

Differential Spectral Characteristics of the Spanish Fricative /s/ in the articulation of individuals with Dysarthria and Apraxia of Speech

Abstract

Purpose: This study examines whether there are differences in the speech of speakers with dysarthria, speakers with apraxia and healthy speakers in spectral acoustic measures during production of the central-peninsular Spanish alveolar sibilant fricative /s/.

Method: To this end, production of the sibilant was analyzed in 20 subjects with dysarthria, 8 with apraxia of speech and 28 healthy speakers. Participants produced 12 sV(C) words. The variables compared across groups were the fricative's spectral amplitude difference (AmpD) and spectral moments in the temporal midpoint of fricative execution.

Results: The results indicate that individuals with dysarthria can be distinguished from healthy speakers in terms of the spectral characteristics AmpD, standard deviation (SD), center of gravity (CoG) and skewness, the last two in context with unrounded vowel, while no differences in kurtosis were detected. Participants with AoS group differ significantly from healthy speaker group in AmpD, SD and CoG and Kurtosis, the first one followed unrounded vowel and the latter two followed by rounded vowels. In addition, speakers with apraxia of speech group returned significant differences with respect to speakers with dysarthria group in AmpD, CoG and skewness.

Conclusions: The differences found between the groups in the measures studied as a function of the type of vowel context could provide insights into the distinctive manifestations of motor speech disorders, contributing to the differential diagnosis between apraxia and dysarthria in motor control processes.

Keywords:

Acoustic analysis, apraxia of speech, dysarthria, fricative, spectral moments, spectral slope.

26 **1 Introduction**

27 Dysarthria (Dys) and apraxia of speech (AoS) are motor speech disorders that may arise
28 following brain injury. Both have been described as different alterations of motor processes: of
29 programing and motor execution in the former and of phonetic-motor planning in the latter.
30 Clinically, Dys is characterized by impairments in breathing, phonation, resonance, articulation,
31 and prosody. These result from injuries to the central or peripheral nervous system, leading to
32 dysfunctions in muscle tone, strength, range, movement speed, and muscular synergies. On the
33 other hand, AoS involves difficulties in translating phonologically well-formed structures into
34 previously learned kinematic information for executing desired articulatory movements.
35 Importantly, there are no impairments in muscle tone, sensorimotor processing, or linguistic
36 information processing. These challenges manifest as phonetic or prosodic alterations (McNeil
37 et al., 2009).

38 According to the Directions Into the Velocities of Articulator (DIVA) model of motor
39 control, dysarthria would occur when there are alterations in any of the perceptual-productive
40 integration processes that make up the feedback control system, whereas apraxia would respond
41 more to alterations in the learned and stored plans and inter- and intra-articulatory commands
42 planned by the feedforward control system (Guenther, 2016).

43 However, both disorders share articulatory difficulties in consonants such as the
44 voiceless alveolar sibilant fricative /s/. This sound is one of the most complex in articulatory
45 terms and, due to its acoustic and temporal stability properties, is an ideal candidate for
46 examining whether there are acoustic differences in its production by individuals with motor

47 speech disorders (Hardcastle, 1976; Haley, 2002; Behrens & Blumstein, 1988; Kim et al.,
48 2010).

49 It is also known that its phonetic realization is influenced by the speaker's sex. Various
50 studies indicate that there are phonetic differences between male speakers and female speakers,
51 which are reflected in the acoustic properties of this sound (Avery & Liss, 1996; Flipsen et al.,
52 1999; Fox & Nissen, 2005; Fuchs & Toda, 2010; Herrmann et al., 2014; Jongman et al., 2000;
53 Koenig et al., 2013; Yeni-Komshian & Soli, 1981).

54 Additionally, one speech phenomenon commonly used to compare these motor
55 disorders is coarticulation, where the production of a specific sound is influenced by the
56 presence of an adjacent one. There are two types of coarticulation: carryover and anticipatory.
57 The latter coarticulation (from right to left) is particularly relevant for this study due to the
58 influence of vocalic rounding on the fricative. It reflects the ability to generate acoustic-
59 articulatory overlaps of posterior segments onto anterior segments through the neuromuscular
60 coordination of intra-segmental and inter-segmental articulators by means of anticipatory
61 cognitive motor planning (d'Alessandro et al., 2019; Daniloff & Moll, 1968; Hertrich &
62 Ackermann, 1999; Katz, 2000; Whalen, 1990).

63 Most studies on the fricative /s/ have focused on acoustically analyzing its properties
64 through differences in spectral amplitude and different spectral moments (Nataraj et al., 2017).
65 These studies have been carried out by analyzing languages other than Spanish. Given the
66 variations in phonetic features across languages attributable to the distribution of their phonetic
67 inventory, it is pertinent to investigate whether spectro-acoustic differences in Spanish parallel
68 those observed in other languages.

69 Below, we describe the most relevant results obtained for this sound in terms of spectral-
70 acoustic parameters.

71 *1.1 Difference in the fricative's spectral amplitude (AmpD)*

72 To examine the spectral shape of the fricative, amplitude differences in different bands
73 of the spectrum have been considered. Specifically, some studies have used the difference in
74 amplitude between minimum frequency in the low-frequency band and peak frequency in the
75 medium-frequency band ($AmpD_{M-LMin}$) as a measure of spectral shape, allowing quantification
76 of the degree of sibilance; or the difference in amplitude between the minimum appearing in
77 the 0 – 2 kHz band and maximum in the 0.5 – 17 kHz band (A_d : dynamic amplitude) (Klein et
78 al., 2019; Koenig et al., 2013; Jesus & Shadle, 2002; Shadle & Mair, 1996). For the English
79 alveolar fricative /s/, Koenig et al. (2013) noted in adolescent speech that $AmpD_{M-LMin}$ vary
80 during production, with values ranging from 21 – 30 dB. In this case, an increase in $AmpD_{M-}$
81 $LMin$ occur in the temporal midpoint of the fricative compared to the temporal initial point. This
82 indicates that as the amount of constriction increases, there is more air turbulence leading to the
83 increased amplitude in medium frequency regions and a decrease in high and low ones.
84 Employing these same measures but with division of the spectrum in different frequency bands,
85 Klein et al. (2019) examined the Russian alveolar fricative in adults. For the /s/ with no auditory
86 feedback alteration, the value of $AmpD_{M-LMin}$ was 45.14 dB for female and 41.46 dB for male.
87 These values are close to those obtained by Jesus and Shadle (2002) for adults in Portuguese,
88 but higher than those reported by Koenig et al. (2013) for adolescents in English. This variation
89 could be attributed to the less consistent production of the /s/ constriction by adolescent
90 speakers compared to adults, as hypothesized by Koenig et al. (2013). No studies have been
91 found employing this measure to assess the speech of individuals with motor speech disorders.

92 Authors as Chen and Stevens (2001) provide a conceptually similar measure, the AmpD.
93 They calculate it by subtracting the average amplitude of peak frequencies below 4 kHz from
94 the amplitude of the peak frequency above 4 kHz. In their analysis of the English alveolar
95 fricative in persons with dysarthric speech, they found that, compared to healthy speaking
96 individuals, these subjects showed a lower amplitude at higher frequencies, determining a
97 smaller AmpD. While the healthy speaker group showed an AmpD of 14 dB within the expected
98 range of 5 – 20 dB, values in participants with Dys were below this range or in its lower region.
99 In the case of speakers with AoS, we are unaware of any study that has measured the difference
100 in spectral amplitude of the voiceless alveolar fricative /s/.

101 When sociophonetic aspects such as sex and its effect are taken into consideration, it is
102 observed that there are differences between healthy adults. Thus, females present a more
103 pronounced spectral slope than males (Fox & Nissen, 2005). The authors attribute the
104 differences to a mixture of behavioral or learned factors together with differences in the size of
105 the oral cavity. Otherwise, the few studies that disaggregate data by sex in dysarthria, such as
106 Chen and Stevens (2001) show that there is no clear sex difference.

107 *1.2 Spectral moments*

108 Other variables employed as measures of the fricative are the spectral moments: center
109 of gravity (CoG), standard deviation (SD), skewness and kurtosis. The measure CoG reflects
110 the mean of the frequencies weighted by their amplitudes. Standard deviation measures the
111 distance of frequencies from the mean and thus describes the dispersion of the spectrum.
112 Skewness is used to assess the region of the frequency spectrum where most energy
113 accumulates in relation to the mean. Kurtosis provides information on the degree of energy

114 concentration at a given frequency and the presence of energy in the more extreme regions of
115 the frequency spectrum. Spectral moments have also been the focus of studies designed to
116 estimate the impact on the fricative's spectrum of segmental linguistic variables such as
117 rounding of the vowel adjacent to the fricative.

118 In Spanish speech, established values for the different spectral moments in healthy-
119 speaking male adults are CoG= 4 827 – 5 911 Hz, SD= 1 552 – 2 353 Hz, skewness= 0.25 –
120 1.85, and kurtosis= 0.41 – 6.75, with existing variations according to the adjacent vowel
121 (Cicres, 2011). Complementarily, in the Spanish spoken in Paraguay, the fricative varies
122 significantly in terms of all spectral moments when adjacent to the vowel /u/ compared to /i/
123 (Jiquilin-Ramirez & Albano, 2014). This vowel rounding effect is also observed in English,
124 whereby fricatives accompanied by unrounded vowels (e.g., /i/) return a higher CoG, lower SD
125 and a lower skewness with a tendency towards negative values. This was more clearly observed
126 in the temporal midpoint of the fricative in different age groups (Jongman et al., 2000; Koenig
127 et al., 2013; Nittrouer et al., 1989).

128 Differences in spectral moments have also been described in persons with motor speech
129 disorders of neurological origin. Hence, although few studies have analyzed spectral
130 characteristics in speakers with AoS, some studies have found lower CoGs than those present
131 in healthy speakers for the English fricative /s/. They have also detected greater intra-subject
132 variability and intra-segment modifications in the production of the fricative (Haley, 2002;
133 Harmes et al., 1984; Katz et al., 2003; Shuster & Wambaugh, 2000; Wambaugh et al., 1995).

134 In the case of speakers with Dys, there is a discrepancy in the results of studies
135 examining the fricative /s/ in English, possibly reflecting the diverse types of dysarthria

136 analyzed. Some authors report that CoG and kurtosis are lower, and higher SD and positive
137 skewness in subjects with cerebral palsy or amyotrophic lateral sclerosis compared to healthy
138 individuals. However, others find no difference in CoG in the latter and multiple sclerosis, or
139 in kurtosis and SD in Parkinson's disease compared to healthy speakers (Burder et al., 1996;
140 Hernandez et al., 2019; Kim, 2017; Tjaden, 2003).

141 In analyses of the fricative in relation to the phonetic context, it has been shown that in
142 dysarthria due to Parkinson's disease there are changes in CoG and SD like those observed in
143 healthy speakers depending on the adjacent vowel. Consequently, a lower CoG and higher SD
144 are found when the fricative is accompanied by a rounded vowel. Notwithstanding, skewness
145 and kurtosis do differ and return opposite values to those found in healthy speakers.
146 Accordingly, skewness in persons with dysarthria due to Parkinson's is less negative showing
147 higher values, and kurtosis is flatter (Martel-Sauvageau et al., 2021).

148 When the variable sex is examined from a sociophonetic perspective, studies in healthy
149 English speakers have shown higher CoG, SD and kurtosis in female than in male, while
150 skewness shows the opposite trend and being more negative in female showing lower or
151 negative absolute values (Flipsen et al., 1999; Fox & Nissen, 2005; Jongman et al., 2000).

152 Few studies have assessed the possible influence of sex on the production of the fricative
153 /s/ in people with a motor speech disorder. For example, Tjaden and Turner (1997) analyzed
154 the fricatives of dysarthria due to amyotrophic lateral sclerosis (ALS). Results indicated lower
155 CoG and higher skewness values in ALS females compared to healthy females. Similarly, males
156 showed no difference in CoG, but did for skewness. Thus, in asymmetry, they were lower than

157 in healthy males. Notwithstanding, over time, fricative execution patterns become like those
158 observed in healthy speakers.

159 So far, it remains to be determined whether this fricative is produced differently in
160 speakers with Dys and AoS as these disorders have distinct pathophysiologies and presumably
161 affect different stages of motor processing. It has also not been established whether in Spanish,
162 given that the phonetic characteristics of the sounds vary in different languages, this fricative
163 presents the same spectro-acoustic characteristics as those described in other languages, if there
164 are differences by sex and for people with these disorders. Furthermore, the analysis of how
165 anticipatory coarticulation depends on the context may reveal differential features between both
166 pathologies (Reetz & Jongman, 2020; Whalen, 1990; Zharkova et al., 2012).

167

168 *1.3 Aims of the study.*

169 The aim of the present study was to investigate potential spectro-acoustic differences in
170 the production of the fricative /s/ among individuals with dysarthria, apraxia of speech and
171 healthy within a population of speakers of central peninsular Spanish. Specifically, we
172 examined whether there were variations in the production of the /s/ sound as an apical-alveolar
173 voiceless fricative. And, if they exist, whether these differences could provide data that suggest
174 variations in different levels of motor control. Furthermore, whether the spectro-acoustic
175 characteristics of the fricative /s/ of these speakers are similar to those present in other
176 languages. And finally, the aim was to test whether there were any differences in spectro-
177 acoustic characteristics that might be linked to the sex of the speaker. For this purpose, objective

178 methods of acoustic analysis and simple non-invasive speech tasks were used. The hypotheses
179 proposed were the following:

180 (1) The spectral amplitude difference (AmpD), CoG and kurtosis will be lower while SD and
181 skewness will be greater in the Dys speakers group than healthy speakers group. These
182 differences are specifically attributed to neuromuscular limitations and acoustic-
183 proprioceptive distortions, potentially suggesting an underlying alteration in the feedback
184 control system.

185 (2) The AoS speakers group will show lower AmpD and higher CoG and SD and lower
186 negative skewness when the fricative is followed by a rounded vowel than the healthy
187 speakers group. This can be attributed to the increased demand for motor planning in the
188 context of a rounded vowel, necessitating intricate intra- and inter-articulatory commands.
189 These observations may suggest an altered feedforward control system responsible for
190 anticipatory coarticulation.

191 (3) The AoS speakers group will return higher AmpD, CoG and skewness and lower SD and
192 kurtosis values than the Dys speakers group. These differences will be greater in unrounded
193 vowel contexts, since in rounded contexts the AoS speakers group will show worse
194 performance.

195 (4) The groups with motor speech disorders will not present differences by sex while healthy
196 females will present higher AmpD, CoG, kurtosis, negative or lower skewness and lower
197 SD than healthy males.

198

199 **2 Methodology**

200 2.1 Participants

201 Three groups of participants were established: Dys (n=20), AoS (n=8) and Healthy
202 speakers (n=28) (Table 1). These participants were selected among the patients of two
203 institutions specializing in brain injury: [blinded for review] and [blinded for review].
204 The clinical diagnosis of the motor speech disorder was conducted by the physicians at the
205 participant's referred hospital center. Inclusion-exclusion criteria were based on the presence of
206 an acquired brain lesion without aphasia and a diagnosis of AoS or Dys according to clinical
207 criteria based on Duffy (2020) (Table 2). Participant were required to demonstrate the capacity
208 to reproduce sounds, be a speaker of central peninsular Spanish, have no prior tracheotomy,
209 self-reported no hearing loss, and exhibit no organic vocal lesions. Fulfillment of these
210 diagnostic criteria was determined by the centers' speech therapists.
211 The severity of motor speech disorder was assessed using the modified Motor Speech Disorders
212 Severity Rating Scale from Hillel et al. (1989), as published in Duffy (2020). Table 1 includes
213 the mean severity for each motor disorder along with the range of scores. This scale measures
214 speech comprehensibility, disregarding specific daily activities, with ratings ranging from
215 normal speech patterns (10 or 9) to noticeable speech disruptions (8 or 7), behavioral
216 adjustments (6 or 5), utilization of Augmentative and Alternative Communication (AAC)
217 methods (4 or 3), to the absence of meaningful speech (2 or 1). Both groups exhibit an average
218 severity of 7, with ranges of 6-8 in the AoS speakers group and 5-8 in the Dys speakers group.
219 The healthy speakers group was recruited a posteriori using the snowball method so that they
220 were matched as much as possible with persons in the motor disorder groups for age and sex.
221 All controls were adults who self-reported no auditory disorder or vocal organic lesions and

222 were speakers of central-peninsular Spanish. Participation was voluntary and written informed
223 consent was required from each participant.

224 The study protocol was approved by the Deontological Ethics Commission of the
225 Faculty of Psychology, [blinded for review] and complied with current [blinded for review] and
226 [blinded for review] legislation regarding personal data protection (Organic Law of Data
227 Protection/ and General Data Protection Regulation, respectively).

228 Table 1 around here

229 Table 2 around here

230

231 *2.2 Materials*

232 A list of 12 monosyllabic real words with structure sV(C) was prepared to include the
233 same number of unrounded (i.e., a, e, i) and rounded (i.e., o, u) vowels: *sal, sus, se, sor, sin, su,*
234 *ser, son, si, sur, sed, sol.*

235 *2.3 Procedure*

236 The experimental task formed part of a wider protocol of sound production tasks and
237 consisted of repeating each word after listening to the examiner. Audio recordings from each
238 participant were made in a single session within a quiet room (ambient noise >30dB signal-to-
239 noise ratio). A Shure SM48 microphone was used connected to a MacBook Pro computer via
240 the Focusrite Scarlett 2i2 audio interface, which allowed sound capture and digitization.
241 Audacity 2.2.2. software was used to record and store the sound with a sampling frequency of
242 44 100 Hz and 16-bit quantization. The instructions for the experimental task were verbally

243 explained during the recording session. To ensure understanding, a pre-test was conducted
244 using similar test items to the ones used in the experiment (e.g., "san" and "so"). The order of
245 word presentation was the same for each participant. In this manner, 672 non-pathological and
246 pathological samples of words starting with the fricative /s/ were obtained in 56 participants
247 (12 words each).

248 *2.3.1 Sample segmentation and labeling*

249 Speech samples were segmented and labeled by three speech therapists trained in
250 acoustic phonetics and with experience with the program Praat 6.0.42 (Boersma & Weenink,
251 2020). For the segmentation and labeling of the samples, a script was developed in Praat
252 (Boersma & Weenink, 2020) and the TextGrid function of the program was used. The script
253 allowed to determine, on the one hand, the onset and end of the fricative including objective
254 criteria of acoustic energy change within the 3500Hz-8500Hz region calculated with the linear
255 predictive coding (LPC) autocorrelation and discrete Fourier transform (DFT) analysis
256 functions of the program and, on the other hand, the onset of the vowel with the presence of
257 vowel formants and glottal pulse in the spectrogram ([blinded for review]). The relative error
258 (the difference between the identification of the segment's onset by the two observers expressed
259 as a percentage of the reference value, which is the total duration of the segment) has been used
260 to calculate the average cumulative relative error. Subsequently, this average has been
261 converted into a percentage, which serves as a measure indicating the average discrepancy
262 between the observers, allowing for comparison and evaluation of the level of agreement
263 between them. Percentage agreement between observers was over 90%: 94% for observer 1
264 versus 2 and 3, and 91% between observers 2 and 3. The same procedure was followed for
265 intraobserver comparisons on two segmentations conducted 3 months apart. Agreement in this

266 case was (95.4%).

267 2.3.2 Acoustic analysis

268 The acoustic measures, namely spectral amplitude differentiation (AmpD) and spectral
269 moments, determined in individuals with motor speech disorders, have been utilized to analyze
270 the production of fricatives in different languages (Chen & Stevens, 2001; Kim, 2017; Tjaden
271 & Turner, 1997). For AmpD, we adapted the procedure designed by Chen and Stevens (2001).
272 To this end, we selected the central 50 ms of the fricative, and millisecond by millisecond,
273 Hamming windows of 25 ms were established and analyzed. In this instance, unlike the
274 procedure of the mentioned authors, we analyzed the central part of the fricative using slightly
275 larger windows to capture relatively rapid spectral changes over the analyzed time. For spectral
276 moments, we examined the central 25 ms applying Hamming windows of duration 3.125 ms
277 each 1 ms. Thus, a smaller speech segment is analyzed with higher temporal and spectral
278 resolution to obtain a more precise measure of spectral moments. In both cases, the data will be
279 averaged, considering multiple windows per analyzed time, to better characterize speech
280 production peculiarities. All measures were calculated on scripts generated *ad hoc* in Praat as
281 indicated below:

282 (1) AmpD was calculated as the difference between the amplitude of the spectral peak of
283 highest frequency situated in the 4 000 – 8 000 Hz band, and the average amplitudes
284 of the second and third amplification peaks in the spectrum of the fricative using the
285 equation:

$$286 \quad AmpD = Ahf - \frac{(A2f + A3f)}{2}$$

287 where A_{hf} is the amplitude of peak frequency above 4 000 Hz, and A_{2f} and A_{3f} are the
288 amplitudes of the second and third amplification peaks in the spectrum in dB. To obtain
289 the values of A_{hf} , A_{2f} and A_{3f} in the different windows, the power spectrum was
290 extracted, and filters applied of band-passes 4 000 – 8 000 Hz, 2 000 – 3 000 Hz and
291 3 000 – 4 000 Hz. From this, we obtained the frequency showing the greater amplitude
292 for each of the measures and the spectral power associated with this frequency. This was
293 then transformed in auditory dB using the equation: $10 \cdot \log_{10}(\text{pow}/4 \cdot 10^{-10})$. With the
294 values obtained for each window, the mean of those amplitude peaks was determined,
295 and the spectral amplitude difference calculated.

296 (2) Spectral moments (CoG, SD, skewness, kurtosis). To each window, a Fast Fourier
297 transform (FFT) and 1 000 – 11 000 Hz bandpass filter were applied to avoid the
298 influence of possible sonority due to the adjacent vowel and a smoothening of 100 Hz.
299 In the spectrum obtained, the formula proposed by the Praat program was used to
300 calculate the different moments with their default values using a modification of the
301 script designed by Elvira-García (2014). Thus, spectral moments weighted by the power
302 spectrum have been computed, but they have not been normalized by the total power of
303 the spectrum.

304 *2.4 Statistical analysis*

305 The data obtained in Praat were analyzed with R (R Core Team, 2020) to generate
306 descriptive and inferential statistics for each variable in each group. The data collected from the
307 12 words were treated as independent observations in the analysis. Robust methods are used
308 due to the presence of outliers, especially in the groups with pathology, together with the
309 absence of normality (measured with Lilliefors' Kolmogorov-Smirnov test) and homogeneity

310 of variances (measured with the Fligner-Killeen test) of the samples. Specifically, the *WRS2*
311 library from the *WRS2* package (Mair & Wilcox, 2020) and the *ggbetweenstats* and *grouped*
312 *ggbetweenstats* libraries from the *ggstatsplot* package (Patil, 2021) are used.

313 Therefore, the robust estimators for the descriptive statistics were the 5% trimmed mean
314 in each group with an alpha of 0.5 (mean function) and the median of the absolute standard
315 deviation (mad function).

316 For inferential statistics, differences between groups were analyzed with an
317 heteroscedastic one-way ANOVA for 5% trimmed means in each group and a bootstrapping of
318 5000 (*t1waybt* function). Subsequently, pairwise comparisons between groups, by vowel
319 rounding and by sex were performed with Yuen's test for 5% trimmed means in each group
320 (*yuen* function) applying a bootstrapping of 5000. A control adjustment for the false discovery
321 rate (FDR) was used in both analyses. In addition, effect size was estimated with the effect size
322 explanatory measure (ξ), for the former, and with the Algina-Keselman-Penfield robust
323 standardized difference (δ_R^{AKP}), for the latter. Due to the composition of the group of
324 participants with dysarthria, where there is a majority of spastic dysarthric cases but some
325 instances of other types of dysarthria, and in order to ensure that the effects were not influenced
326 by the type of dysarthria, additional analyses were performed considering only the spastic cases.

327

328 **3 Results**

329 Descriptive data for the measures of articulatory precision obtained are provided by
330 groups as overall values and values stratified by the factors adjacent vowel rounding and
331 speaker sex (Table 3).

332 Table 3 around here

333 The results of the analyses of the factors group, vowel rounding, and sex are summarized
334 in Table 4 and the pairwise comparisons of these factors in Table 5.

335 Tables 4 and 5 around here

336 Below we provide the results obtained for each acoustic measure. For each measure, we
337 first describe the effects of vowel rounding and speaker sex followed by a description of the
338 group effect.

339 *3.1 Difference in spectral amplitude of the fricative (AmpD)*

340 When we examined the effect of vowel rounding, we observed that fricatives followed
341 by an unrounded vowel showed a higher spectral AmpD. Further, an interaction between vowel
342 rounding and subject group was detected in healthy speakers and AoS speakers groups, but not
343 in the Dys speakers group. These differences were greater in the healthy control group than
344 AoS speakers group (Figure 1).

345 Fig. 1 around here

346 For the factor sex, although females returned a higher spectral AmpD, both sexes
347 showed more AmpD when the fricative was followed by an unrounded vowel (female speakers:
348 $t_{Yuen} = 6.86$; $p < 0.001$; $df = 195.29$, male speakers: $t_{Yuen} = 4.73$; $p < 0.001$; $df = 385.44$).
349 However, the effect of rounding was higher in female speakers than in male speakers, with a
350 larger difference in AmpD between unrounded and rounded vowel context in female speakers.
351 Moreover, differences between male and female speakers were present for fricatives followed
352 by both vowel types (unrounded: $t_{Yuen} = 6.56$; $p < 0.001$; $df = 157.79$; rounded: $t_{Yuen} = 2.21$; $p =$

353 0.03; $df = 183.53$). When we considered only the healthy speakers group, both male and female
354 speakers exhibited greater spectral AmpDs when the adjacent vowel to the fricative was
355 unrounded (male: $t_{Yuen} = 8.06$; $p < 0.001$; $df = 178.64$, female: $t_{Yuen} = 9.45$; $p < 0.001$; $df =$
356 89.85). Male speakers had reduced spectral AmpD compared to female speakers when the
357 vowel accompanying the fricative was unrounded ($t_{Yuen} = 13.67$; $p < 0.001$; $df = 88.48$) and
358 rounded ($t_{Yuen} = 5.59$; $p < 0.001$; $df = 96.84$). On the other hand, in the AoS speakers group,
359 female speakers obtained higher spectral AmpD compared to male speakers, but only in the
360 unrounded vowel context ($t_{Yuen} = 3.26$; $p = 0.002$; $df = 40.94$). In fact, only females showed
361 differences in vowel rounding ($t_{Yuen} = 3.93$; $p < 0.001$; $df = 40.76$). In contrast, the dysarthria
362 speakers group did not differ significantly by sex, obtaining a similar AmpD.

363 For the group factor, differences emerged between the dysarthria speakers and healthy
364 speakers groups, spectral AmpD for the latter being greater than for the former. The difference
365 between groups was greater when the fricative was followed by an unrounded. The AoS
366 speakers and Dys speakers groups show the same trend, with higher values for the former.
367 However, the differences between the group of speakers with Dys and the group of speakers
368 with AoS disappear when considering only speakers with spastic dysarthria for rounded vowels,
369 and they only occur for unrounded vowels. On other hand, the AoS speakers group differs from
370 the healthy speakers group only when fricatives followed by unrounded vowels are compared,
371 attaining lower spectral AmpD values.

372 *3.2 Center of gravity (CoG)*

373 These results indicate an effect of vowel rounding in the sense that fricatives followed
374 by an unrounded vowel showed higher CoG than those followed by a rounded vowel. In our

375 analysis of vowel rounding in the three groups, this difference was detected in the healthy
376 speakers and AoS speakers group, but not in dysarthria's, being greater in the healthy speakers
377 group (Figure 2).

378 Fig. 2 around here

379 When we considered the effect of the factor speaker sex, it appears that female speakers
380 showed a higher CoG than male speakers. This is also true when looking at the healthy
381 speakers group in isolation. Both male and female speakers featured different CoG values
382 according to rounding of the vowel adjacent to the fricative (male speakers: $t_{Yuen} = 6.38$; $p <$
383 0.001 ; $df = 202.52$, female speakers: $t_{Yuen} = 7.85$; $p < 0.001$; $df = 97.93$). Moreover, they differed
384 between each other when the vowel was unrounded ($t_{Yuen} = 10.54$; $p < 0.001$; $df = 86.52$) and
385 rounded ($t_{Yuen} = 5.62$; $p < 0.001$; $df = 94.71$). Likewise happens in the AoS speakers group, with
386 female speakers also achieving higher CoGs, although this difference is only significant for
387 fricatives with unrounded vowels ($t_{Yuen} = 4.95$; $p < 0.001$; $df = 32.13$). In this group, only female
388 speakers show different CoGs according to the adjacent vowel, being higher in unrounded (t_{Yuen}
389 $= 3.78$; $p < 0.001$; $df = 41.91$). On the other hand, the dysarthria speakers group does not show
390 differences by sex. Male and female speakers also do not differ when their CoGs are analyzed
391 by vowel rounding. Similarly, neither does each sex distinguish between unrounded and
392 rounded CoG.

393 Finally, we confirmed an effect of the factor group. Accordingly, the CoG was higher
394 in the healthy speakers group than dysarthria speakers group. Intergroup differences were
395 however only significant when the vowel adjacent to the fricative was unrounded. For the AoS
396 speakers group, CoG was higher than in the healthy speakers group and was higher for rounded

397 vowels than unrounded vowels, although these differences were only significant for rounded
398 vowels. In another way, the AoS speakers and Dys speakers groups differ significantly, with
399 AOS speakers group showing higher values, especially for unrounded vowels.

400 3.3 Standard deviation (SD)

401 Rounding of the vowel that accompanies the fricative did not lead to significant
402 differences in SD. Notwithstanding, in all groups there was a trend towards a greater SD for
403 rounded adjacent vowels. Consequently, the largest differences are recorded in the AoS
404 speakers group followed by the dysarthria group and, finally, the healthy speakers group.

405 Similarly, no significant differences were found for the sex factor. When examining the
406 sexes separately, it appeared that female SDs were higher when the vowel adjacent was rounded
407 ($t_{Yuen} = 3.72$; $p < 0.001$; $df = 207.36$). Otherwise, male speakers showed the opposite pattern but
408 without significance ($t_{Yuen} = 1.43$; $p = 0.15$; $df = 387.11$). Because of this, there were only
409 differences by sex when the fricative was followed by an unrounded vowel ($t_{Yuen} = 4.63$; $p <$
410 0.001 ; $df = 198.3$). When analyzing each group separately, it was observed that male speakers
411 of the healthy group exhibited greater dispersion than female speakers counterparts, but only
412 in fricatives with unrounded vowels ($t_{Yuen} = 5.63$; $p < 0.001$; $df = 96.9$). However, female
413 speakers are the only ones who differentiate by rounding, obtaining higher values for their
414 fricatives with rounded vowel ($t_{Yuen} = 2.72$; $p < 0.001$; $df = 86.8$). The other two groups did not
415 differ by sex.

416 Analysis of group differences revealed higher SD in the Dys speakers and AoS speakers
417 groups than in healthy speakers group, regardless of the vowel following the fricative. Although
418 the Dys speakers group differed the most from the healthy speakers group, Dys speaker group

419 showed the greatest differences in fricatives with unrounded vowel, while the AoS speakers
420 and healthy speakers groups differed more in fricative with rounded vowel. However, SD
421 values were similar in the AoS speakers and Dys speakers groups and their differences not
422 being significant.

423 3.4 Skewness

424 Our results reveal an effect of rounding of the vowel following the fricative such that
425 fricatives accompanied by unrounded vowels showed a skewness that was more positive than
426 in the case of rounded vowels. In our examination of vowel rounding within each group, the
427 data for the individual groups reveal that there were significant differences only in the dysarthria
428 speakers group, where skewness was more positive in unrounded contexts.

429 In addition, with respect to the sex, male speakers showed a higher positive skewness
430 than female speakers, confirming that there was a sex effect. However, only male speakers
431 showed a skewness that differed significantly according to the vowel adjacent to the fricative.
432 Greater positive skewness was seen for the fricatives accompanied by unrounded vowels than
433 rounded ($t_{Yuen} = 3.60$; $p < 0.001$; $df = 384.74$). As for the groups, the healthy speakers and Dys
434 speakers groups are the only ones that show significant differences by sex. These differences
435 are greater in the healthy speakers group. This group was the only one to show significant
436 differences in skewness by sex, but only for unrounded vowels with more positive skewness
437 for male speakers ($t_{Yuen} = 4.09$; $p < 0.001$; $df = 51.17$). In the Dys speakers group, both sexes
438 showed similar values for skewness in fricatives without differentiation, regardless of the
439 adjacent vowel. Similarly, neither male speakers nor female speakers were observed to vary in
440 skewness of the fricative as a function of the vowel.

441 A group effect was also observed on skewness. Although initially the Dys speakers
442 group was distinguished from the AoS speakers and healthy speakers groups, when analyzing
443 the fricatives separated by vowel rounding, the groups behave differently. Thus, differences
444 between Dys speakers and healthy speakers groups were only found for those fricatives that
445 were accompanied by unrounded vowels. While these differences are not significant when
446 considering only the participants with spastic dysarthria. In contrast, differences between the
447 AoS speakers and Dys speakers groups were more significant in fricatives with rounded vowels.
448 Therefore, the Dys speakers group showed a positive moderate skewness that was greater than
449 that the observed for the remaining groups. Differently, there were no skewness differences
450 between the healthy speakers and AoS speakers groups.

451 3.5 Kurtosis

452 Kurtosis of the fricative's power spectrum failed to vary according to rounding of
453 adjacent vowels. However, the healthy control group showed an inverse pattern to that shown
454 by the AoS speakers and Dys speakers groups. Thus, the healthy speakers group showed a
455 higher kurtosis when the fricative was accompanied by a rounded vowel.

456 On the contrary, kurtosis did indeed vary according to sex. Accordingly, female
457 speakers showed a significantly higher kurtosis than male. Nevertheless, neither female
458 speakers nor male speakers showed different values of kurtosis according to the vowel
459 accompanying the fricative. Otherwise, only the healthy speakers group showed differences by
460 sex, with the kurtosis being higher in female speakers. Specifically, the difference occurred
461 when the fricative was followed by an unrounded vowel ($t_{Yuen} = 2.91$; $p < 0.001$; $df=67.6$). As

462 before, neither male speakers nor female speakers showed a different kurtosis according to the
463 adjacent vowel.

464 Likewise, all three participant groups showed similar kurtosis values. While the greater
465 difference was recorded between the Dys speakers group with the higher kurtosis, and the AoS
466 speakers group with the lower kurtosis, it lacked significance. However, there were significant
467 differences when looking at vowel type. Thus, when vowels adjacent to the fricative were
468 rounded, kurtosis was greater in the Dys speakers group than in the AoS speakers group and
469 similarly in the healthy speakers group. However, the healthy speakers group and the AoS
470 speakers group were significantly different, with greater values in the healthy speakers group.

471 **4 Discussion**

472 This study sought to identify acoustic measures related to the spectral shape of the
473 fricative /s/ that could serve to distinguish among healthy, Dys and AoS speakers groups. Our
474 study also provides values of acoustic variables of spectral distribution used in the production
475 of the voiceless alveolar fricative /s/ in a healthy population of speakers of central-peninsular
476 Spanish. For this purpose, participants produced monosyllabic words of sV(C) structure.
477 Acoustic measures previously used in other languages such as spectral moments and spectral
478 amplitude difference were used (Chen & Stevens, 2001; Jongman et al., 2000; Klein et al.,
479 2019; Koenig et al., 2013; Jesus & Shadle, 2002; Shadle & Mair, 1996). Our study also
480 examines the effect on these acoustic measures of factors linked to the phonetic context such
481 as vowel rounding and of sociophonetic factors such as speaker sex. We also introduce new
482 variations to the acoustic analysis methods applied in other studies (fricative segment
483 windowing or weighting and normalization of spectral moments).

484 *4.1 Healthy control group*

485 Our results in healthy speakers showed a high AmpD, although within the range
486 reported by Chen and Stevens (2001). This difference could be attributed to different
487 methodological approaches: the sampling frequency in Chen and Stevens (2001) was 16 kHz,
488 as opposed to 44.1 kHz in the present study, and the bandpass filter was 4 kHz - 7 kHz, as
489 opposed to a similar range but with a slightly higher upper limit (7.5 kHz). In terms of spectral
490 moments, a high CoG with low SD, low kurtosis and near-zero skewness was obtained. These
491 data are like, but lower, than those obtained by Martel-Sauvageau et al. (2021) for French,
492 possibly due to the sharper realization of the fricative in French, together with its greater
493 articulatory tension and lip stretching. Relative to the data available for Spanish, CoG and
494 skewness were similar, but SD was higher and kurtosis lower than those reported by Cicres
495 (2011) for six male speakers, the difference probably being attributable to a different position
496 of the sound in the syllable, medial position in Cicres (2011) study rather than initial position.

497 According to the rounding of the vowel adjacent to the fricative in the healthy speakers
498 group, the results are partly in agreement with those obtained in other languages such as
499 English, Portuguese and Paraguayan Spanish (Jesus & Shadle, 2002; Jiquilin-Ramirez, 2014;
500 Jongman et al., 2000; Klein et al., 2019; Koenig et al., 2013). In these languages, the differences
501 for unrounded vowels also consist of higher CoG and lower SD, but a negative skewness is
502 described, while our values are close to zero indicating symmetry, as pointed out by Blumer
503 (1979). Lower spectral AmpD and CoG and higher SD in a rounded vowel context could reflect
504 a lengthening of the oral tract leading to a drop in high-frequency amplitude and increased
505 energy dispersion in the spectrum. Using a similar measure, A_d (discrepancy between the
506 maximum amplitude within the averaged power spectrum ranging from 500 Hz to 20 kHz and

507 the minimum amplitude within the 0 to 2 kHz range), Jesus and Shadle (2002) also found that
508 elongation of the oral cavity or rounding of the lips results in a drop in energy at high
509 frequencies. These observations have been noted in studies with English speakers (Katz et al.,
510 2003; Nittrouer, 1995; Nittrouer et al., 1989). As for skewness, higher values we observed in
511 unrounded contexts and lower or negative values in rounded contexts in all groups. This spectral
512 moment also seems to reflect that the Spanish fricative /s/ is less sibilant than in other languages,
513 as its lower CoG also confirms.

514 In relation to speaker sex, our results detect the same pattern for spectral AmpD, CoG,
515 skewness, and kurtosis, although it differs for SD, which is higher in females than in males in
516 English studies (Fox & Nissen, 2005; Jongman et al., 2000; Klein et al., 2019; Koenig et al.,
517 2013; Tjaden & Turner, 1997). It can be speculated that our higher CoG and AmpD values and
518 negative skewness values together with lower SD and higher kurtosis might reflect a smaller
519 mean mouth size in females or a somewhat more anterior tongue position leading to sharper
520 spectra with lower dispersion.

521 *4.2 Differences between dysarthria and healthy control*

522 When we compared the healthy speakers and Dys speakers groups, the AmpD, CoG,
523 SD and skewness served to distinguish between them. In terms of the direction and magnitude
524 of the differences observed, the Dys speakers group showed a significantly lower spectral
525 AmpD and CoG, greater SD and higher and positive skewness compared to the healthy speakers
526 group. However, while kurtosis was higher in this group than the healthy speakers group, this
527 time the difference was not significant. A higher kurtosis could indicate the presence of energy
528 at the more extreme frequencies (Westfall, 2014). Hence, in persons with dysarthria, the

529 characteristics of articulation of the voiceless alveolar sibilant /s/ resemble those of a palato-
530 alveolar sibilant fricative. It is known that spectral AmpD, CoG and skewness are measures
531 related to the necessary adjustments of speakers to find the adequate place of articulation such
532 that, compared with palate-alveolar sibilants in alveolar sibilant fricatives, spectral AmpD and
533 CoG are higher, skewness is less positive or sometimes even negative, and SD is lower (Forrest
534 et al., 1998; Fox & Nissen, 2005; Jongman et al., 2000; Maniwa & Jongman, 2009). Our
535 findings are like those obtained for dysarthric speech in other languages, even in disorders of
536 different underlying etiology (i.e., Amyotrophic Lateral Sclerosis, Spastic Cerebral Palsy,
537 Cerebellar Ataxia, Athetoid Cerebral Palsy and Parkinson disease). Several studies have shown
538 a lower spectral CoG and AmpD, more positive skewness and higher SD than in healthy speech
539 (Burder et al., 1996; Chen & Stevens, 2001; Hernandez et al., 2019; Martel-Sauvageau et al.,
540 2021). Further, results for spectral AmpD and CoG also coincide with a lower spectral peak
541 frequency in the mid frequency ($Freq_{Mid}$) region of the central zone of the fricative in persons
542 with dysarthria [blinded for review]. However, in general the studies mentioned usually show
543 a lower kurtosis in persons with dysarthria while our data indicate the opposite. This may be
544 explained by the greater presence of high amplitudes at extreme frequencies of the spectrum
545 reflecting differences in articulatory adjustment. Our results also contrast with those of Kim
546 (2017) in a study about dysarthria in Parkinson's disease when speaking English. This author
547 found no significant differences in spectral moments compared with healthy persons, possibly
548 because they retain their coarticulatory abilities, while we did detect differences for CoG and
549 SD. We believe that the neurophysiological limitations present in individuals with dysarthria
550 in our study (primarily of spastic type) could explain the lower CoG and higher SD by causing
551 a reduced articulatory constriction.

552 While few studies have examined the effect of accompanying vowel rounding in persons
553 with dysarthria, our results coincide with those of Martel-Sauvageau et al. (2021). These
554 authors, who examined dysarthria due to Parkinson's in French speakers, confirmed that
555 fricatives adjacent to unrounded vowels showed a greater CoG and smaller SD compared to
556 rounded vowels, as in healthy speech. Differently, having a greater skewness and kurtosis in a
557 context of unrounded vowels differed from the healthy control group. This could be explained
558 by difficulties in tongue position and constriction to produce the frication noise such that the
559 tongue remains either more descended in the Dys speakers group —potentiating coupling of
560 the anterior and posterior cavities to the place of articulation — or wider — generating a
561 shallower constriction groove and increasing the surface of lingual contact. The latter would
562 reduce the rate of airflow through the constriction. Indeed, tongue misposition would affect
563 both unrounded and rounded vocalic phonetic contexts (Harmes et al., 1984; Heinz & Stevens,
564 1961; Hoole et al., 1989; Shadle, 1990; Stevens, 1971; Weismer et al., 1995). Additionally, our
565 Dys speakers group differs most clearly on the measures that significantly distinguish them
566 from the healthy speakers group when fricatives are followed by unrounded vowels (i.e.,
567 AmpD, CoG, SD and skewness). Since both these vowels like the fricative /s/ are very resistant
568 to coarticulation and both require tongue tip activation for their correct execution, this could
569 account for these differences. Therefore, we believe that the neuromuscular alterations observed
570 in persons with dysarthria, coupled with the distorted somato-acoustic feedback, are responsible
571 for the observed differences. The diminished capacity to enact mechanical compensations by
572 different articulators during the fricative-vowel movement could suggest a dysfunction in the
573 feedback control system (Ghosh et al., 2010; Iskarous et al., 2011; Recasens & Rodríguez,
574 2016).

575 Regarding sex factor, although there are no significant differences, dysarthric females
576 showed lower AmpD, CoG and SD and higher skewness and kurtosis than males. However,
577 Tjaden and Turner (1997) describe that women with ALS dysarthria in their study have higher
578 CoG and SD, and lower kurtosis than men. This means that, of the two interpretations earlier
579 proposed, a smaller mean size of the mouth in the case of female does not explain the data, as
580 mouth size does not vary according to the disorder considered. Hence the most reasonable
581 explanation would be related to differences in the position of the tongue. A more anterior or
582 lower position could indicate a greater dispersion of energy, especially towards low
583 frequencies, affecting precision more in the case of females, who tend to be more precise
584 (Simpson, 2009).

585 *4.3 Differences between apraxia of speech and healthy control*

586 While our AoS speakers group featured a lower AmpD, skewness and kurtosis but
587 greater CoG and SD than the healthy speakers group, the only measures significantly
588 differentiating these groups were unrounded AmpD, rounded CoG, mainly rounded SD, and
589 rounded kurtosis. This could be interpreted as a higher SD reflecting more distributed energy
590 throughout the spectrum, which would be consistent with the lower AmpD. The presence of a
591 higher CoG in both vowel contexts, but only significant in rounded, could indicate a tendency
592 towards a tongue position closer to the palate or a more forward position together with a lower
593 lip rounding in a rounded context which would generate higher negative skewness in the
594 spectrum and lower kurtosis, as the presence of energy at very extreme frequencies is reduced.
595 Additionally, in our AoS speakers group, while AmpD and CoG varied significantly according
596 to vowel rounding, differences were reduced compared to the healthy control group.
597 Specifically, AmpD exhibits more variation in the unrounded vowel context. This could

598 possibly indicate a lesser slope due to an anterior position of the tongue or an inadequate tongue
599 shape for sound execution. This observation aligns with the findings of Harmes et al. (1984)
600 and Bartle-Meyer et al. (2009). On the other hand, CoG shows more variation in rounded vowel
601 context. This may suggest, once again, less lip rounding in the apraxia group than in the healthy.
602 This inference is supported by the higher values observed in the temporal endpoint of the
603 fricative for the rounded CoG and SD. Additionally, there is a smaller difference of CoG
604 between its temporal midpoint and temporal endpoint (Diff_{M-F} CoG) compared to healthy
605 speakers ([blinded for review]), as well as in other studies focusing on the English language
606 (Ziegler & von Cramon, 1985). Furthermore, the differences for rounding in kurtosis are greater
607 in the apraxia group than in the control, although for both it is not significant. However, the
608 AoS speakers group registers less kurtosis when the context is a rounded vowel and more when
609 the context is an unrounded vowel than the healthy speakers group. These measures appear to
610 indicate challenges in the anticipatory coarticulatory planning of vowel rounding, which should
611 be present in the fricative, suggesting an anomalous functioning of the feedforward control
612 system in the AoS speakers group. Additionally, the data recovered for the AoS speakers group
613 were always intermediate between those of the other two groups. This could be the outcome of
614 the elevated standard errors observed in the AoS speakers group reflecting the high intra-subject
615 variability known for this disorder (Haley, 2002; Shuster & Wambaugh, 2000; Wambaugh et
616 al., 1995).

617 By sex, although differences were detected in GoG, with higher value in female, there
618 was a slight tendency for higher AmpD and kurtosis values and lower SD and skewness in
619 female than male. This meant that the results obtained in the AoS speakers group were in line
620 with those of the healthy control group.

621 *4.4 Differences between apraxia of speech and dysarthria*

622 The AoS speakers and Dys speakers groups are more distinguishable in AmpD and
623 CoG, when the fricative was followed by unrounded vowels, and skewness in the context of
624 rounded vowels, but not in SD and kurtosis. Therefore, this could be indicating that there are
625 differences between these pathologies related to different ways of producing the sound. That is,
626 the significantly different values according to the vowel context, rounded or unrounded,
627 between the pathological groups and with respect to the healthy speakers group, may reflect
628 different ways of articulatory production of the fricative /s/ and could suggest how different
629 motor control processes behave in individuals with motor speech disorders, serving as a
630 consequence of the distinct clinical manifestations of these disorders.

631 **5 Limits and future directions**

632 Although an attempt was undertaken to conduct the study with scientific and
633 methodological rigor, some limitations were encountered that should be considered when
634 interpreting and extrapolating the results.

635 One limitation was the unbalanced sample size between the groups, particularly
636 regarding the sex of the speakers. This limitation was addressed by recruiting participants over
637 a longer period of time and in several centers, by making an effort to align healthy participants
638 closely with those with motor speech disorders, and by employing statistical techniques to
639 mitigate the effect (i.e., bootstrapping with replacement; robust parametric analysis). However,
640 it is advisable for future research to conduct a larger multicenter study with the collaboration
641 of other researchers.

642 Another limitation was the consideration of the dysarthria group without distinguishing
643 between the existing subtypes. In this sense, it would be interesting to segregate the subtypes
644 in further research and to increase the sample size of participants in each subtype to improve
645 the understanding of the variations of this disorder.

646 Furthermore, the use of the repetition paradigm in task performance could affect the
647 results of the study by inducing imitation with respect to speech rate and accuracy. Therefore,
648 it is recommended to consider the use of reading aloud in future studies, especially as
649 participants did not show linguistic problems.

650 Finally, an articulatory interpretation of the acoustic results was attempted based on
651 partial knowledge in the literature, which should be validated by research that simultaneously
652 examines articulatory and acoustic aspects.

653 Data emerging from this study could provide direction for future clinical studies
654 designed to compare the impacts of different motor speech disorders. It would be interesting to
655 increase knowledge of acoustic-articulatory relationships to better understand the differences
656 found in acoustic measures in each motor disorder and to resolve the various possible
657 explanatory conjectures presented in the discussion. Beyond this, we hope our findings will
658 contribute to advances in explanatory models of the motor control of articulation, to
659 standardizing diagnostic methods, and to understanding the nature and severity of motor speech
660 problems. Similarly, the use of acoustic parameters will help us more effectively guide
661 treatments and monitor their effects.

662

663 **6 Conclusion**

664 In short, the spectral amplitude difference (AmpD), center of gravity (CoG), standard
665 deviation (SD) and Skewness of the fricative /s/, especially followed by unrounded vowel,
666 distinguishes most significantly the Dys speakers and healthy speakers groups with lower
667 values in the first two and higher values in the last two for dysarthria. On the other hand, AmpD
668 unrounded, CoG and Kurtosis rounded and SD, mainly in rounded, distinguish the AoS
669 speakers group from the healthy speakers group with higher values in CoG and SD and lower
670 values in AmpD and kurtosis. Finally, Dys speakers and AoS speakers groups are differentiated
671 in AmpD and CoG, mainly unrounded, and skewness, mainly rounded, with higher values in
672 the first two and lower in the last-for apraxia.

673

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677 **Declaration of interest**

678 The authors declare no conflict of interest.

679 **References**

- 680 Avery, J. D., & Liss, J. M. (1996). Acoustic characteristics of less-masculine-sounding male
681 speech. *The Journal of the Acoustical Society of America*, 99(6), 3738-3748.
682 <https://doi.org/10.1121/1.414970>
- 683 Bartle-Meyer, C.J., Murdoch, B.E. & Goozée, J.V. (2009). An electropalatographic
684 investigation of linguopalatal contact in participants with acquired Apraxia of Speech: a.

685 quantitative and qualitative analysis. *Clinical Linguistics and Phonetics*, 23(9), 688-716.
686 <https://doi.org/10.1080/02699200903075388>

687 Behrens, S., & Blumstein, S. (1988). Acoustic characteristics of English voiceless fricatives: A
688 descriptive analysis. *Journal of Phonetics*, 16, 295–298. [https://doi.org/10.1016/S0095-](https://doi.org/10.1016/S0095-4470(19)30504-2)
689 [4470\(19\)30504-2](https://doi.org/10.1016/S0095-4470(19)30504-2)

690 Blumer, M.G. (1979). *Principles of Statistics*. Dover Publications, Inc. New York.

691 Boersma, P., & Weenink, D. (2020). Praat: doing phonetics by computer [Computer program]
692 (Version 6.1.16). Retrieved from www.praat.org

693 Burder, E.H., Kent, R.D., Kent, J.F., Milenkovic, P. & Workinger, M. (1996). Formoffa: an
694 automated formant, moment, fundamental frequency, amplitude analysis of normal and
695 disordered speech. *Clinical, Linguistics and Phonetics*, 10(1), 31-54.
696 <https://doi.org/10.3109/02699209608985160>

697 Chen, H., & Stevens, K.N. (2001). An acoustical study of the fricative /s/ in the speech of
698 individuals with Dysarthria. *Journal of Speech, Language, and Hearing Research*, 44, 1300-
699 1314. [https://doi.org/10.1044/1092-4388\(2001/101\)](https://doi.org/10.1044/1092-4388(2001/101))

700 Cicles, J. (2011). Los sonidos fricativos sordos y sus implicaciones forenses. *Estudios*
701 *Filológicos*, 48, 33-48. <http://dx.doi.org/10.4067/S0071-17132011000200003>

702 d'Alessandro, D., Pernon, M., Fougeron, C., & Laganaro, M. (2019). *Anticipatory VtoV*
703 *coarticulation in French in several Motor Speech Disorders*. *Phonetics and Phonology in*
704 *Europe* (PAPE 2019). <https://hal.science/hal-02427864>

705 Daniloff, R., & Moll, K. (1968). Coarticulation of lip rounding. *Journal of Speech and Hearing*
706 *Research, 11*(4), 707-721. <https://doi.org/10.1044/jshr.1104.707>

707 Elvira-García, W. (2014). [Script for Praat]. Zero-crossings-and-spectral-moments (version 2)
708 <https://github.com/wendylviragarcia/fricatives>

709 Flipsen, P., Shriberg, L. Weismer, G., Karlsson, H., & McSweeny, J. (1999). Acoustic
710 characteristics of /s/ in adolescents. *Journal of Speech, Language, and Hearing Research,*
711 *42* (3), 663-677. <https://doi.org/10.1044/jslhr.4203.663>

712 Forrest, K., Weismer, G., Milenkovic, P., & Dougall, R.N. (1988). Statistical analysis of word-
713 initial voiceless obstruent : Preliminary data. *The Journal Acoustical Society of America, 84*
714 (1), 115-123. <https://doi.org/10.1121/1.396977>

715 Fox, R.A. & Nissen, S.L. (2005). Sex-related acoustic changes in voiceless English fricatives.
716 *Journal of Speech, Language, and Hearing Research, 48*(4), 753-765.
717 [https://doi.org/10.1044/1092-4388\(2005/052\)](https://doi.org/10.1044/1092-4388(2005/052))

718 Fuchs, S., & Toda, M. (2010). Do differences in male versus female /s/ reflect biological or
719 sociophonetic factors? En S. Fuchs, M. Toda, & M. Zygis (Eds.), *Turbulent Sounds* (pp. 281-
720 302). De Gruyter Mouton. <https://doi.org/10.1515/9783110226584.281>

721 Ghosh, S.S., Matthies, M.L., Maas, E., Hanson, A., Tiede, M., Ménard, L., Guenther, F.H.,
722 Lane, H., & Perkell, J.S. (2010). An investigation of the relation between sibilant production
723 and somatosensory and auditory acuity. *The Journal of the Acoustical Society of America,*
724 *128*(5), 3079-3087. <https://doi.org/10.1121/1.3493430>

725 Guenther, F.H. (2016). *Neural Control of Speech*. MIT Press.

726 Haley, K. (2002). Temporal and spectral properties of voiceless fricatives in Aphasia and
727 Apraxia of Speech. *Aphasiology*, 16(4/5/6), 595-607.
728 <https://doi.org/10.1080/02687030244000257>

729 Hardcastle, W. (1976). *Physiology of Speech Production: An Introduction for Speech Scientists*.
730 Academic Press.

731 Harmes, S., Daniloff, R.G., Hoffman, P.R., Lewis, J., Kramer, M.B., & Absher, R. (1984).
732 Temporal and articulatory control of fricative articulation by speakers with Broca's aphasia.
733 *Journal of Phonetics*, 12, 367-385. [https://doi.org/10.1016/S0095-4470\(19\)30897-6](https://doi.org/10.1016/S0095-4470(19)30897-6)

734 Heinz, J.M., & Stevens, S. (1961). On the properties of fricative consonants. *The Journal of the*
735 *Acoustical Society of America*, 33, 589-593. <https://doi.org/10.1121/1.1908734>

736 Hernandez, A., Lee, H., & Chung, M. (2019). Acoustic analysis of fricatives in dysarthric
737 speakers with cerebral palsy. *Phonetics and Speech Science*, 11, 3: 23-29.
738 <https://doi.org/10.13064/KSSS.2019.11.3.023>

739 Hertrich, I., & Ackermann, H. (1999). Temporal and spectral aspects of coarticulation in ataxic
740 dysarthria: An acoustic analysis. *Journal of Speech, Language, and Hearing Research*,
741 42(2), 367-381. <https://doi.org/10.1044/jslhr.4202.367>

742 Herrmann, F., Cunningham, S. P., & Whiteside, S. P. (2014). Speaker sex effects on temporal
743 and spectro-temporal measures of speech. *Journal of the International Phonetic Association*,
744 44(1), 59-74. <https://doi.org/10.1017/S0025100313000315>

- 745 Hillel, A.D., Miller, R.M., Yorkston, K., McDonald, E., Norris, F.H., & Konikow, N. (1989).
746 Amyotrophic Lateral Sclerosis Severity Scale. *Journal of Neuroepidemiology*, 142-150.
747 <https://doi.org/10.1159/000110176>
- 748 Hoole, P., Ziegler, W., & Hartmann, E. (1989). Parallel electropalatographic and acoustic
749 measures of fricatives. *Clinical Linguistics and Phonetics*, 3, 59-69.
750 <https://doi.org/10.3109/02699208908985271>
- 751 Iskarous, K., Shadle, C.H. & Proctor M. (2011). Articulatory-acoustic kinematics: The
752 production of American English /s/. *The Journal of Acoustical Society of America*, 129 (2),
753 944-954. <https://doi.org/10.1121%2F1.3514537>
- 754 Jesus, L.M.T., & Shadle, C.H. (2002). A parametric study of the spectral characteristics of
755 European Portuguese fricatives. *Journal of Phonetics*, 30, 437-464.
756 <https://doi.org/10.1006/jpho.2002.0169>
- 757 Jiquilin-Ramirez, D. & Albano, E. C. (2014). The effect of adjacent vowels on the spectrum of
758 back fricatives in Guarani and Spanish. In: 1st International DINAFON Meeting, 2014,
759 Campinas. Book of abstracts.
- 760 Jongman, A., Wayland, R., & Wong, S. (2000). Acoustic characteristics of English fricatives.
761 *The Journal of the Acoustical Society of America*, 108(3), 1252-1263.
762 <https://doi.org/10.1121/1.1288413>
- 763 Katz, W. F. (2000). Anticipatory coarticulation and aphasia: Implications for phonetic theories.
764 *Journal of Phonetics*, 28(3), 313-334. <https://doi.org/10.1006/jpho.2000.0118>

765 Katz, W.F., Bharadwaj, S.V. & Stettler, M.P. (2003). Influences of electromagnetic
766 articulography sensor on speech produced by healthy adults and individuals with aphasia
767 and apraxia. *Journal of Speech, Language, and Hearing Research*, 49, 645-659.
768 [https://doi.org/10.1044/1092-4388\(2006/047\)](https://doi.org/10.1044/1092-4388(2006/047))

769 Kim, H., Martin, K., Hasegawa-Johnson, M., & Perlman, A. (2010). Frequency of consonant
770 articulation errors in Dysarthria speech. *Clinica, Linguistics and Phonetics*, 24(10), 759-770.
771 <https://doi.org/10.3109/02699206.2010.497238>

772 Kim, Y. (2017). Acoustic Characteristics of fricatives /s/ and /ʃ/ Produced by speaker with
773 Parkinson's Disease. *Clinical Archives of Communication Disorders*, 2(1), 7-14.
774 <https://doi.org/10.21849%2Fcacd.2016.00080>

775 Klein, E., Brunner, J., & Hoole, P. (2019). The relevance of auditory feedback for consonant
776 production: The case of fricatives. *Journal of Phonetics*, 77, 1-18.
777 <https://doi.org/10.1016/j.wocn.2019.100931>

778 Koenig, L.L., Shadle, C.H., Preston, J.L., & Mooshammer, C.R. (2013). Toward improved
779 spectral measure of /s/: Results from adolescents. *Journal of Speech, Language, and Hearing*
780 *Research*, 56, 1175-1189. [https://doi.org/10.1044%2F1092-4388\(2012%2F12-0038\)](https://doi.org/10.1044%2F1092-4388(2012%2F12-0038))

781 Mair, P. & Wilcox. R.R. (2020). Robust Statistical Methods in R Using the WRS2 Package.
782 *Behavior Research Methods*, 52, 464-488. <https://doi.org/10.3758/s13428-019-01246-w>

783 Martel-Sauvageau, V., Breton, M., Chabot, A., & Langlois, M. (2021). The impact of clear
784 speech on the perceptual and acoustic properties of fricative–vowel sequences in speakers
785 with Dysarthria. *American Journal of Speech-Language Pathology*, 30, 1410-1428.
786 https://doi.org/10.1044/2021_AJSLP-20-00157

787 McNeil, M. R., Robin, D. A., & Schmidt, R. A. (2009). Apraxia of Speech: Definition,
788 differentiation, and treatment. In. M. R. McNeil (Ed.), *Clinical management of Sensorimotor*
789 *Speech Disorders* (2nd ed.) (pp. 249-268). New York: Thieme.

790 Nataraj, K.S., Pandey, P.C., & Dasgupta, H. (2017). Estimation of place of articulation of
791 fricatives from spectral characteristics for speech training. *Interspeech*, 20-24, 339-343.
792 <https://doi.org/10.21437/INTERSPEECH.2017-1074>

793 Nittrouer, S. (1995). Children learn separate aspect of speech production at different rate:
794 Evidence from spectral moments. *Journal of Speech, Hearing and Research*, 32, 120-132.
795 <https://doi.org/10.1121/1.412278>

796 Nittrouer, S., Studdert-Kennedy, M., & McGowan, R.S. (1989). The emergence of phonetic
797 segments: Evidence from the spectral structure of fricative-vowel syllables spoken by children
798 and adults. *Journal of Speech and Hearing Research*, 32(1), 120-132.
799 <https://doi.org/10.1044/jshr.3201.120>

800 Patil, I. (2021). statsExpressions: R Package for Tidy Dataframes and Expressions with
801 Statistical Details. *Journal of Open-Source Software*, 6(61), 3236.
802 <https://indrajeetpatil.github.io/statsExpressions/>

803 R Core Team (2020). R: A language and environment for statistical computing. R Foundation
804 for Statistical Computing, Vienna, Austria. URL: <https://www.R-project.org/>

805 Recasens, D. & Rodríguez, C. (2016). A study on coarticulation resistance and aggressiveness
806 for front lingual consonants and vowels using ultrasound. *Journal of Phonetics*, 59, 58-75.
807 <https://doi.org/10.1016/j.wocn.2016.09.002>

808 Reetz, H., & Jongman, A. (2020). *Phonetics: Transcription, production, acoustics, and*
809 *perception*. John Wiley & Sons.

810 Shadle, C.H. (1990). Articulatory-acoustic relationships in fricative consonants. In W.J.
811 Hardcastel & A. Marchal (Ed.), *Speech production and speech modeling*. The Netherlands:
812 Kluwer.

813 Shadle, C.H. & Mair, S.J. (1996). Quantifying spectral characteristics of fricatives. In
814 Proceedings of the International Conference on Spoken Language Processing (ICSLP 96),
815 Philadelphia, U.S.A., pp. 1517–1520. <https://doi.org/10.1109/ICSLP.1996.607906>

816 Shuster, L., & Wambaugh, J.L. (2000). Perceptual and acoustic analyses of speech sound errors
817 in apraxia of speech accompanied by aphasia. *Aphasiology*, *14*(5/6), 635-651.
818 <https://doi.org/10.1080/026870300401360>

819 Simpson, A. P. (2009). Phonetic differences between male and female speech. *Language and*
820 *Linguistics Compass*, *3*(2), 621–640. <https://doi.org/10.1111/j.1749-818X.2009.00125.x>

821 Stevens, K. (1971). Airflow and turbulence noise for fricative and stop consonants: Static
822 considerations. *The Journal of the Acoustical Society of America*, *50*, 1180-1192.
823 <https://doi.org/10.1121/1.1912751>

824 Tjaden, K. (2003). Anticipatory coarticulation in Multiple Sclerosis and Parkinson’s Disease.
825 *Journal of Speech, Language, and Hearing Research*, *46*, 990-1008.
826 [https://doi.org/10.1044/1092-4388\(2003/077\)](https://doi.org/10.1044/1092-4388(2003/077))

827 Tjaden, K., & Turner, G.S. (1997). Spectral properties of fricatives in Amyotrophic Lateral
828 Sclerosis. *Journal of Speech, Language, and Hearing Research*, 40(6), 1358-1372.
829 <https://doi.org/10.1044/jslhr.4006.1358>

830 Wambaugh, J.L., Doyle, P.J., West, J.E., & Kalinyak, M.M. (1995). Spectral analysis of sound
831 errors in persons with Apraxia of Speech and Aphasia. *American Journal of Speech-*
832 *Language Pathology*, 4(4), 186-192. <https://doi.org/10.1044/1058-0360.0404.186>

833 Weismer, G., Guhan, V., & Kent, R.D. (1995). Prediction of consonant spectra from the slope
834 of preceding and following second formant transitions. *The Journal of the Acoustical Society*
835 *of America*, 97, 3416. <https://doi.org/10.1121/1.412479>

836 Westfall, P. H. (2014). kurtosis as Peakedness, 1905–2014. "R.I.P.". *The American Statistician*,
837 68 (3),191-195. <https://doi.org/10.1080%2F00031305.2014.917055>

838 Whalen, D. H. (1990). Coarticulation is largely planned. *Journal of Phonetics*, 18(1), 3-35.
839 [https://doi.org/10.1016/S0095-4470\(19\)30356-0](https://doi.org/10.1016/S0095-4470(19)30356-0)

840 Yeni-Komshian, G. H., & Soli, S. D. (1981). Recognition of vowels from information in
841 fricatives: Perceptual evidence of fricative-vowel coarticulation. *The Journal of the*
842 *Acoustical Society of America*, 70(4), 966-975. <https://doi.org/10.1121/1.387031>

843 Zharkova, N., Hewlett, N., & Hardcastle, W. J. (2012). An ultrasound study of lingual
844 coarticulation in/sV/syllables produced by adults and typically developing children. *Journal*
845 *of the International Phonetic Association*, 42(2), 193-208.

846 Ziegler, W., & von Cramon, D. (1985). Anticipatory coarticulation in a speaker with Apraxia
847 of Speech. *Brain and Language*, 26, 117-130. [https://doi.org/10.1016/0093-934x\(85\)90032-](https://doi.org/10.1016/0093-934x(85)90032-)
848 [x](#)

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

	N	Mean age (age range)	Sex male:female	Mean Severity* (range)
Healthy speakers	28	42.6 (21-71)	19: 9	
Apraxia	8	41.5 (30-61)	4:4	7 (6-8)
Dysarthria	20	41.8 (21-72)	14:6	7 (5-8)
** 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 Motor Speech Disorders Severity Rating Scale (Modified by Duffy, 2020 from Hillel et al. 1989)

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

Table 2. *Clinical inclusion-exclusion criteria based on Duffy (2020) for the selection of participants with motor speech disorders.*

Motor Speech Disorder	Dysarthria	Apraxia of speech	
Neurophysiological and perceptual characteristics	No difficulties in language comprehension or production	Strained-strangled quality in speech Harshness in voice	
	Muscle atrophy or palsy	Voice tremor Breathiness	
	Hypotonia	Hypernasality or hyponasality	
	Spasticity	Imprecise articulation	
	Fasciculation	Monopitch	
	Tremor	Monoloudness	
	Rigidity	Excess and equal stress	
	Hypokinetic issues	Slow or variable rate	
	Presence of visible involuntary movements	Slow, regular, or irregular speech alternant motion rates (AMRs)	
	Pathological or hyperactive oromotor reflexes		
			No difficulties in verbal comprehension, written production, or overall comprehension
			No neurophysiological diseases (atrophy or palsy in speech muscles, hypotonia, spasticity, fasciculation, tremor, rigidity, hypokinetic issues, or the presence of visible involuntary movements). Furthermore, there would be no hypernasality, no pathological or hyperactive oromotor reflexes.
		Slow articulatory rate. Syllable segregation. Increased interword intervals. Effortful visible and audible articulation. Ability to recognize their articulatory errors. Making attempts at self-correction. Difficulty with speech sequential motion rates (SMRs). No difficulty with speech alternant motion rates (AMRs). Trial and error groping for articulatory postures. False articulatory starts. Consonant and vowel distortions. Word complexity effects (increased error rates for syllables with consonant clusters and on complex syllables and words).	

Table 3. Descriptive data for spectral measures of articulatory precision: α -trimmed means (and median absolute deviation) in ms according to group, rounding of the vowel following the fricative /s/ and sex.

		n	Center of gravity (Hz)	Standard deviation (Hz)	Skewness	Kurtosis	AmpD (dB)
Healthy Speakers	Total	336	5 724 (941)	1 318 (402)	0.19 (0.90)	1.55 (2.03)	10.33 (6.23)
	Unrounded	168	6 140 (919)	1 301 (390)	0.26 (0.82)	1.41 (2.05)	13.25 (5.63)
	Rounded	168	5 330 (881)	1 334 (423)	0.11 (1.05)	1.69 (2.08)	7.24 (5.74)
	Female	108	6 452 (887)	1 105 (416)	-0.14 (1.14)	2.29 (2.21)	15.14 (7.06)
	Male	228	5 406 (713)	1 374 (370)	0.33 (0.78)	1.21 (2.02)	8.26 (4.86)
AoS	Total	96	5 913 (936)	1 538 (370)	0.01 (0.78)	1.06 (1.55)	7.69 (4.60)
	Unrounded	48	6 196 (847)	1 508 (368)	0.12 (0.86)	1.63 (1.59)	9.59 (5.87)
	Rounded	48	5 666 (1 015)	1 575 (374)	-0.11 (0.68)	0.68 (1.61)	6.07 (3.61)
	Female	48	6 259 (1 213)	1 533 (366)	-0.20 (0.78)	1.33 (1.86)	9.03 (6.42)
	Male	48	5 630 (417.41)	1 5456 (370)	0.16 (0.68)	0.81 (1.42)	6.74 (3.04)
Dys	Total	240	5 205 (1 175)	1 599 (437)	0.42 (0.95)	1.61 (1.73)	4.57 (5.38)
	Unrounded	120	5 302 (1 102)	1 585 (387)	0.55 (0.90)	1.65 (1.81)	4.69 (6.99)
	Rounded	120	5 110 (1 116)	1 612 (437)	0.27 (0.87)	1.60 (1.57)	4.48 (4.39)
	Female	84	4 912 (1 085)	1 581 (371)	0.75 (0.96)	3.44 (1.58)	4.53 (5.81)
	Male	156	5 321 (1 192)	1 608 (447)	0.33 (0.98)	1.35 (1.77)	4.60 (5.38)

AmpD ($Ahf - \frac{(A2f+A3f)}{2}$); n (number of observations), AoS: apraxia of speech speakers; Dys: dysarthria speakers

Table 4. Results of spectral measures of articulatory precision by group (heteroscedastic robust one-way ANOVA), by vowel rounding and by sex (Yuen's Test).

Factor	Group			Vowel rounding			Sex		
	F _{Trimmed means}	p	Effect size ξ	T _{Yuen}	p	δ_R^{AKP}	T _{Yuen}	p	δ_R^{AKP}
Center of gravity	15.95	0.001 ^a	0.34	6.68	0.001 ^a	0.48	5.26	0.001 ^a	-0.55
Standard deviation	34.49	0.001 ^a	0.36	1.32	0.19	-0.11	2.18	0.03	0.20
Skewness	6.81	0.007 ^b	0.23	2.76	0.004 ^b	0.22	2.02	0.04 ^c	0.21
Kurtosis	1.38	0.25	0.14	0.13	0.89	0.01	2.14	0.03 ^c	-0.32
AmpD	66.35	0.001 ^a	0.47	7.51	0.001 ^a	0.52	5.88	0.001 ^a	-0.65

AmpD ($Ahf - \frac{(A2f+A3f)}{2}$); significance level: a) $p < 0.001^{***}$; b) $p < 0.01^{**}$; c) $p < 0.05^*$

Table 5. Results of pairwise comparison between groups, rounding vowels and sexes (Yuen's Test)

	Center of gravity			Standard deviation			Skewness			Kurtosis			AmpD		
	T	U	R	T	U	R	T	U	R	T	U	R	T	U	R
HS vs Dys	4.90	5.67	1.54	7.77	5.67	5.34	2.54	2.37	1.22	0.16	0.44	0.19	11.52	12.33	4.24
$T_{Yuen} (p)$	(0.001 ^a)	(0.001 ^a)	(0.13)	(0.001 ^a)	(0.001 ^a)	(0.001 ^a)	(0.01 ^c)	(0.02 ^c)	(0.22)	(0.87)	(0.66)	(0.85)	(0.001 ^a)	(0.001 ^a)	(0.001 ^a)
δ_R^{AKP}	0.52	0.87	0.56	-0.74	-0.80	-0.67	-0.22	-0.29	-0.15	-0.02	-0.07	0.03	0.88	1.51	0.46
HS vs AoS	1.57	0.30	2.41	5.01	3.47	3.57	1.64	0.82	1.63	1.49	0.37	2.61	4.04	3.52	1.60
$T_{Yuen} (p)$	(0.12)	(0.77)	(0.02 ^c)	(0.001 ^a)	(0.001 ^a)	(0.007 ^b)	(0.10)	(0.41)	(0.11)	(0.14)	(0.71)	(0.009 ^b)	(0.001 ^a)	(0.001 ^a)	(0.11)
δ_R^{AKP}	-0.19	-0.06	-0.39	-0.58	-0.58	-0.58	0.17	0.14	0.21	0.13	-0.06	0.26	0.40	0.65	0.19
A vs Dys	5.06	4.12	3.17	1.25	1.14	0.52	3.55	2.40	2.59	1.39	0.02	1.94	4.83	4.52	2.22
$t_{Yuen} (p)$	(0.001 ^a)	(0.001 ^a)	(0.001 ^a)	(0.21)	(0.26)	(0.60)	(0.001 ^a)	(0.02 ^c)	(0.01 ^c)	(0.16)	(0.98)	(0.05)	(0.001 ^a)	(0.001 ^a)	(0.03 ^c)
δ_R^{AKP}	0.67	0.76	0.66	-0.16	-0.21	-0.09	-0.45	-0.40	-0.51	-0.22	0.00	-0.54	0.58	0.75	0.42
	HS	Dys	AoS	HS	Dys	AoS	HS	Dys	AoS	HS	Dys	AoS	HS	Dys	AoS
U vs R	8.02	1.07	2.53	0.78	0.47	0.84	1.33	2.06	1.24	0.71	0.09	1.60	9.38	0.30	3.22
$T_{Yuen} (p)$	(0.001 ^a)	(0.28)	(0.01 ^c)	(0.44)	(0.64)	(0.40)	(0.18)	(0.04 ^c)	(0.22)	(0.48)	(0.93)	(0.11)	(0.001 ^a)	(0.76)	(0.001 ^a)
δ_R^{AKP}	0.84	0.14	0.45	-0.09	-0.06	-0.18	0.15	0.28	0.22	-0.08	0.01	0.25	1.06	0.04	0.54
F vs M	9.47	1.98	3.01	3.87	0.42	0.17	3.70	2.07	1.80	2.17	1.67	1.02	9.44	0.09	2.02
$t_{Yuen} (p)$	(0.001 ^a)	(0.05)	(0.003 ^b)	(0.001 ^a)	(0.67)	(0.86)	(0.001 ^a)	(0.04 ^c)	(0.08)	(0.03 ^c)	(0.10)	(0.31)	(0.001 ^a)	(0.93)	(0.05)
δ_R^{AKP}	-1.31	0.31	-1.04	0.51	0.06	0.04	0.49	-0.44	0.45	-0.34	-0.69	-0.25	-1.30	0.01	-0.57

Total: total comparison; U: unrounded vowel; R: rounded vowel; HS: healthy speakers; Dys: dysarthria; AoS: apraxia; F: female; M: male; significance level: a) $p < 0.001^{***}$;

b) $p < 0.01^{**}$, c) $p < 0.05^*$

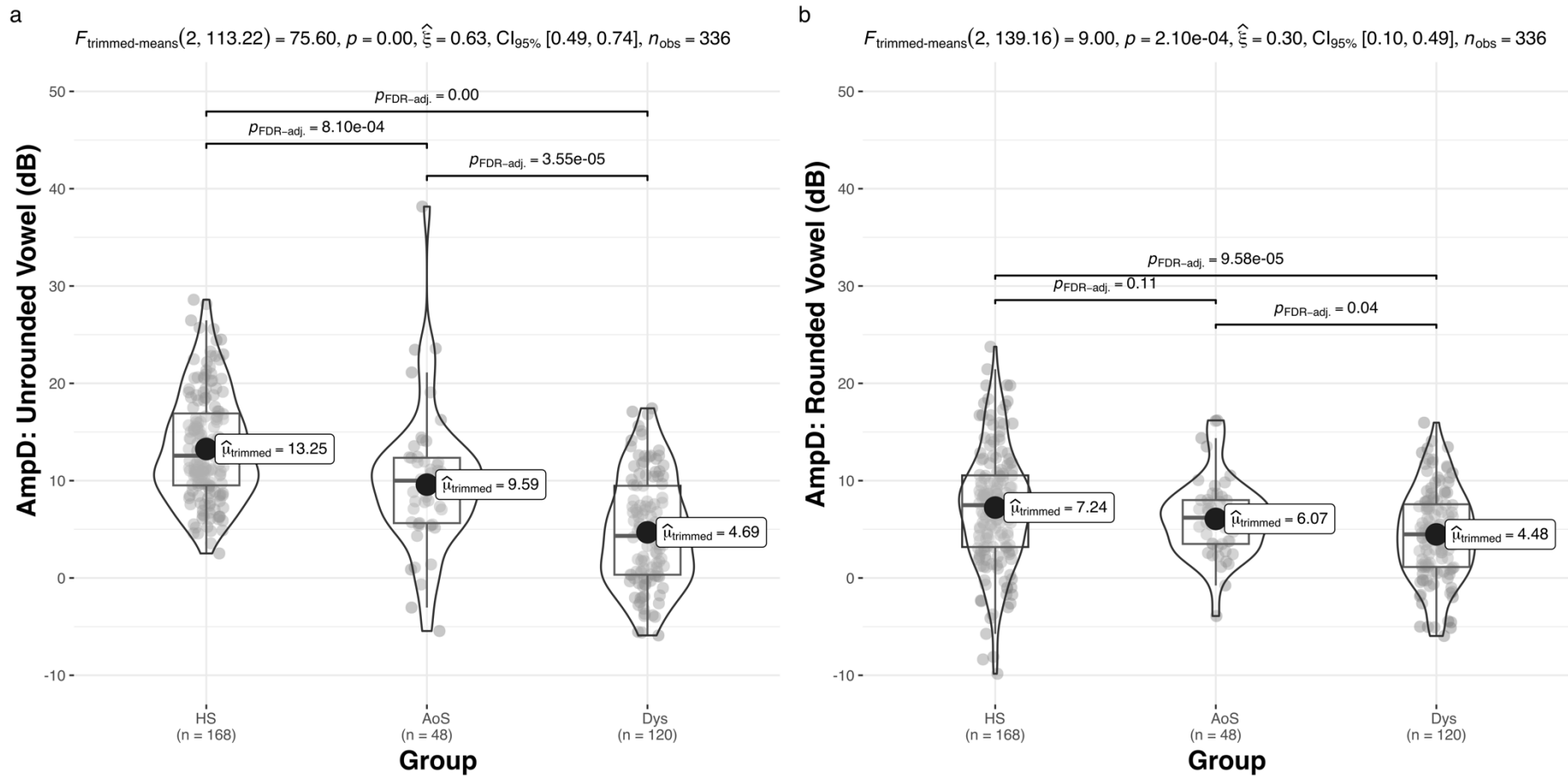


Fig.1. Differences in Spectral Amplitude Difference between groups for fricatives followed by unrounded and rounded vowels. HS: healthy speakers; AoS: apraxia of speech; Dys: dysarthria

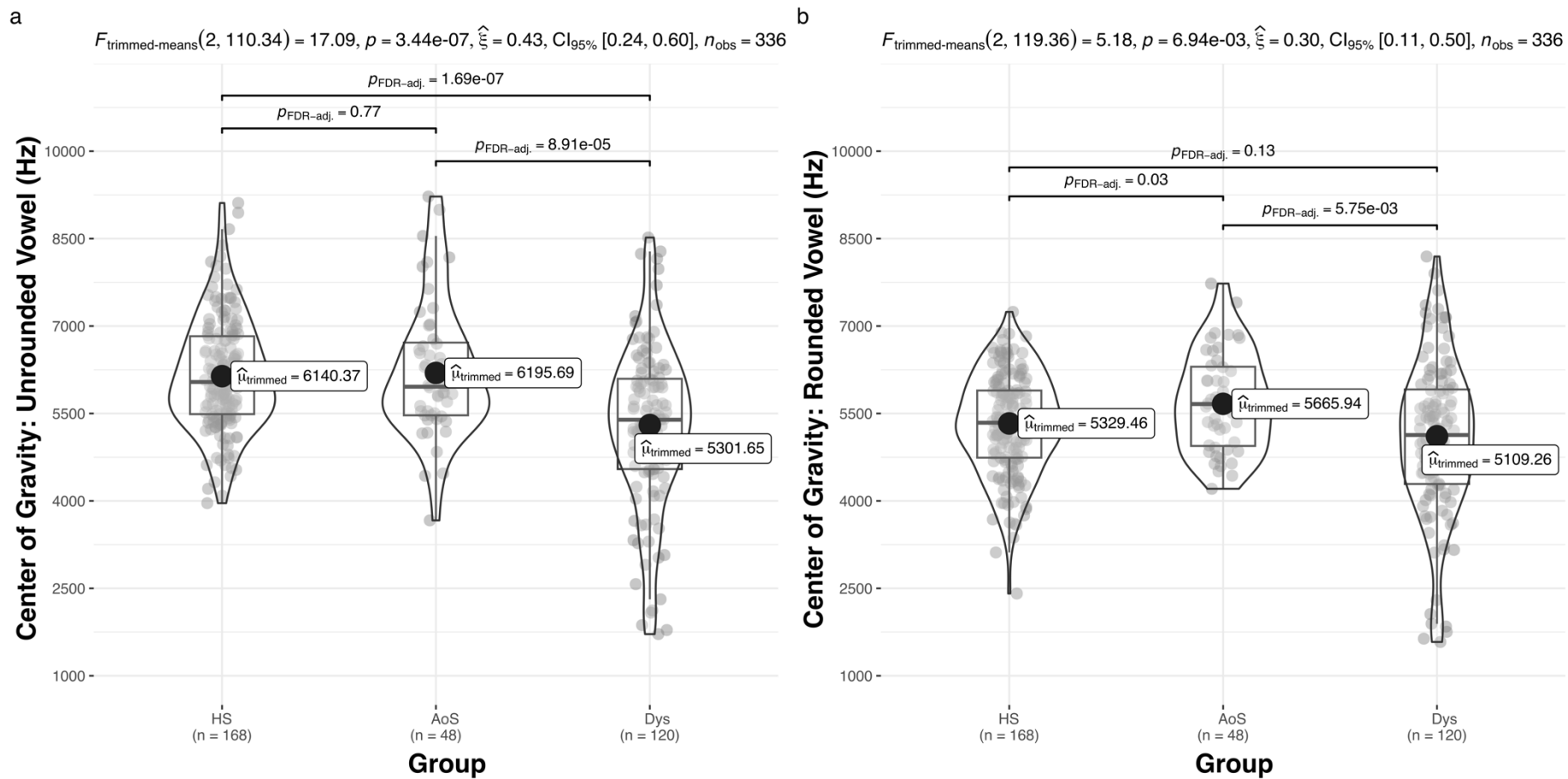


Fig.2. Differences in Centre of Gravity between groups for fricatives followed by unrounded and rounded vowels. HS: healthy speakers; A: apraxia of speech; Dys: dysarthria