a). In contrast, no difference in ΔFreq was observed between the control and AoS group.

Center of gravity (CoG)

CoG was higher in the context of an unrounded vowel, but only the dysarthria and control groups showed significantly different CoGs according to the vowel context, with the latter showing the greatest difference (Table 4b). In contrast, the AoS group showed high CoGs in a rounded vowel context that were close to those recorded for unrounded vowels.

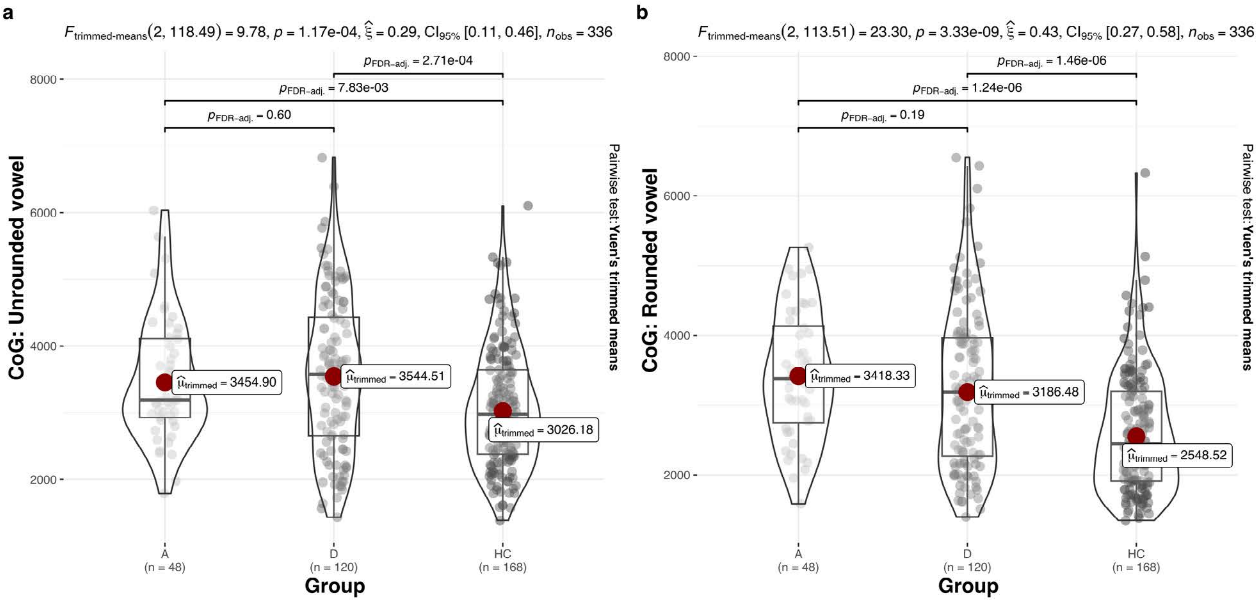

Figure 2. Differences in spectral center of gravity between groups according to vowel rounding context.

Females showed higher CoG values, although the control group was the only one that showed significant differences when analyzed separately, but only in a rounded vowel context ($t_{Yuen}\ (_{71.64}) = 2.49$, $p < .01$) (Table 4b).

When comparing the groups, the control group could be distinguished from the dysarthria and AoS groups (Figure 2). In both cases, a difference in CoG was present both when the vowel adjacent to the fricative was unrounded or rounded, being greater in the latter case in the two comparisons (Table 4b). In contrast, the pathological groups showed no CoG differences between them.

Standard deviation (SD)

Our results indicate an effect of vowel rounding on spectral dispersion (Table 3). However, only the dysarthria group showed significantly different SD values, which were higher when the fricative was accompanied by a rounded vowel. Although differences were not significant in the other two groups, dispersion was greater in the AoS group in a rounded vowel context and slightly higher in the control group when the vowel produced was unrounded.

When the groups were stratified by sex, it was found that females in the control and AoS groups obtained significantly higher SDs, the difference being greater in the former (Table 2). Further, while in the control group the SD difference between sexes was significant for an unrounded vowel context (t_{Yuen} ($_{87.76}$) = 2.68, *p* < .01**), in the AoS group this occurred when the vowel following the fricative was rounded (t_{Yuen} ($_{31.18}$) = 2.08, *p* < .05*).

Significant differences in SD were also observed between the control and pathological groups, although the AoS and dysarthria groups showed similar SDs (Table 4). In the dysarthria group and only in a rounded vowel context, SDs were higher than in the control group. In contrast, in the AoS group, SDs differed from control values in both vowel contexts although significance was greater for rounded vowels.

Skewness

In all groups, skewness was unaffected by the vowel rounding context of the fricative (Tables 2 and 3). Neither were significant differences detected by sex in general, although when the groups were studied separately, both the control and dysarthria group showed skewness differences by sex. Thus, while in the control group females had less positive skewness values, in the dysarthria group it was males that had the lower values (Tables 2 and 4b). In this latter group, skewness also varied according to the vowel context such that males and females differently produced the fricative preceding a rounded vowel (t_{Yuen} ($_{57.08}$) = 2.49, *p* < .02).

By group, once again, skewness differences were only found between the control and pathological groups. The behavior of the latter groups in relation to the control group, although always significant, varied depending on the vowel context in which the fricative was found. While the dysarthria group differed significantly more from the control group in an unrounded vowel context, the AoS group did so in a rounded vowel context (Table 4b).

Magnitude of the $\text{CoG}_{\text{middle-end}}$ difference ($\text{Diff}_{\text{M-E}}$ CoG)

Differences in $\text{Diff}_{\text{M-F}}$ CoG by vowel rounding were only produced in the control group, this variable being greater for an unrounded vowel context (Table 4b).

Similarly, in the control group only, $\text{Diff}_{\text{M-F}}$ CoG values were higher in females for both an unrounded (t_{Yuen} ($_{84.8}$) = 5.58, *p* < .001) and rounded (t_{Yuen} ($_{97.45}$) = 3.66, *p* < .001) vowel context (Table 4b).

In contrast, when comparing the groups among themselves, all showed significant differences in *Diff*$_{M\text{-}F}$ *CoG* for both vowel contexts (Figure 3). Accordingly, the control and dysarthria groups showed a greater significant difference when the vowel accompanying the fricative was unrounded, while this was observed in the control and AoS groups when it was rounded, although only approaching significance. Finally, the AoS and dysarthria groups varied more in terms of this variable in an unrounded vowel context (Table 4b).

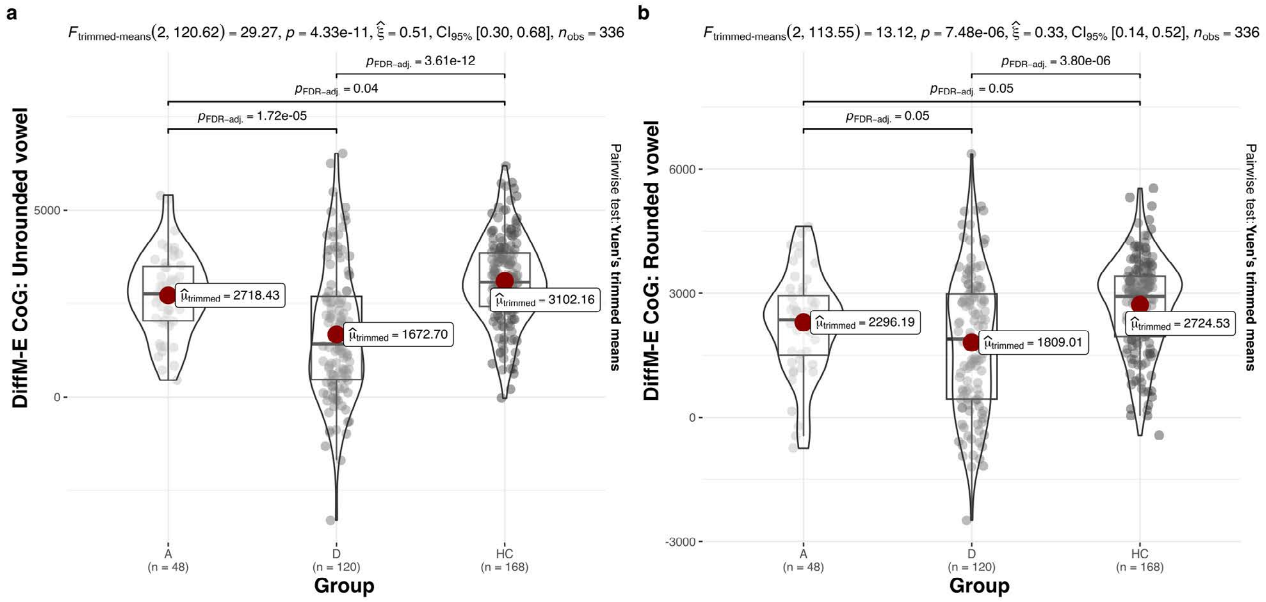

Figure 3. Differences in $\text{Diff}_{\text{M-E}}$ CoG between groups according to vowel rounding context.

Discussion

Our study sought to determine whether spectral measures of the alveolar voiceless fricative /s/ in Central-Peninsular Spanish could serve to identify differences in intra-syllabic anticipatory coarticulation among dysarthric, AoS, and healthy speech. To this end, several variables (peak spectral frequency in the mid-band (Freq_{Mid}), magnitude of the change in peak spectral frequency in this band during fricative production (DFreq), and spectral moments) were measured in speech samples obtained during the production of monosyllabic words with the fricative /s/ in initial position and an unrounded or rounded vowel in second position adjacent to the fricative.

Intra- and inter-group differences according to vowel context

As expected, our control group showed significant differences in spectral measures depending on vowel rounding, as in English, except in the second and third moments. Hence, our measures were higher in an unrounded vowel context, as reported previously for all measures except ΔFreq, which has been described as lower in this context (Jongman et al., 2000; Katz et al., 1991; Koenig et al., 2013; Nittrouer et al., 1989; Martel-Sauvageau et al., 2021). We nevertheless detected lower Freq_{Mid} and CoG values which may be explained by retracted apical-alveolar realization of the Central-Peninsular Spanish fricative having a lower frequency spectral profile compared to the two sibilant fricatives in English (/s/ and /ʃ/). Another explanation could be the choice of a smaller mid-frequency range (3 000 – 5 000 Hz), based on the maximum spectral peak records of Spanish (Barreiro, 1995; Martínez Celdrán, 1995; Martínez Celdrán & Fernández Planas, 2013) and also that we set out to examine the first spectral peak frequency and the effects of vowel rounding on it. Contrary to ΔFreq data found for English, we believe that a higher ΔFreq in an unrounded vowel context could be related to the frequency range where Freq_{Mid} appears (unrounded vowel context = 4 150 – 4 550; rounded = 3 750 – 4 050 Hz) and its transition towards the fourth formant of the adjacent vowel (unrounded vowel context = 3 600 – 4 100 Hz; rounded = 3 300 – 3 700 Hz). Similarly, this applies to $\text{Diff}_{\text{M-F}}$ CoG but this time the transition would be towards the third vowel formant (unrounded vowel context = 2 200 – 2 800 Hz; rounded = 2 400 – 2 600 Hz), considering the frequencies where the middle and end CoGs appear (unrounded vowel context = 6 140 Hz and 3 026 Hz, respectively; rounded = 5 329 Hz and 2 549 Hz, respectively). As is known, both high formants vary depending on the length of the vocal tract, which in turn may be affected by tongue position and lip rounding (San Segundo, 2010; Albalá et al., 2008). Therefore, it is possible that the ΔFreq measurement is higher in an unrounded vowel context because Freq_{Mid} and CoG in the middle zone are further apart in relation to the fourth and third vowel formants, creating a sharp change in the end zone of the fricative. In a rounded vowel context, however, the data reflect that lip coarticulation occurs from the fricative onset, with Freq_{Mid} and CoG values closer to those corresponding to the fourth or third vowel formants, resulting in a lower ΔFreq. In a way, this conceptually coincides with the rationale of Koenig et al. (2013), as with this measurement this author tries to reflect the extent of coarticulation, and our data seem to illustrate the different ways in which coarticulation takes place according to the adjacent vowel. In general terms, lower values of these measurements in a rounded vowel context would indicate greater anterior cavity resonance and a smaller labial aperture because of lip rounding (Heinz & Stevens, 1961). Thus, it is also possible that SD is lower, consistent with data from English, but without reaching significance (Koenig et al., 2013), as in a rounded vowel context, the constriction's opening is narrower, generating less sound dispersion than in an unrounded vowel context.

In our AoS group, differences in spectral measures according to vowel rounding were not fully confirmed. While Freq_{Mid} and ΔFreq were found to vary depending on the adjacent vowel as in the control group and contrary to what was expected, there were no significant differences in spectral moments, as expected. The fact that Freq_{Mid} and ΔFreq varied significantly according to the extent of vowel rounding in both this and the other two groups (dysarthria and control) suggests that these measures are perhaps more sensitive to anticipatory changes in coarticulation than spectral moments. In general, our AoS group seemed to show some signs of anticipatory coarticulation in both unrounded and rounded vowel contexts, although differences with the control group were greater in a rounded vowel context for CoG, SD and skewness. Addit$_{\text{iona}}$lly, ΔFreq was also higher and DiffM-F CoG was lower in AoS in this context, but not significantly so. Thus, we consider that all of this points to lesser adjustment to lip rounding from the start of the fricative and/or a more anterior tongue position when producing rounded vowel sequences. In contrast, in an unrounded vowel context in AoS, ΔFreq was smaller and Freq_{Mid} lower in all zones, CoG and SD were higher, skewness was lower, and $\text{Diff}_{\text{M-F}}$ CoG smaller, significantly distinguishing this group from the control group. This would also indicate reduced coarticulation due to less constriction and/or a less anterior lingual position in these sequences. These data are consistent with the findings of other acoustic, kinematic, and perceptual studies in terms of delayed lip rounding, less anticipatory lingual displacement, misdirected articulatory gestures, and distorted spatial configurations (Bartle-Meyer et al., 2009; Bartle-Meyer & Murdoch, 2010: Southwood et al., 1997; Ziegler & von Cramon, 1985, 1986a, 1986b). These results might therefore point to a problem not only in inter-articulator planning but also in intra-articulator planning in individuals with AoS, and thus in the feedforward control system.

In our dysarthria group, neurophysiological limitations were clearly reflected by a smaller difference in Freq_{Mid} due to adjacent vowel rounding during the course of the fricative when compared to the other two groups. The same occurred with CoG when compared to the control group. Hence, our Freq_{Mid} measures in the dysarthric speaker group were lower than those of the other groups in an unrounded vowel context of the fricative, and higher than those recorded in the control group but like values observed in the AoS group in a rounded vowel context. This suggests similar difficulties in both dysarthria and AoS. However, Freq_{Mid} and $\text{Diff}_{\text{M-F}}$ CoG measures in an unrounded vowel context were able to distinguish the pathological groups from each other. This suggests that tongue tip involvement in producing the fricative + unrounded vowel sequence, along with the extent of restriction to coarticulation of these sounds, had a more marked effect in the dysarthria group, possibly because of the speakers' neurophysiological and proprioceptive limitations (Ghosh et al., 2010) negatively affecting the feedback control system's ability to make context adjustments. Conversely, in a rounded vowel context, our AoS group showed higher CoG and SD values, and although the difference was not significant, this could reflect greater limitations in these individuals. In fact, the AoS group showed a greater difference versus the control group in these spectral measures. Thus, while both disorders seem to affect the functioning of the feedforward control system, we speculate that underlying mechanisms vary in each case. In AoS, in the absence of neurophysiological alterations, the problem could lie in failure of the feedforward control system. However, in dysarthric speakers, neurophysiological dysfunction could lead to abnormal proprioceptive feedback (acoustic and somatosensory) affecting processes of comparison and fine adjustment of motor commands via the feedback control system, with an indirect effect on the feedforward control system.

Differences according to speaker sex

As in other languages, females produce the fricative sound more anteriorly and with a narrower constriction, as indicated by their higher initial and middle CoG and $Freq_{Mid}$ measures (Avery & Liss, 1996; Flipsen et al., 1999; Fox & Nissen, 2005; Fuchs & Toda, 2010; Jongman et al., 2000; Yeni-Komshian & Soli, 1981). Similarly, transition to the adjacent vowel seems more pronounced in females, who show a lower end $Freq_{Mid}$ and greater ΔFreq, SD and $Diff_{M-F}$ CoG while maintaining lower skewness than males. Negative skewness values were not, however, observed here, possibly due to phonetic differences between the fricatives of different languages. Both sexes in our control group were able to acoustically differentiate the vowel rounding context in terms of $Freq_{Mid}$, CoG and ΔFreq, closely related to the articulatory place. In contrast, while our pathological groups with motor disorders showed a similar pattern in almost all spectral measures to that of the control group, scarce differences by sex were observed indicating a role played by articulatory precision besides anatomic-physiological variations. Thus, for example, in this study males with dysarthria displayed a significantly higher CoG and SD at the fricative end, indicating less anteriorization and greater tongue width than same-sex controls. This was not the case of females in both groups. $Freq_{Mid}$ in the middle zone also serves as an example whereby when compared by sex, both sexes in the control and dysarthria groups showed significant differences with lower values observed in dysarthric speakers, especially in females, yet when comparing AoS and control, differences were only seen in females with values being lower in AoS.

Conclusions

In our control group of healthy speakers, some of the measures examined here clearly indicated an effect of rounding of the vowel adjacent to the fricative /s/ in that these were higher in an unrounded vowel context. This effect, however, was not as clear in the dysarthric and apraxic speakers. Some measures also varied significantly according to speaker sex, their values being higher in females, except for skewness which was less positive. Compared to the control group, greater differences in most spectral measures were observed in a rounded vowel context in AoS, and in an unrounded vowel context in dysarthria. Both pathological groups seemed to present alterations in both motor control systems, but presumably for different reasons. It would be interesting to obtain both acoustic and articulatory measures in larger samples to better understand the differences between these speech disorders.

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Declaration of Interest

The authors declare no conflict of interest.

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