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1 **Title:**  
2 **Temporal Acoustic Properties of the Sibilant Fricative /s/ for the Differential Diagnosis of**  
3 **Dysarthria and Apraxia of Speech in Spanish Speakers**

4

5 **Abstract**

6 Dysarthria and Apraxia of Speech (AoS) are motor speech disorders in which neurological lesions  
7 differentially affect motor control, possibly leading to noticeable differences in articulation and  
8 consequently sound production. Among the sounds requiring greater motor capacity because of its  
9 articulatory complexity is the voiceless alveolar sibilant fricative /s/. The aim of this study was to  
10 identify acoustic variables able to distinguish between dysarthria and AoS, and between these disorders  
11 and normal speech in Spanish speakers. The production of this fricative was acoustically examined in  
12 28 individuals with motor neurological disorders (20 with dysarthria, 8 with AoS) and in 28  
13 neurologically healthy persons. Participants repeated 12 monosyllabic words containing the fricative  
14 plus one of the five Spanish vowels. The variables measured were absolute durations of the fricative,  
15 vowel, and fricative+vowel sequence, along with the vowel-to-fricative duration ratio. Findings indicate  
16 that duration of the fricative can distinguish between controls and speakers with dysarthria, but not  
17 between controls and speakers with AoS. Measures related to vowel duration served to distinguish  
18 between speakers with dysarthria and speakers with AoS and between each of them and controls.  
19 Further, speakers with dysarthria and those with AoS differed from each other and from controls in  
20 terms of articulatory variability; speakers with dysarthria showing most variability. In the latter  
21 participants, articulatory variability was higher for unrounded segments, vowels and fricatives, while in  
22 speakers with AoS this variability was higher for rounded segments. These observations are discussed  
23 within a framework of motor control models.

24

25

26 **Keywords:** apraxia of speech, dysarthria, differential diagnosis, fricative, segmental duration.

27

28 **Number of words: 7000**

29 **Introduction**

30 Apraxia of speech (AoS) and dysarthria are motor speech disorders that may arise following  
31 neurological damage. In clinical terms, AoS characteristically shows modifications at the  
32 phonetic and prosodic levels in the absence of neuromuscular and linguistic involvement, while  
33 dysarthria causes modifications in breathing, phonation, resonance, articulation, or prosody, as  
34 a reflexion of neurophysiological damage to the musculature needed for these functions (Duffy,  
35 2020). While both feature motor impairment, this impairment seems to involve a different  
36 processing level in each disorder. Hence, AoS is the outcome of impaired phonetic-motor  
37 planning, while dysarthria manifests when there is a motor programming or execution problem  
38 (McNeil et al., 2009). In the Directions Into the Velocities of Articulator (DIVA, Guenther,  
39 2016) motor control model, AoS would correspond to an alteration of the feedforward control  
40 system (FFCS), which plans learned and stored inter- and intra-articulatory motor commands  
41 without alteration of the feedback control system (FBCS). This last system compares intended  
42 somato-acoustic results with actual somato-acoustic results. The FFCS is predominant and the  
43 FBCS is only activated if there are discrepancies between estimated and obtained results. Any  
44 planning failure in AoS generates poorly specified or erroneous commands, relying more on  
45 the FBCS to make the necessary corrections, resulting in slow speech and articulatory  
46 adjustments that involve greater spatial and temporal articulatory variability (Terband et al.,  
47 2019). In dysarthria, the perceptual-productive integration processes of the FBCS may be  
48 impaired. These serve to detect error. Moreover, interactions between the FFCS and FBCS,  
49 which help correct the error, may also be impaired.

50 The neurophysiological impairment present in dysarthria generates distorted somatosensory  
51 and acoustic feedback, disrupting the perceptual-productive integration that activates detection  
52 and correction of the mismatch and recalibration of the internal sound model. Therefore, in

53 dysarthria, articulation is distorted and slowed, but an attempt is made to preserve a certain  
54 degree of intelligibility (Parrel & Houde, 2019). In both AoS and dysarthria, problems in  
55 articulation have been described, the most frequent being errors in the production of consonants.  
56 Anticipatory coarticulation (right-to-left/forward) of speech reflects the ability to generate  
57 acoustic-articulatory overlaps of posterior segments in anterior segments. This occurs through  
58 neuromuscular coordination of intra-segmental and inter-segmental articulators by motor  
59 planning of movement (Daniloff & Moll, 1968; Whalen 1990). Among the consonant sounds,  
60 the voiceless alveolar sibilant fricative /s/ is interesting for phonetic analysis, as its acoustic and  
61 temporal properties are fairly stable, yet its articulatory complexity demands high precision in  
62 its execution. This makes this sound among the most investigated of motor speech disorders in  
63 languages such as English (Haley, 2002; Kim, Martin, et al., 2010). Based on the models motor  
64 equivalence and Degree of Articulatory Constraint (DAC), the degrees of freedom for the  
65 movement of the tongue tip in anticipatory coarticulation of the sequence /si/ or /se/ are subject  
66 to intra-articulator mechanical and temporal coordination restrictions, as both sounds are highly  
67 resistant to coarticulation and demand high articulatory precision. Conversely, resistance to  
68 coarticulation in the sequence /su/ or /so/ is lower because these vowels demand the use of the  
69 tongue dorsum, and the fricative that of the tongue tip. There is, however, inter-articulator  
70 demand for lip rounding (Ohala & Solé, 2010; Kelso & Tuller, 1984; Recasen & Rodríguez,  
71 2016; Zharkova et al., 2012). Lip electromyographic (EMG) recordings indicate that rounding  
72 is needed for segments prior to the vowel, indicating anticipatory planning of the movement  
73 (Forrest et al., 1991; Hough & Klich, 1998; Lubker & Gay; 1982).

74 Given this background, it remains to be determined whether Castilian Spanish (specifically the  
75 Central-Peninsular variant) exhibits similar spectral-temporal characteristics as other  
76 languages. Similarly, the exact nature of the articulation difficulties that occur in each speech  
77 disorder is not known. Specifically, there could be variability in the acoustic duration of sound

78 indicating differences in the duration of articulatory movements in each speech disorder. To  
79 examine articulatory impairment, it is necessary to consider phonetic systems of different  
80 languages, especially when assessing differences in motor planning, programming, or execution  
81 disorders. The use of objective acoustic analysis methods and simple non-invasive speech tasks  
82 could help construct global (trans-linguistic) motor control models, help standardize diagnostic  
83 methods, understand the nature and severity of speech problems, and guide speech therapy and  
84 patient management.

85

### 86 *Temporal Properties of the Voiceless Alveolar Fricative /s/*

#### 87 *Temporal Parameters in Normal Speech*

88 Studies in neurologically-healthy participants focusing on the voiceless alveolar fricative /s/  
89 have shown that some segmental linguistic variables, along with sociolinguistic variables may  
90 affect the duration of the fricative /s/ and of its adjacent vowel (Del barrio, & Tornel, 1999;  
91 Crystal & House, 1988; Jongman et al., 2000; Marín, 1994; Cuenca, 1996). The duration of the  
92 voiceless alveolar fricative /s/ in Spanish in word onset position is between 83 and 192 ms,  
93 although it is shortened by the extrinsic effect of the subsequent adjacent vowel. The higher the  
94 first formant of the vowel, the more the fricative is shortened. Moreover, vowels of the same  
95 height have been found to produce different shortening effects. Thus, the Spanish vowel /i/  
96 lengthens some preceding consonants more than /u/, but this does not occur in the case of the  
97 fricative /s/ (Del Barrio & Tornel, 1999; Cicres, 2011; Mendoza et al., 2003; Navarro Tomás,  
98 1918). Further, the duration of vowels in Spanish is around 55 - 127 ms, and there are intrinsic  
99 variations depending on jaw opening. Although vowels demanding the same amount of opening  
100 are of similar duration, there are differences, for example, between /i/ and /u/, the former being  
101 shorter than the latter (Cuenca, 1996; Marín, 1994-1995; Mendoza et al., 2003; Navarro Tomás,  
102 1916). Jaw opening for these vowels correlates positively with different aspects. Hence, while

103 for /i/ this is related to elevation of the anterior dorsum of the tongue, for the vowel /u/ it is  
104 related to the lip rounding closure (Fletcher & Harrington, 1999). This closure also demands  
105 coordinated movements of the tongue dorsum and lips in an asynchronous and inverse manner  
106 in order to achieve the acoustic target /u/, which could increase the duration of the sound  
107 (Perkell et al., 1993; Perrier & Fuchs, 2015; Slama & Weismer, 2001).

108 Studies on fricative duration by sex are lacking in Spanish, and the few existing reports in other  
109 languages have been inconclusive. Some authors find no differences (Fox & Nissen, 2005),  
110 others observe that females make the fricative shorter (Crystal & House, 1988; Jongman et al.,  
111 2000; Nirgianaki, et al., 2009) and others the opposite, that they make the fricative longer  
112 (Weglarski et al., 2000).

113 Something similar occurs with the duration of vowels. Studies have shown that males make  
114 vowels longer than females (Simpson; 2009; Whiteside, 1996), while others indicate that  
115 although this tendency exists, there are no significant differences between sexes (Herrmann et  
116 al., 2014). The production of more accurate phonetic vowel forms in females (i.e., of higher  
117 quality) reaching wider vowel acoustic spaces, despite smaller articulatory spaces, is one of the  
118 more plausible explanations for the increase in vowel duration in females compared to males  
119 (Herrmann et al., 2014; Simpson 2009; Whiteside, 2001).

#### 120 *Temporal Parameters in Neurologically-Affected Speech*

121 Most studies examining temporal speech parameters in persons with a neurological disorder  
122 have focused on the English language, and this type of study is lacking in Spanish speakers.  
123 Such investigations have analysed friction noise duration, adjacent vowel duration and the  
124 vowel-to-fricative duration ratio. These studies have revealed longer durations of segments and  
125 transitions between consonants and vowels. Results so far indicate that persons with AoS show  
126 a longer duration of fricatives and greater inter- and intra-speaker variation in these durations  
127 compared to healthy individuals (Code & Ball, 1982; Collins et al., 1983; Haley, 2002;

128 [Hardcastle 1987; Kent & Rosenbek, 1983](#)). Other studies have analysed the absolute and  
129 relative duration of vowels in different syllabic structures and productions of varying  
130 complexity and length. The most relevant findings of these studies have been differences in  
131 absolute duration measurements and in token-to-token variability. Effectively, significantly  
132 higher values of both factors were detected in participants with aphasia-apraxia compared to  
133 healthy participants or those with aphasia alone ([Caligiuri & Till, 1983; Code & Ball, 1982;](#)  
134 [Collins et al., 1983; Seddoh et al., 1996; Ziegler & von Cramon, 1986a; Ziegler & von Cramon,](#)  
135 [1986b](#)). Research on the fricative that uses perceptual analysis, Electromagnetic Articulography  
136 (EMA), Electromyography (EMG), and/or Electropalatography (EPG) has identified temporal  
137 alterations (i.e., increased duration of tongue movement ), distortion and high spatial variability  
138 (i.e., lip and tongue overshoots, inadequate tongue-palate contact, etc.), difficulty in  
139 independent tongue control (i.e., tongue tip, tongue back, jaw), and anticipatory coarticulatory  
140 movements of lip rounding that are slower, imprecise and disorganized, and accompanied by  
141 delayed onset of lip activity ([Bartle-Meyer, Goozée, & Murdoch., 2009; Bartle-Meyer &](#)  
142 [Murdoch, 2010; Bartle-Meyer, Murdoch & Goozée., 2009; Southwood, et al., 2009; Straus &](#)  
143 [Klich, 2001; von Cramon & Ziegler, 1985](#)). In the case of dysarthria, when fricative and  
144 adjacent vowel sounds are analysed, results vary according to the type of dysarthria. For  
145 example, speakers with ataxic dysarthria show greater vowel duration and imprecision, greater  
146 variability in segment duration, segment prolongation, hyperarticulation of unstressed  
147 segments, less vowel distinction, and less anticipatory coarticulation. Kinematically, movement  
148 duration is longer, articulatory velocity is reduced, acceleration and deceleration of movement  
149 are also reduced; and distance for the approach phase in consonant production is increased,  
150 there is articulatory undershoot, and the durations of consonant occlusion and vowels are longer  
151 ([Ackermann et al., 1995; Ackermann & Hertrich, 1994; Kent et al.,1979; Kent & Netsell, 1975;](#)  
152 [Forrest et al., 1991](#)). In speakers with spastic dysarthria, data from various studies indicate

153 greater fricative and vowel duration in relation to temporal and spatial kinematic alterations  
154 (i.e., longer constriction phase, difficulties in decelerating tongue movement during the  
155 approach phase, a wider and more posterior tongue-palate contact surface, and narrower tongue  
156 displacement range). These alterations are usually attributed to reductions in kinaesthetic and/or  
157 proprioceptive feedback, neurophysiological disorders, and coordination problems (Goozée, et  
158 al., 2000; Goozée et al., 2003; Hernandez et al., 2019; Kim et al., 2011; Kim, Rong, et al., 2010;  
159 Rong et al., 2012; Ziegler & von Cramon, 1986c). In relation to the variable sex, few studies in  
160 English or Spanish have assessed differences in the durations of fricatives and vowels in motor  
161 speech disorders.

162

163 Neither are we aware of prior work focusing on temporal parameters in the production of the  
164 Castilian Spanish alveolar fricative in individuals with motor speech impairment. Thus, it  
165 remains to be ascertained how the different disorders are expressed in terms of duration of the  
166 fricative in this language. To resolve these questions, the main objective of this study was to  
167 identify in the two types of disorder (dysarthria and AoS) sensitive temporal measures that  
168 could be useful for their differential diagnosis in Spanish speakers. The present study was thus  
169 designed to determine whether differences exist in the articulatory duration of the voiceless  
170 alveolar sibilant fricative among speakers of Castilian Spanish with dysarthria or AoS or  
171 neurologically healthy speakers. Our general working hypotheses were that:

172 (1) Acoustic duration and variability will be greater in the dysarthria group relative to  
173 the control group because of slowed down speech production arising from the  
174 neuromuscular deficit which causes a discrepancy in the FBCS. Specifically, we  
175 would expect longer durations of the fricative, vowel, and vowel-to-fricative  
176 duration ratio.

177 (2) Acoustic duration and variability will be greater in AoS compared to the control  
178 group for the fricative and rounded vowel. This is because of a need for anticipatory  
179 planning for inter-articulator coarticulation performed by the FFCS.

180 (3) Acoustic duration and variability will be greater in the dysarthria than in the AoS  
181 group for fricatives, vowels, and vowel-to-fricative duration ratio because of  
182 neuromuscular alterations that distort feedback. Furthermore, differences between  
183 the groups will be greater for unrounded segments as speakers with AoS will be  
184 more efficient in their production compared to rounded ones, as the latter requires  
185 anticipatory planning.

186 (4) Owing to their presumed greater articulatory precision, females should show a  
187 shorter acoustic duration of the fricative and a longer acoustic duration of the vowel,  
188 consonant+vowel sequence, and vowel-to-fricative duration ratio than males.

## 189 **Methods**

### 190 *Participants*

191 Participants were three groups of adults: 20 with different dysarthria profiles, 8 with AoS and  
192 28 controls. Descriptive data are provided in Table 1. The difference in numbers of the two  
193 motor disorders reflects the prevalence of the two conditions among acquired neurological  
194 speech disorders. In a report by Duffy (2020), prevalences were: dysarthria 47.3% and AoS  
195 2.4% for a total of 9430 cases in the US from 2009 to 2016. No equivalent data exist for the  
196 Spanish population.

### 197 *[Table\_1]*

198 Participants for the dysarthria and AoS groups were recruited among the patients of two centres  
199 in Madrid, Spain, *Centro Estatal de Daño Cerebral Adquirido (CEADAC)* and *Fundación Pita*  
200 *López*, according to a set of diagnostic inclusion-exclusion criteria applied by speech therapists.  
201 The criteria for selecting participants included a history of acquired brain lesions without

202 aphasia, clinical diagnosis of AoS or dysarthria based on Duffy's criteria (2020), accurate sound  
203 reproduction ability, being a native speaker of central peninsular Spanish, no prior tracheotomy,  
204 and no history of hearing loss or organic vocal lesion. Speech motor disorders were diagnosed  
205 by physicians from collaborating institutions. The control group consisted of individuals of  
206 similar age and sex selected through the non-probability snowball sampling technique. All  
207 participants were adult Castilian Spanish speakers who were free of hearing difficulties or  
208 organic voice disorders. Participation was voluntary and non- remunerated. Written informed  
209 consent was obtained from each participant. The study protocol was approved by the  
210 Complutense University's institutional review board and data management was conducted  
211 according to data protection laws and other relevant legislation.

212

### 213 ***Experimental Speech Task and Materials***

214 The task formed part of a wider protocol of motor speaking tasks and involved repeating a list  
215 of 12 monosyllabic words that started with the alveolar fricative /s/ sound. The syllable structure  
216 was sV(C) containing the same number of rounded and unrounded vowels. Participants  
217 repeated the word they heard each time until the 12 words were completed. The order of word  
218 presentation was designed to avoid successively repeating words with rounded and unrounded  
219 vowels and was the same for all participants (*sal, sus, se, sor, sin, su, ser, son, si, sur, sed, sol*).  
220 Sessions were recorded in a quiet room with an environmental noise level above 30 dB of SNR  
221 (*Signal to Noise Ratio*) using a Shure SM48 microphone placed at 45°, and 15 cm from the  
222 participant's mouth. The sound was digitized using a USB interface Focusrite Scarlett 2i2. The  
223 sample was captured and recorded with the software Audacity 2.2.2 at a sampling frequency of  
224 44 100 Hz, 16-bit quantization installed in a MacBook Pro with Catalina 10.15.5. At the start  
225 of the session, the task was orally explained to the participants with a few practice trials to make  
226 sure they had correctly understood. In this way, 672 productions of words with the fricative

227 sound were obtained from 56 participants (12 words each).

228

### 229 *Segmentation and Labelling Procedure*

230 Once the speech sample was obtained, it was segmented and labelled using the software Praat  
231 (Boersma & Weenink 2020) according to objective identification criteria of fricative onset and  
232 start and finish of the following vowel as detailed below.

233 • Onset of the fricative was established by visually inspecting the spectrogram and  
234 waveform, localizing the acoustic energy at around 3 500 Hz – 8 500 Hz above the prior  
235 background noise. A single 30-ms window was selected spanning from 15 ms before to  
236 15 ms after approximate fricative onset. We employed linear predictive coding (LPC)-  
237 autocorrelation with ‘predictor order’ set to 24 and discrete Fourier transform (DFT) to  
238 determine whether the aperiodic noise of the fricative in the mentioned frequency band  
239 showed an intensity at least 10 dB greater than the fragment preceding the onset of the  
240 fricative.

241 • Vowel onset was established by visual inspection of the spectrogram and waveform,  
242 locating a drop in acoustic energy at around 3 500 Hz – 8 500 Hz and the start of the  
243 periodic wave with its first glottal pulse. The pointer was placed on this pulse and a 20  
244 ms window was selected at the vowel's onset zone. As from this point, LPC-  
245 autocorrelation and DFT were applied to record the 10 dB drop in energy at the  
246 frequency showing the greatest value in the fricative.

247 • The vowel end was established by visually inspecting the spectrogram and waveform,  
248 localizing the ends of the vowel formants and glottal pulses.

249 To establish the level of inter-judge agreement in segmentations, 10% of the samples randomly  
250 selected (30 control, 30 pathological) were independently segmented in a blind fashion by

251 another two speech therapists. These collaborators had experience with acoustic phonetics and  
252 the use of the Praat programme. Along with an investigator, both also underwent a training  
253 session to apply segmentation and labelling criteria to samples that were not included in this  
254 study.

255 According to the segmentation and labelling results, an inter-judge agreement study was  
256 performed. For this, we used a specific script created *ad hoc* in Praat that calculates the lapse  
257 between the initial boundary of the segment as deemed by two judges and notes down this  
258 difference in relative terms to total segment duration. The mean of these measurements (a  
259 proportion value from 0 to 1) was subtracted from 1 and the result was interpreted as agreement  
260 between both judges. Accordingly, agreement between judges 1 and 2 was 94.4%; judges 1 and  
261 3 was 94%; and judges 2 and 3 was 91.7%.

262 To examine intra-judge agreement on 10% of randomly selected samples, one of the speech  
263 therapists undertook a new segmentation and labelling procedure in two sessions 3 months  
264 apart. In this case, intra-judge agreement was 95.4%.

265

### 266 ***Analysis Procedure and Temporal Acoustic Measurements***

267 On each of the labelled segments, acoustic duration measurements were made as described in  
268 a study examining motor speech disorders in English speakers (Kim, 2017): fricative, vowel,  
269 and consonant+vowel sequence durations in milliseconds, and the vowel-to-fricative duration  
270 ratio.

271

### 272 ***Statistical Analysis***

273 The data obtained in Praat was analysed with R (R Core Team, 2020). Due to the lack of  
274 normality (tested by the Lilliefors Kolmogorov-Smirnov test) and homoscedasticity of  
275 variances (tested by the Fligner-Killeen test) together with the presence of outliers, especially

276 in the groups with a pathology, robust statistics were applied using the ggstatsplot package  
277 (Patil, 2021).

278 For descriptive data, 5% trimmed means with an alpha of 0.5 (mean function) and the median  
279 of the absolute standard deviation (mad function) were calculated. Further, the robust  
280 coefficient of variation (mad/median with 95% confidence intervals) was estimated using the  
281 medCV function in the MKdescr package (Kohl, 2022).

282 The group factor was analysed using a heteroscedastic one-way ANOVA for trimmed means  
283 (t1waybt function; bootstrapping = 5000; tr = 5%). Pairwise comparisons between groups,  
284 vowel rounding, and sexes were analysed using Yuen's test for trimmed means (Yuen function;  
285 bootstrapping = 5000; tr = 5%). A control adjustment of the false discovery rate was applied in  
286 both analyses. In addition, effect size was calculated using the explanatory measure of effect  
287 size ( $\xi$ ), for the former, and the Algina-Keselman-Penfield robust standardized difference  
288 ( $\delta_R^{AKP}$ ), for the latter.

289

## 290 **Results**

291 The results of analysis of each of the acoustic measurements obtained in the three study groups  
292 (dysarthria, AoS, control) are separately presented.

293 Descriptive data for acoustic duration measurements are summarized for all three groups in  
294 Table 2. The results of our inferential analyses are provided in Tables 3 and 4.

295 *[Tables\_2\_3\_4]*

296

### 297 *Duration of the Fricative*

298 In both the dysarthria and AoS groups, fricative duration was significantly longer compared to  
299 the control group, the dysarthria group displaying the largest difference in duration. However,

300 there were no significant differences in fricative duration between the dysarthria and AoS  
301 groups.

302 Fricative duration did not differ significantly according to vowel rounding for the whole dataset  
303 or when each group was separately considered (Tables 3 and 4). However, in pairwise  
304 comparisons, while fricative durations in both vowel rounding contexts were similar between  
305 the dysarthria and AoS groups (Table 4), the dysarthria group differed from the control group  
306 in both rounded and unrounded contexts, and the apraxia group only differed from the control  
307 group in the rounded context (Figure 1). Interestingly, the AoS group behaved like the control  
308 group in that speakers pronounced the fricative longer than the vowel whatever the vowel type,  
309 while those in the dysarthria group did the opposite such that their fricatives were shorter than  
310 their vowels.

311 No significant sex differences were observed, except for a tendency in all groups for males to  
312 produce longer fricatives than females. *[Figure 1]*

313  
314 *Duration of the Vowel*

315 For vowel duration, no effects were observed of rounding such that similar durations were  
316 recorded for rounded and unrounded vowels. However, participants in all study groups showed  
317 a tendency, albeit not significant, to make unrounded vowels longer than rounded vowels.

318 An effect of group was, however, produced. In this case, it was the dysarthria group that showed  
319 a significantly longer vowel duration compared to the control and AoS groups, while in the AoS  
320 group, vowels were of longer duration than in the control group. Although there was no effect  
321 of vowel rounding, in the pairwise analysis, significant differences were observed for both  
322 unrounded and rounded vowels, which were longer in the dysarthria group. The dysarthria  
323 group showed the greatest difference from the AoS and control groups in the duration of  
324 unrounded vowels, but the latter two showed greater differences in the durations of rounded  
325 vowels (Figure 2).

326 Differences by sex were only observed in the control group, whereby females produced  
327 significantly longer vowels than males (Figure 3).

328

329 *[Figure\_2]*

330

331 *Duration of the Consonant+Vowel Sequence*

332 A significant effect of the factor group was produced on consonant plus vowel duration. Hence,  
333 the dysarthria group featured longer segments than the control and the AoS groups. The AoS  
334 and control groups also differed significantly in that the former showed a longer duration of  
335 this sequence. Differences were observed in all cases for between vowel types. Nonetheless,  
336 while the dysarthria and control groups differed more for unrounded vowel sequences, the AoS  
337 and control groups differed more in terms of rounded vowel sequences.

338 Significant sex differences were observed in the control group, in that females produced longer  
339 sequences than males.

340

341 *Ratio of Vowel-to-Fricative Duration*

342 Our analysis indicated a differential group effect. This meant that the dysarthria group showed  
343 a significantly higher vowel-to-fricative duration ratio than the control and AoS groups. In all  
344 groups, while differences were not significant, the vowel-to-fricative duration ratio tended to  
345 be higher for unrounded vowels. When the dysarthria and control groups were compared  
346 according to vowel rounding, a higher ratio noted for rounded vowels. Similarly, the ratio was  
347 significantly higher for the dysarthria group compared to the AoS group, and for the AoS group  
348 compared to the control group. In both cases, the vowel-to-fricative duration ratio was higher  
349 for unrounded vowels.

350 As observed in previous instances, only the control group demonstrated differences by sex such  
351 that females achieved higher ratios (Figure 3).

352 *[Figure\_3]*

353

## 354 **Discussion**

355 This study sought to identify simple acoustic measurements that might be specific to the  
356 different types of motor speech disorder. These measurements were made in simple tasks in  
357 which listeners repeated monosyllabic words that started with the fricative /s/ sound. The  
358 variables compared in the disorders dysarthria and AoS, as well as in normal Spanish speaking  
359 controls, were the acoustic durations of the fricative, vowel, consonant+vowel sequence and  
360 the relative measurement vowel-to-fricative duration ratio. In addition, we examined whether,  
361 besides varying in the two disorders, these variables could differ according to sex or linguistic  
362 factors such as rounding of the vowel adjacent to the fricative.

363 As expected, the dysarthria group showed longer acoustic durations than the control group,  
364 indicating prolonged sound production of both the fricative sound and its adjacent vowel. These  
365 findings are consistent with those reported by others (Ackermann & Hertrich, 1994; Ken &  
366 Netsell, 1975; Kent, Netsell, & Abbs, 1979; Kim et al., 2011; Kim, Rong, et al., 2010;  
367 Hernandez et al., 2019; Jongman et al., 2000; Ziegler & von Cramon, 1986c). Specifically, the  
368 longer duration consisted more in lengthening of the vowel, although there was also an increase  
369 in the length of the fricative. Further, as expected, the greater duration of both sounds in the  
370 dysarthria group gave rise to a longer duration of the consonant+vowel segment, and a higher  
371 ratio of vowel-to-fricative duration in this group relative to the control group. The increase in  
372 duration could be explained by different factors. Kinematic studies based on EMA or EPG have  
373 shown the reduced amplitude and speed of tongue movements during the production of the  
374 fricative /s/ and diphthongs, and temporal and spatial alterations in articulatory contacts of

375 fricatives (Ackermann et al., 1995; Goozée et al., 2000; Goozée et al., 2003; Rong et al., 2012).  
376 Another explanation could be impaired mechanoreceptors in dysarthric participants disrupting  
377 intraoral proprioception (Creech et al., 1973). It is possible that proprioceptive alterations and  
378 the acoustic distortion produced when pronouncing sounds activate the correction processes of  
379 the FBCS and require tuning of the movement by the FFCS. Therefore, the increase in the  
380 duration of the non-rounded segments (fricative and vowel) could partially reflect the effect  
381 that the restriction to coarticulation and the demands for articulatory precision both sounds have  
382 on the neurophysiological alteration. Further, distorted proprioceptive and acoustic feedback  
383 could further increase processing time and lead to high variability in sound realizations due to  
384 the corrections and adjustments triggered by the FFCS. For rounded fricatives, although there  
385 was less variability, the longer duration possibly reflects the complexity of planning  
386 anticipatory lip coarticulation by the FFCS, considering the proprioceptive alterations of  
387 different articulators. All of this seems to be in line with the failures in both systems described  
388 by Guenther (2016) for spastic and ataxic dysarthria, which made up most of our sample.

389 Our group of individuals with AoS showed longer durations of the fricative, its adjacent vowel,  
390 and the consonant+vowel sequence as well as a higher vowel-to-fricative duration ratio  
391 compared to the control group of Spanish speakers. Notwithstanding, the only non-significant  
392 difference was the fricative duration followed by unrounded vowels. These findings coincide  
393 with those of other studies on duration of the fricative /s/ and vowel, as longer durations in the  
394 AoS group also attain significance (Collins et al., 1983; Haley, 2002; Ziegler & von Cramon,  
395 1986a). However, in our AoS group, there was a tendency, although not significant, to make  
396 the consonant+vowel sequence longer and with greater variability when the vowel was rounded,  
397 while in the control group the opposite pattern was produced. This difference is mainly due to  
398 the longer duration of the rounded fricative, since both vowel types last equally, possibly related  
399 to reduced anticipatory coarticulation (Bartle-Meyer & Murdoch, 2010; Ziegler & von Cramon,

400 1985). Thus, differences in durations and variability could be explained by difficulty in  
401 generating the motor programme and in the planning of anticipatory lip coarticulation as  
402 functions attributed to the FFCS (Guenther, 2016), which is altered in AoS, as pointed out by  
403 Terband et al. (2019). Further, this is consistent with greater contact instability and temporal  
404 variation as indicated by studies employing EMA and EPG. Thus, reductions have been  
405 detected in maximum acceleration, deceleration and peak velocity during the approach and  
406 closure/constriction phases of fricative production in monosyllables (Bartle-Meyer, Goozée, &  
407 Murdoch., 2009; Bartle-Meyer & Murdoch, 2010; Bartle-Meyer, Murdoch & Goozée, 2009;  
408 Southwood, et al., 2009; Straus & Klich, 2001; von Cramon & Ziegler, 1985).

409 Comparing our two pathological groups, parameters of vowel duration, consonant+vowel  
410 sequence and vowel-to-fricative duration ratio were clearly different. The dysarthria group  
411 showed a longer vowel duration and consonant+vowel sequence together with higher ratio than  
412 the AoS group. Moreover, the dysarthria group displayed a consistently longer pattern in the  
413 vowel than consonant, whereas in the AoS and control groups, the fricative was longer than the  
414 vowel. We also examined whether rounding of the vowel adjacent to the fricative could affect  
415 fricative duration, as having or not to articulate the lips could influence this parameter.  
416 However, no such effect of vowel rounding was detected in either pathological group. While  
417 both the dysarthria and apraxia groups produced longer fricatives when accompanied by  
418 rounded vowels, group differences were more noticeable (yet not significant) in unrounded  
419 vowel contexts. In addition, the dysarthria group showed more variability than AoS, especially  
420 for unrounded segments, and participants with AoS showed more variability for the rounded  
421 segments. This could reflect a different cause of prolonged speech in the two groups. In the  
422 case of AoS, the longer duration and variability of the rounded fricative and the greater  
423 variability in the rounded vowel may reflect difficulties in planning the inter-articulator  
424 coordination necessary for rounding that is already present in the fricative (Daniloff & Moll,

425 1968; Fletcher & Harrington, 1999; Lubker & Gray, 1982), and for which the FFCS is  
426 responsible (Guenther, 2016). In dysarthria, the longer duration and greater variability of  
427 unrounded segments, which demand intra-articulator precision as they involve the same main  
428 articulator (tongue tip) and are resistant to coarticulation (Recasen & Rodriguez, 2016), and the  
429 longer duration and greater variability of rounded segments, which require inter-articulator  
430 coordination as well as articulatory precision for the fricative, are consequences of  
431 neurophysiological restrictions that reduce the agility needed for movements of the articulatory  
432 organs, especially tongue movements, and of intraoral proprioceptive problems (Creech et al.,  
433 1973). Therefore, the FBCS needs to make adjustments based on the altered feedback it  
434 receives, indirectly causing the FFCS to recalibrate movements, which is particularly complex  
435 in terms of lip rounding due to distortions by different articulators.

436 Sex differences were only observed in our control group. Females tend to make fricatives  
437 shorter, in line with the findings of other studies (Crystal & House, 1988; Jongman et al., 2000;  
438 Koenig et al., 2013; Nirgianaki, et al., 2009), but not significantly, as noted by Fox and Nissen  
439 (2005) for English. In contrast, significant differences were produced in vowel duration, such  
440 that females lengthened their vowel sounds. This finding is consistent with a smaller physical  
441 articulatory space, promoting longer articulatory contacts and a larger vowel space with the  
442 consequence of more articulatory precision in females (Simpson 2009; Whiteside, 2001).

443

#### 444 **Limitations and Future Lines of Investigation**

445 No subclasses were defined within our group of dysarthric persons. It could be that different  
446 categories of dysarthria produce varying effects on the length of the /s/ sound such that their  
447 differentiation would lead to more accurate results. Our sample size of persons with AoS was  
448 small because of the lower prevalence of this disorder. This determined different sized groups  
449 prompting the types of analysis used with possible effects on results and statistical power. The

450 contribution of this study could be extended by expanding the size of the cohorts and by  
451 distinguishing the different categories of dysarthria. In future work, we propose the use of  
452 techniques such as electropalatography, electromagnetic articulography and magnetic  
453 resonance, along with acoustic analysis methods.

454 The present study examines the duration of this Castilian Spanish fricative in individuals with  
455 dysarthria and AoS. Several duration measurements were able to distinguish between normal  
456 and dysarthric, normal and AoS, and dysarthric and AoS speech productions. More work is  
457 needed to understand why our AoS group showed intermediate values between normality and  
458 dysarthria in many of the measurements made.

459

## 460 **Conclusions**

461 The group of participants with dysarthria showed significantly longer fricative and following  
462 vowel durations, and a higher vowel-to-fricative duration ratio than the control group. The  
463 dysarthria and AoS groups also differed in terms of these parameters, although the difference  
464 in fricative duration was not significant. Differences between the two groups were more  
465 prominent in unrounded vowel sound contexts, suggesting the AoS group could be more skilled  
466 at producing unrounded sounds than the dysarthria group. This may be attributed to the fact that  
467 rounded sounds require more inter-articulatory planning by the deficient FFCS in AoS. Further,  
468 the AoS group differed significantly from the control group in terms of longer durations of the  
469 fricative+rounded vowel, vowel, consonant+vowel, and a higher vowel-to-fricative duration  
470 ratio. These findings indicate that the AoS group adopted an intermediate position between the  
471 dysarthria and control groups. Moreover, the differences noted between the AoS and control  
472 groups were more significant for rounded segments, suggesting difficulties in inter-articulatory  
473 planning, which is dependent on an effective FFCS.

474

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478

479 **Disclosure of interest**

480 The authors report no conflict of interest.

481

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484

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Table 1. *Descriptive data of the study population*

	N	Mean age (range, years)	Sex (M,F)
Control	28	42.6 (21-71)	19M; 9F
Apraxia	8	41.5 (30-61)	4M; 4F
Dysarthria	20	41.8 (21-72)	14M; 6F

*Dysarthria category	N	Aetiology	N
Spastic	15	Head trauma	10
Ataxic	2	Stroke	10
Flaccid	1	Tumour	3
Mixed	2	Other (encephalopathy, toxoplasmosis)	5

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

Table 2.

*Descriptive data of acoustic duration measurements:  $\alpha$ -trimmed mean 5% (and median absolute deviation) in ms and robust coefficient of variation (mad/median with 95% Confidence Intervals) by group and number of observations (n)*

	Unrounded vowel					Rounded vowel					Total (unrounded and rounded)				
	n	FrD	VD	CVD	VFR	n	FrD	VD	CVD	VFR	n	FrD	VD	CVD	VFR
Control	168	159.65	125.32	285.21	0.80	168	158.70	123.18	283.64	0.79	336	159.19	124.32	283.78	0.80
		(27.43)	(34.10)	(45.96)	(0.25)		(25.20)	(29.65)	(47.44)	(0.21)		(26.69)	(34.10)	(46.70)	(0.24)
		0.173	0.294	0.164	0.326		0.158	0.240	0.167	0.279		0.168	0.277	0.166	0.304
Apraxia	48	171.48	162.57	338.02	0.99	48	179.64	162.25	343.20	0.94	96	175.65	161.93	340.63	0.96
		(45.22)	(57.82)	(83.77)	(0.44)		(58.56)	(63.01)	(94.15)	(0.37)		(50.04)	(59.30)	(88.95)	(0.39)
		0.283	0.371	0.270	0.440		0.332	0.407	0.275	0.410		0.303	0.383	0.282	0.407
Dysarthria	120	185.81	244.28	435.92	1.41	120	189.67	224.22	414.02	1.27	240	187.70	234.20	424.97	1.33
		(63.75)	(98.59)	(136.40)	(0.52)		(61.52)	(83.77)	(134.18)	(0.45)		(65.23)	(94.15)	(135.66)	(0.48)
		0.352	0.445	0.329	0.432		0.333	0.418	0.341	0.404		0.355	0.446	0.340	0.424

FrD: fricative duration; VD: vowel duration; CVD: consonant+vowel sequence duration; VFR: vowel-to-fricative duration ratio

Table 3. Results of comparisons by group (robust one-way ANOVA, 5% trimmed means) and of comparisons by vowel rounding and by sex (Yuen's test for 5% trimmed means).

Factor	Group			Vowel rounding			Sex		
	$F_{\text{Trimmed means}}$	p	Effect size $\xi$	$t_{\text{yuen}}$	p	$\delta_{\text{R}}^{\text{AKP}}$	$t_{\text{yuen}}$	p	$\delta_{\text{R}}^{\text{AKP}}$
Fricative duration	20.19	0.001***	0.27	0.45	0.65	-0.04	0.46	0.65	0.05
Vowel duration	91.52	0.001***	0.65	1.28	0.20	0.09	2.44	0.02*	-0.22
Consonant+vowel sequence duration	95.31	0.001***	0.59	0.90	0.37	0.07	1.70	0.09	-0.16
Vowel-to-fricative duration ratio	44.17	0.001***	0.56	1.16	0.25	0.09	2.71	0.007**	-0.24

Table 4. *Pairwise comparisons by group, vowel rounding and sex in acoustic duration measurements (Yuen's test for 5% trimmed means).*

	Fricative duration			Vowel duration			Consonant+vowel sequence duration			Vowel-to-fricative Duration ratio		
	<b>T</b>	<b>U</b>	<b>R</b>	<b>T</b>	<b>U</b>	<b>R</b>	<b>T</b>	<b>U</b>	<b>R</b>	<b>T</b>	<b>U</b>	<b>R</b>
<b>C vs D</b>	6.66	3.99	4.59	12.85	9.52	8.80	13.24	10.06	8.78	8.86	6.67	6.55
$t_{\text{yuen}}(p)$	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
$\delta_R^{\text{AKP}}$	-0.99	-0.94	-1.06	-3.07	-3.07	-3.06	-2.97	-2.99	-2.33	-2.18	-2.30	-2.04
<b>C vs A</b>	2.42	1.24	2.19	5.08	3.28	3.36	4.71	2.96	3.58	3.78	2.67	2.56
$t_{\text{yuen}}(p)$	(0.03*)	(0.22)	(0.05*)	(0.001***)	(0.002**)	(0.001***)	(0.001***)	(0.004**)	(0.001***)	(0.001***)	(0.01**)	(0.01**)
$\delta_R^{\text{AKP}}$	-0.57	-0.42	-0.72	-1.05	-0.96	-1.18	-1.20	-1.05	-1.29	-0.67	-0.71	-0.65
<b>A vs D</b>	1.51	1.29	0.29	6.59	5.02	4.17	5.38	4.32	5.38	5.17	3.78	3.62
$t_{\text{yuen}}(p)$	(0.13)	(0.22)	(0.38)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.002**)	(0.001***)	(0.001***)	(0.001***)
$\delta_R^{\text{AKP}}$	-0.18	-0.22	-0.15	-1.03	-1.08	-0.91	-0.73	-0.81	-0.73	-0.92	-0.90	-0.84
	<b>C</b>	<b>D</b>	<b>A</b>	<b>C</b>	<b>D</b>	<b>A</b>	<b>C</b>	<b>D</b>	<b>A</b>	<b>C</b>	<b>D</b>	<b>A</b>
<b>U vs R</b>	0.31	0.43	0.62	0.58	1.22	0.02	0.11	1.07	0.22	0.48	1.22	0.55
$t_{\text{yuen}}(p)$	(0.76)	(0.66)	(0.54)	(0.56)	(0.23)	(0.98)	(0.92)	(0.28)	(0.83)	(0.63)	(0.23)	(0.58)
$\delta_R^{\text{AKP}}$	0.03	-0.06	-0.13	0.06	0.15	0.004	0.01	0.14	0.04	0.05	0.14	0.10

<b>F vs M</b>	0.43	0.48	0.23	4.43	1.79	0.31	3.50	1.04	0.24	3.63	1.65	0.05
t <sub>yuen</sub> (p)	(0.67)	(0.63)	(0.82)	(0.001***)	(0.08)	(0.76)	(0.001***)	(0.30)	(0.81)	(0.001***)	(0.10)	(0.96)
$\delta_R^{AKP}$	0.04	0.07	0.09	-0.45	-0.31	0.07	-0.35	-0.17	0.08	-0.41	-0.27	-0.00

Total: Total comparison; U: Unrounded vowel; R: Rounded vowel; C: Control; D: Dysarthria; A: Apraxia; F: Female; M: Male

# Differences in fricative duration between the groups

## Length fricative according to vowel rounding

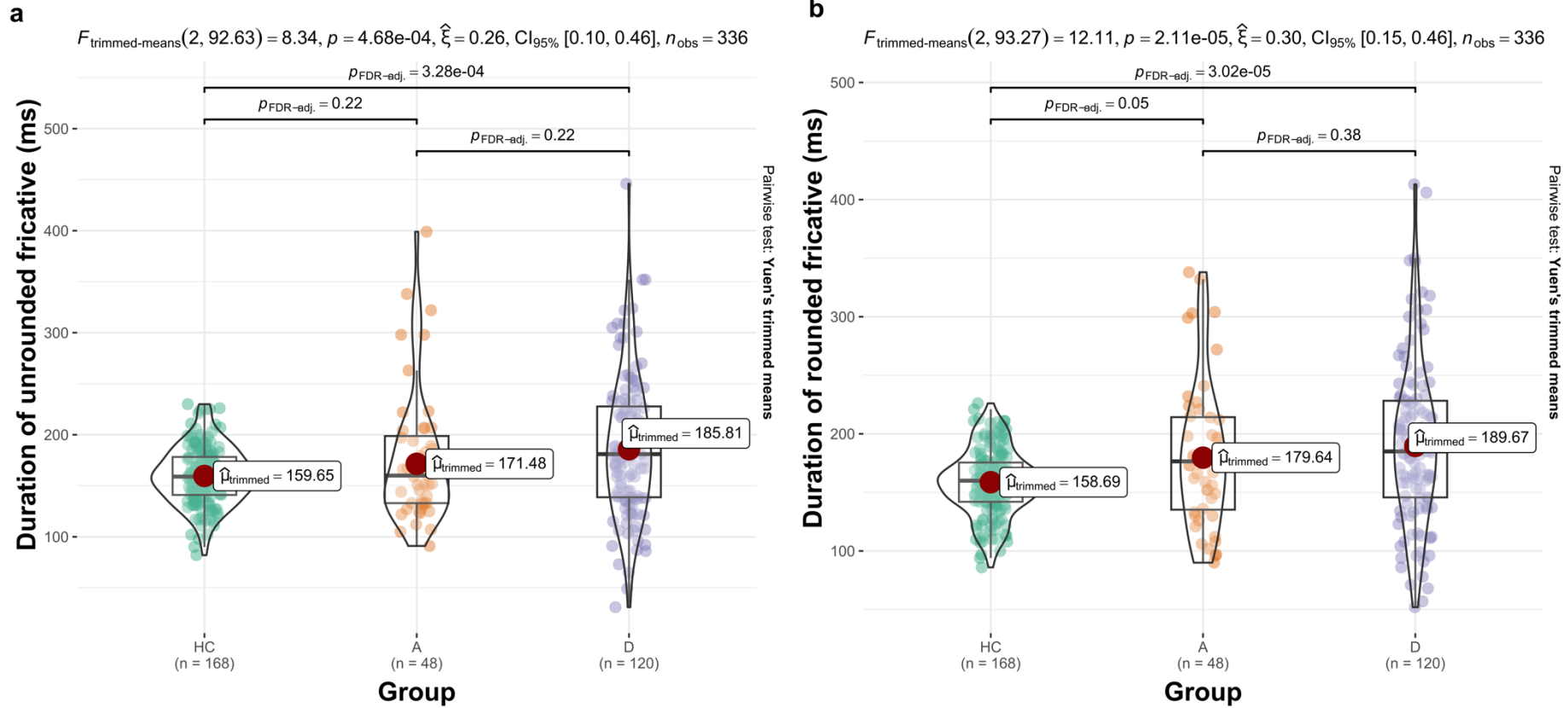


Figure 1 Differences in fricative duration between Healthy Control (HC), Apraxia of Speech (A) and Dysarthria (D) groups according to vowel rounding. Bars show pairwise comparison with Yuen's Test (p-levels).

## Differences in vowel duration between the groups

### Length vowel according to vowel rounding

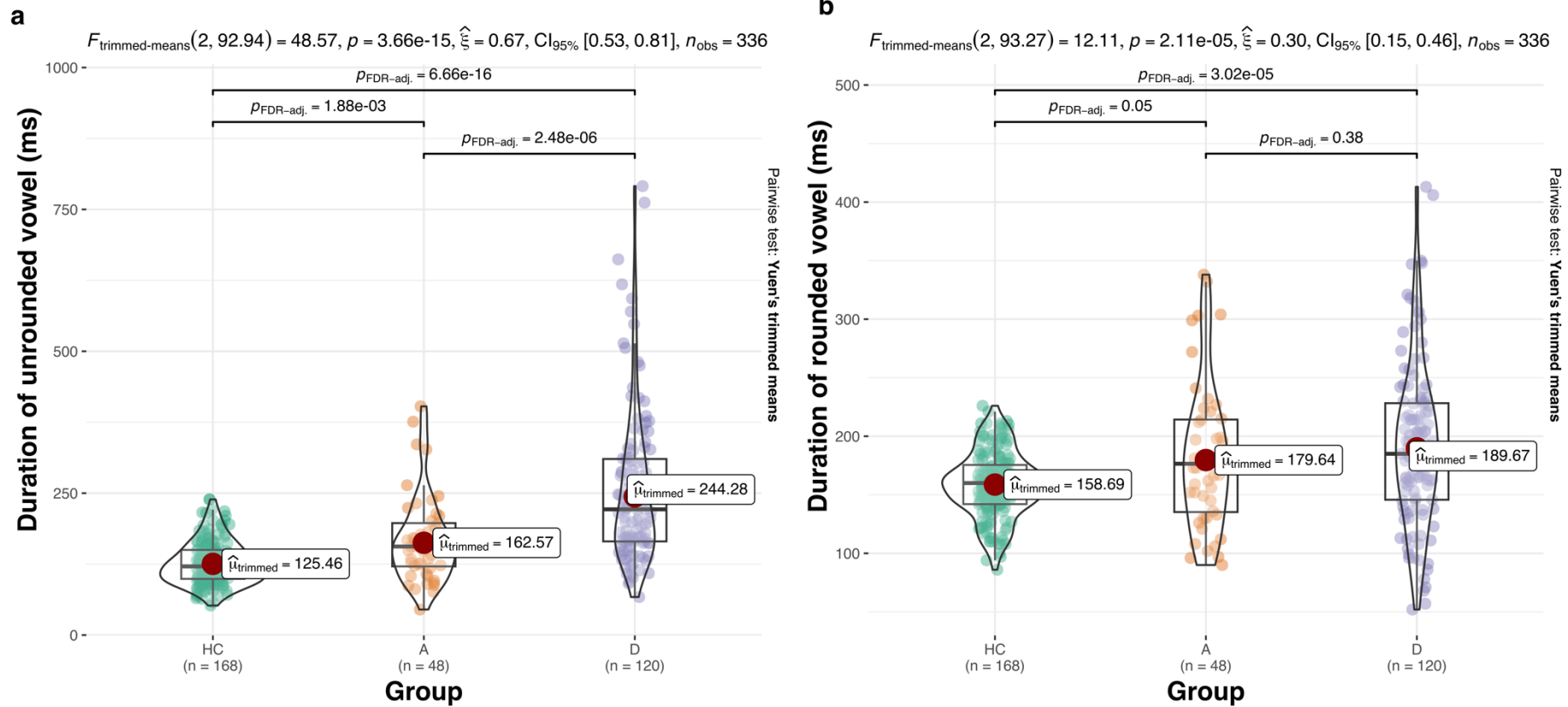


Figure 2 Differences in vowel duration between Healthy Control (HC), Apraxia of Speech (A) and Dysarthria (D) groups according to vowel rounding. Bars show pairwise comparison with Yuen's Test (p-levels).

## Sex differences in Healthy Control Group Length vowel and VFR

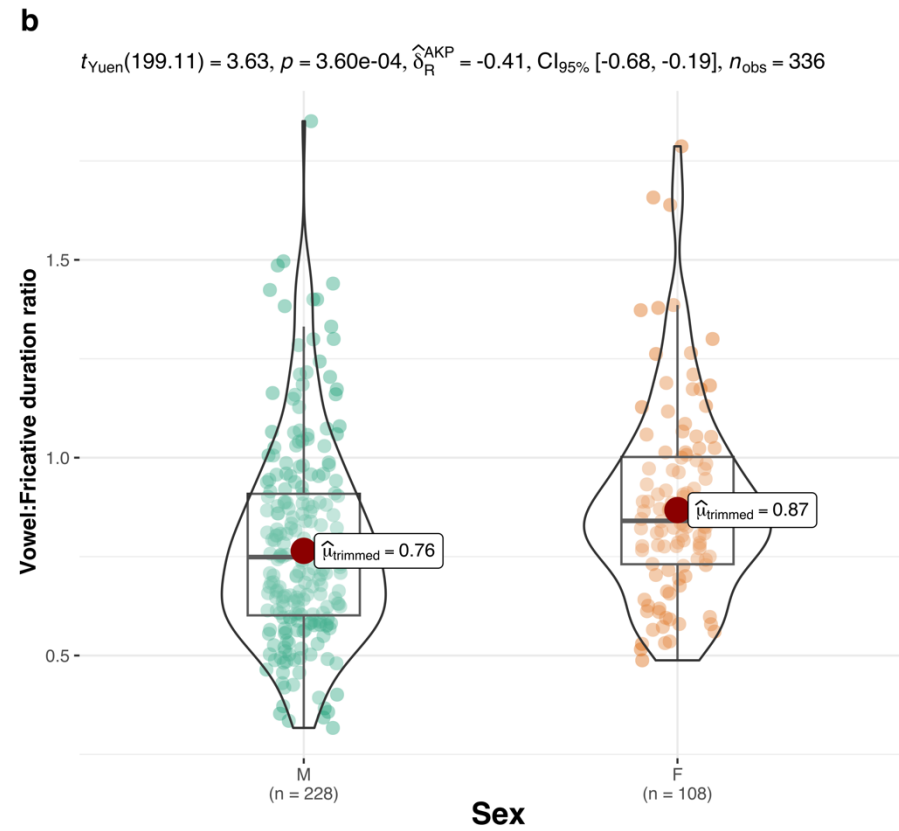
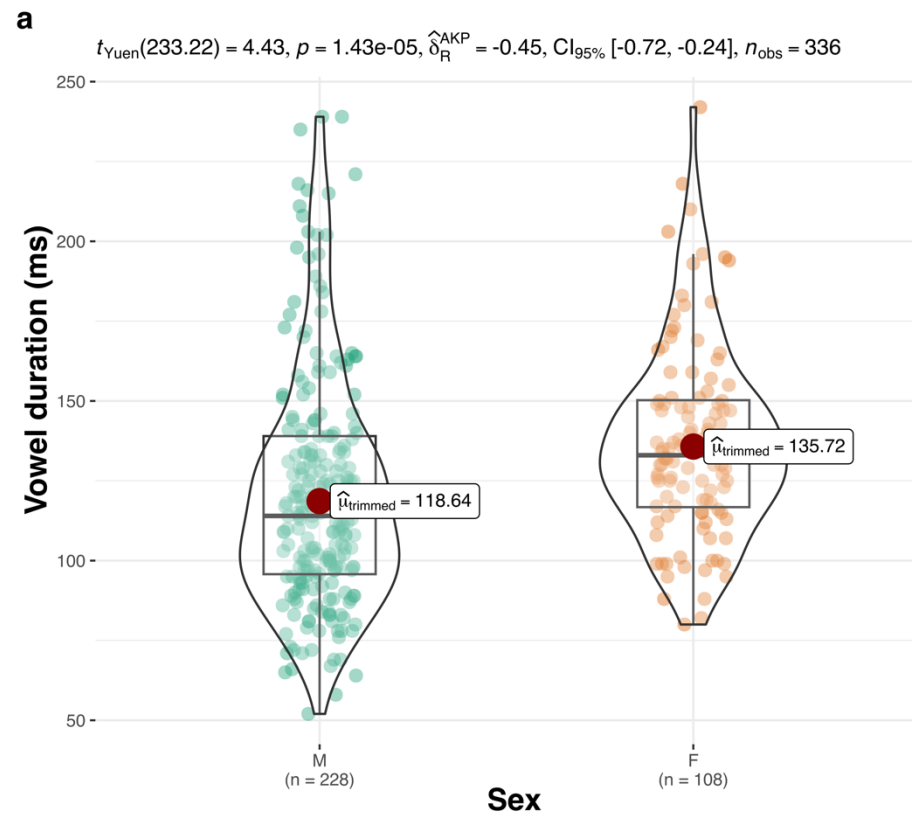


Figure 3 Differences in vowel duration and ratio vowel-to-fricative duration between males and females of the healthy control group.