



HAL
open science

Acoustic Change Over Time in Spastic and/or Flaccid Dysarthria in Motor Neuron Diseases

Nathalie Lévêque, Anneke Slis, Leonardo Lancia, Gaëlle Bruneteau, Cécile
Fougeron

► **To cite this version:**

Nathalie Lévêque, Anneke Slis, Leonardo Lancia, Gaëlle Bruneteau, Cécile Fougeron. Acoustic Change Over Time in Spastic and/or Flaccid Dysarthria in Motor Neuron Diseases. *Journal of Speech, Language, and Hearing Research*, 2022, 65 (5), pp.1767-1783. 10.1044/2022_JSLHR-21-00434 . hal-03928163

HAL Id: hal-03928163

<https://hal.science/hal-03928163>

Submitted on 9 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Acoustic change over time in spastic and/or flaccid dysarthria in motor neuron diseases

Nathalie Lévêque^{1,2}, Anneke Slis, A.¹, Leonardo Lancia¹, Gaëlle Bruneteau², Cécile Fougeron¹

¹ LPP, UMR 7018, CNRS/University Sorbonne-Nouvelle, Paris, France.

² APHP, Department of Neurology, Hôpital Pitié-Salpêtrière, ALS Reference Center, Paris, France

Correspondence to Nathalie Lévêque: nathalie.leveque@aphp.fr

The authors declare no conflict of interest.

This research was funded by Assistance Publique – Hôpitaux de Paris, Délégation de la Recherche Clinique et de l'Innovation (DRCI) (awarded to the first author) and by the Swiss National Science Foundation, Sinergia program (CRSII5_173711, 10.2017-9.2020).

Abstract

Purpose: This study aims to investigate acoustic change over time as biomarkers to differentiate among spastic-flaccid dysarthria associated with amyotrophic lateral sclerosis (ALS), spastic dysarthria associated with primary lateral sclerosis (PLS), flaccid dysarthria associated with spinal and bulbar muscular atrophy (SBMA), and to explore how these acoustic parameters are affected by dysarthria severity.

Method: Thirty-three ALS patients with mixed flaccid-spastic dysarthria, seventeen PLS patients with pure spastic dysarthria, eighteen SBMA patients with pure flaccid dysarthria and seventy controls, all French speakers, were included in the study. Speakers produced vowel-glide sequences targeting different vocal tract shape changes. The mean and coefficient of variation of the total squared change of Mel Frequency Cepstral Coefficients were used to capture the degree and variability of acoustic changes linked to vocal tract modifications over time. Differences in duration of acoustic events were also measured.

Results: All pathological groups showed significantly less acoustic change compared to controls, reflecting less acoustic contrast in sequences. Spastic and mixed spastic-flaccid dysarthric speakers showed smaller acoustic changes and slower sequence production compared to flaccid dysarthria. For dysarthria subtypes associated with a spastic component, reduced degree of acoustic change was also associated with dysarthria severity.

Conclusions: The acoustic parameters partially differentiated among the dysarthria subtypes in relation to motor neuron diseases. While similar acoustic patterns were found in spastic-flaccid and spastic dysarthria, crucial differences were found between these two subtypes relating to variability. The acoustic patterns were much more variable in ALS. This method forms a promising clinical tool as a diagnostic marker of articulatory impairment, even at mild stage of dysarthria progression in all subtypes.

1 **Introduction**

2 Motor neuron diseases (MND) embrace a group of neurodegenerative diseases
3 affecting lower motor neuron (LMN) and/or upper motor neuron (UMN) systems. One of the
4 diseases that involves the LMN system is Spinal and Bulbar Muscular Atrophy (SBMA), also
5 known as Kennedy's disease (Kennedy et al., 1968). Primary Lateral Sclerosis (PLS) purely
6 affects the UMN system (Gordon et al., 2006) and Amyotrophic Lateral Sclerosis (ALS) is
7 defined as a disease affecting both systems resulting in heterogenous clinical profiles
8 depending on the predominance of LMN or UMN involvement (Charcot & Joffroy, 1869; Ince
9 et al., 1998). The major challenge in clinical practice is the lack of biomarkers to validate
10 LMN and UMN involvement (Bede & Pradat, 2019). SBMA and PLS are frequently
11 misdiagnosed as ALS, at least at onset of the disease. A correct distinction between these
12 diseases is of utmost interest because the median disease duration until death is much longer
13 in PLS (Pringle et al., 1992) and in SBMA (Atsuta et al., 2006) than in ALS (Logroscino et al.,
14 2008). It is crucial to find objective and reliable tools to assist the neurologic differential
15 diagnosis, to monitor and predict disease progression across MNDs.

16 When the lower and/or upper motor neurons, which both innervate the orofacial and
17 laryngeal regions, are damaged, motor speech function is altered. As a result, dysarthria is
18 common in these three pathologies (Atsuta et al., 2006; Banno et al., 2017; Bede & Finegan,
19 2018; Finegan et al., 2019; Miyata et al., 2019; Pedroso et al., 2018; Praline et al., 2008;
20 Querin et al., 2018; Tomik et al., 2006; Turner et al., 2020; Yunusova et al., 2019). The Mayo
21 Clinic system (Darley et al., 1969a, 1969b, 1975) classifies dysarthria perceptually into several
22 subgroups, based on the underlying neuropathology. Speech impairment, associated with
23 LMN lesions, such as in SBMA, is categorized as flaccid dysarthria; speech impairment due to
24 UMN damage, such as in PLS, is typically classified as spastic dysarthria. And finally, ALS is
25 classified as mixed flaccid-spastic dysarthria, involving both LMN and UMN impairment.
26 The degree of spasticity and flaccidity affecting the orofacial and laryngeal regions depends in
27 this latter case on the extent of damage of the UMN and LMN systems respectively (Tomik &

28 Guilloff, 2010). In the Mayo Clinic classification, articulatory distortions, described as
29 distorted vowels and imprecise consonant productions, figure among the most deviant
30 speech characteristics encountered in these three dysarthria subtypes. Slow rate is also
31 described to be a prominent feature in both spastic and flaccid-spastic dysarthria subtypes.
32 In the field of motor speech disorders, there are ongoing efforts to identify acoustic
33 biomarkers to support the differential diagnosis in dysarthria. The motivation of this study is
34 that, to our knowledge, no study compared the nature of dysarthric speech deficits in these
35 three neurodegenerative MNDs. Hence, the current study investigates acoustic parameters as
36 biomarkers to differentiate dysarthria subtypes between these three MNDs.

37 Acoustic and kinematic studies examining flaccid dysarthria subtypes due to different
38 etiologies have shown several important articulatory, spectral, and temporal characteristics.
39 Flaccid dysarthria is explained by muscular weakness involving the lingual, laryngeal and
40 velopharyngeal systems. In this broad subtype of flaccid dysarthrias originating from
41 different lesions in the motor unit, speech impairments are usually characterized by
42 velopharyngeal insufficiency, resulting in hypernasality, distorted labial and/or lingual
43 phonemes and distorted vowels. Slow speech rate and slow labial and/or lingual alternating
44 motion rates have also been described. Yet, reduced speech rate is usually not perceived in
45 flaccid dysarthria, unless impairment is severe (Duffy, 2019). In SBMA specifically,
46 hypernasality has been shown to be significantly higher in patients compared to controls and
47 increased vocal cords adduction during phonation has been observed as well, which is
48 associated with laryngospasms (Tanaka et al., 2014, 2019). Although muscular atrophy and
49 weakness of the tongue have been related to swallowing troubles in SBMA (Banno et al.,
50 2017; Hashizume et al., 2017; Mano et al., 2014, 2015), to our knowledge, acoustic and
51 articulatory studies investigating the effect of SBMA on the articulatory dimension do not
52 exist.

53 Acoustic and articulatory studies examining spastic dysarthria due to various
54 etiologies, demonstrate slow and incomplete velopharyngeal and lingual movements,
55 reduced speech rate, increased duration of phoneme-to-phoneme transitions, reduced

56 alternating motion rates, reduced speed and range of tongue and jaw movements, reduced
57 rate and slope of F2 transitions, smaller vowel space and centralization of vowel formants
58 (Clark et al., 2014; Hirose et al., 1982; Kent et al., 1999; Ozawa et al., 2001; Portnoy &
59 Aronson, 1982; Rong et al., 2012; Roy et al., 2001; Schölderle et al., 2016; Ziegler & von
60 Cramon, 1986). Many of these observations, however, were based on studies including one or
61 a few speakers (Duffy, 2019), and articulatory impairments specifically arising in speakers
62 with PLS have not been investigated yet.

63 Articulatory deficits in ALS have been examined the most extensive. Dysarthria
64 associated with ALS can be either flaccid or spastic at onset, becoming mixed spastic-flaccid
65 as dysarthria progresses. Both acoustic and kinematic studies report impaired articulatory
66 range of movement with flattened F2 slopes and reduced vowel space, decreased range of
67 movement of the tongue and exaggerated range or the movement of the jaw (DePaul
68 Roxanne & Brooks Benjamin R., 1993; Kuruvilla-Dugdale & Chuquilin-Arista, 2017;
69 Langmore Susan E. & Lehman Mark E., 1994; A. S. Mefferd et al., 2012; Rong et al., 2015;
70 Shellikeri et al., 2016; Yunusova et al., 2008, 2010, Lee et al., 2018, 2020; Lee & Bell, 2018;
71 A. S. Mefferd & Dietrich, 2020; Rong et al., 2018; Shellikeri et al., 2016; Yunusova et al.,
72 2010, 2012, 2013). The range of movement of the tongue was shown to decrease across the
73 severity continuum of dysarthria (Lee et al., 2018, 2020; Lee & Bell, 2018; A. S. Mefferd &
74 Dietrich, 2020; Rong et al., 2018; Shellikeri et al., 2016; Yunusova et al., 2010, 2012, 2013).
75 Whereas Slis et al. (2021) found higher variability in acoustic energy change, indicating more
76 variability in vocal tract shape change, variability of the tongue, lips and jaw movements were
77 demonstrated to be reduced in several other studies (Kuruvilla-Dugdale & Chuquilin-Arista,
78 2017; Kuruvilla-Dugdale & Mefferd, 2017; A. S. Mefferd et al., 2014). Acoustic and kinematic
79 studies also showed impaired temporal aspects of speech rate and articulatory movements
80 (Mefferd, 2015; Mefferd & Dietrich, 2020; Shellikeri et al., 2016; Yunusova et al., 2008,
81 2010, 2012, Ball et al., 2002; Mefferd et al., 2014; Turner et al., 1995; Turner & Weismer,
82 1993; Weismer et al., 2000, Turner & Weismer, 1993; Rong et al., 2018; Caruso & Burton,
83 1987; Kuruvilla-Dugdale & Chuquilin-Arista, 2017). Speech rate was shown to decline with

84 the progression of the dysarthria (Allison et al., 2019; Lee et al., 2018; Lee & Bell, 2018;
85 Yunusova et al., 2016, 2019).

86

87 Because dysarthria is presumably spastic only in PLS and flaccid only in SBMA, the
88 correct distinction between spastic dysarthria, flaccid dysarthria and mixed spastic-flaccid
89 dysarthria associated with ALS can assist neurologic differential diagnosis. The current study
90 includes these three distinct groups to investigate whether a set of acoustic biomarkers
91 differentiates among flaccid, spastic, and mixed spastic-flaccid dysarthria, associated with
92 these three neurodegenerative MNDs.

93 Acoustic measures can be used as biomarkers of dysarthria in neurodegenerative
94 diseases. A method using Mel Frequency Cepstral Coefficients (MFCCs), which provide a
95 measure of spectral energy changes over time, recently showed to be a sensitive tool in
96 capturing and identifying specificities in vocal tract shape changes from one articulatory
97 configuration to the next, in flaccid-spastic dysarthria in ALS and hypokinetic dysarthria
98 associated with Parkinson Disease (Slis et al., 2021). MFCCs provide a measure of spectral
99 energy in a temporal window; changes in these values from window to window reflect how
100 this spectral energy changes over time. These spectral changes have shown to correlate with
101 vocal
102 tract shape modifications (Goldstein, 2019). Slis et al. (2021) measured the spectral energy
103 changes over time during the productions of successive identical vowel-glide syllables. These
104 productions were characterized in terms of the overall amount of acoustic change in the
105 sequence - which is expected to be large to reflect the acoustic contrast between the segments
106 -, and in terms of variability of these acoustic changes - which is expected to be low to reflect
107 the fact that the successive identical syllables are articulated the same way. Compared to
108 controls and dysarthric patients with Parkinson Disease, dysarthric patients with ALS
109 showed reduced values of these spectral changes over time, suggesting hypoarticulation, and
110 more variability indicating instability in articulatory movements.

111 The goal of the current study was to capture spectral changes over time using MFCCs
112 during the production of successive identical vowel-glide sequences to differentiate among
113 the three dysarthria subtypes, associated with ALS, PLS and SBMA. Based on previous
114 studies, we expected a smaller amount of spectral change, suggesting hypoarticulation, in
115 speakers with ALS and PLS, and higher variability in speakers with ALS compared to
116 controls, suggesting instability in articulatory movements. Due to the lack of research
117 available for dysarthric speech of speakers diagnosed with PLS and SBMA, no specific
118 hypotheses related to variability were formulated for these speakers. To further differentiate
119 dysarthria subtypes, we also examined temporal measures during the production of the same
120 sequences. Based on previous literature, slower sequence productions were expected in
121 speakers with ALS and PLS compared to speakers with SBMA.

122 Finally, we explored the relation between the acoustic measures and dysarthria
123 severity. For speakers with ALS, it was expected that the amount of the spectral changes
124 correlated negatively with severity, and thus decreased, and duration of utterances correlated
125 positively, and increased with the severity of dysarthria. Due to the lack of research available
126 in dysarthric speech associated with PLS and SBMA, no specific hypotheses were formulated
127 about the relation between the acoustic measures and dysarthria severity for speakers with
128 these two pathologies.

129

130 **Methods**

131 ***Participants***

132 One hundred and thirty-eight participants aged between 23 and 90 years, were
133 enrolled in this experiment: seventy non-dysarthric French controls (forty from Paris and
134 thirty from Geneva) who reported no history of neurological impairment or speech and
135 language disorders and sixty-eight participants diagnosed with MNDs contributed speech
136 recordings to this study. Among the patients, thirty-three patients with ALS, seventeen
137 patients diagnosed with PLS and eighteen patients diagnosed with SBMA were recruited (see

138 Table 1 for distribution of the groups). All patients were diagnosed by neurologists of the
139 “ALS and other rare MNDs expert center” of the Pitié-Salpêtrière University Hospital (Paris,
140 France). ALS patients were diagnosed based on the El Escorial criteria (Brooks et al., 2000)
141 and had “probable” or “definite” ALS. PLS patients were diagnosed based on the consensus
142 diagnostic criteria and had “probable” or “definite” PLS (Gordon et al., 2006; Turner et al.,
143 2020). SBMA patients were diagnosed based on the genetic test that estimates CAG
144 expansion number in the androgen-receptor genes, considering more than 38 repeats to be
145 pathologic. The protocol for the study (including participant recruitment, data management,
146 consent forms and information leaflets) was approved by the following Ethics Committees:
147 CPP Sud-Est III, ClinicalTrial.gov ID: NCT03560661 for the patients and the Commission
148 Cantonale d’Ethique de la Recherche – 2018-00212 (Switzerland) and CPP Sud Ouest et
149 Outre Mer (ID_RCB: 2019-A02553-54) (France) for the control group recruitment. Prior to
150 inclusion, all study participants provided informed consent.

151 To be eligible for this study, patients had to show presence of functional signs of
152 bulbar involvement and be diagnosed with mild to moderate dysarthria. Subjects were
153 ineligible for inclusion if they showed evidence of cognitive impairment and/or respiratory
154 troubles according to the routine neurologist examination.

155 The presence of functional signs of bulbar involvement was assessed by an
156 experienced SLP (first author) using the bulbar subscore of the ALSFRS-R scale (Cedarbaum
157 et al., 1999). This subscore reflects the bulbar related handicap across three items (speech,
158 salivation, and swallowing) that are rated on a 5-point scale (from 0 = severe impairment to 4
159 = normal function) yielding a maximum bulbar subscore of 12. A bulbar subscore less than 12
160 indicates impaired orofacial function.

161 The severity of dysarthria was assessed by the perceptive score (PS) from the “Batterie
162 d’Evaluation Clinique de la Dysarthrie” (BECD) (Auzou & Rolland-Monnoury, 2019). The
163 perceptive score (PS) is a composite score summing the evaluation of five speech dimensions
164 (intelligibility, naturalness of speech, prosody, voice quality and articulatory precision) with a
165 five-point scale score for each dimension (0 = normal, 1 = mild, 2 = moderate, 3 = severe and

166 4 = very severe impairment). A recent study investigating clinician-based adjectival rating of
167 dysarthria severity in ALS found excellent intrarater and interrater reliability (Stipancic et
168 al., 2021). The total sum /20 indicates the severity of dysarthria following the cutoffs for
169 severity group assignment suggested in the BECD: 1-6 = mild dysarthria and 7-13 = moderate
170 dysarthria. Two experienced SLPs rated the dysarthria severity by listening to three-to-five-
171 minutes samples of connected speech. One of the SLPs (first author) recorded the patients
172 and provided the severity ratings at the same time. The other SLP performed the ratings on
173 the recordings of the same sample of connected speech. Since the first rater was not blind to
174 the participants neurological deficits, the second rater was informed about the patients'
175 diagnosis. Based on the level of overall score/20, intraclass correlations (ICCs) were used to
176 calculate the PS score interrater reliability (as described in Koo & Li, 2016). ICCs estimates
177 and their 95% confidence intervals (CI) were calculated, based on a single rating, absolute-
178 agreement, two-way random-effects model in R. Overall reliability between the two raters
179 were excellent with a value greater than .90 (ICC = .94, $p < .0001$, 95%-CI: .91 < ICC < .96).
180 For ALS and PLS, reliability was excellent as well (ICC = .94, $p < .0001$, 95%-CI: .87 < ICC <
181 .97 and ICC = .97, $p < .0001$, 95%- CI: .92 < ICC < .99 respectively). For SBMA, reliability
182 was good (ICC = .89, $p < .0001$, 95%-CI: .72 < ICC < .96). Based on these high levels of inter-
183 rater reliability, the PS scores were averaged.

184 Table 1 presents the population. As shown by the ALSFRS-R bulbar subscore, the
185 population was quite homogenous in terms of functional signs of bulbar involvement.
186 However, even though both mild and moderate cases of dysarthria were present in all
187 subgroups (see regression Figure 3), speakers in the SBMA group showed milder scores for
188 dysarthria overall which is also frequently observed in clinical practice. During recruitment,
189 a first screening of the patients made by the first author permitted to determine the subtypes
190 of dysarthria based on the cardinal speech features corresponding to each dysarthria subtype
191 (Darley et al., 1969a).

192

193 ***Speech material and recording procedure***

194 The speakers were instructed to produce three sequences composed of three
195 repetitions of the same syllable, either a vowel-glide syllable in /ajajaj/ and /ujujuj/, both
196 meaning “ouch, ouch, ouch” in French; or a glide-vowel syllable in /wiwiwi/ meaning “yes,
197 yes, yes” in French. The stimuli were selected because they elicit successive vocal tract shape
198 modifications which result in easily traceable acoustic outcomes with continuous resonances.
199 During /ajajaj/, the aperture of the vocal tract changes during the transition from vowel to
200 glide with active tongue and/or jaw movements resulting in dominant resonance changes in
201 the lower part of the spectrum (F1 area). /ujujuj/ and /wiwiwi/ require back/front movement
202 of the tongue and successive rounding/unrounding of the lips, which induce acoustic changes
203 dominant in mid frequency range. These last two sequences also vary in terms of syllabic
204 structure with a nucleus-coda structure in /ujujuj/ and an onset-nucleus structure for
205 /wiwiwi/.

206 The orthographic forms “äie, äie, äie”, “ouille, ouille, ouille” and “oui, oui, oui” were
207 presented on the screen of a laptop and produced at a comfortable rate and loudness. Each
208 sequence was repeated four times (n = 12 sequences per speaker) and sequences were
209 presented in the same order for all speakers. The participants were instructed to produce
210 each sequence in a continuous manner. Each participant attended a single recording session.
211 Recordings took place in a quiet room with the first author present. A high-quality acoustic
212 recording equipment was used with a Focusrite Scarlett (2i4) external audiocard and a
213 professional quality Shure SM35-XLR earset microphone that was positioned approximately
214 3 cm from the mouth during recordings. The speech was recorded at a sampling rate of 22.5
215 KHz and 16-bit resolution.

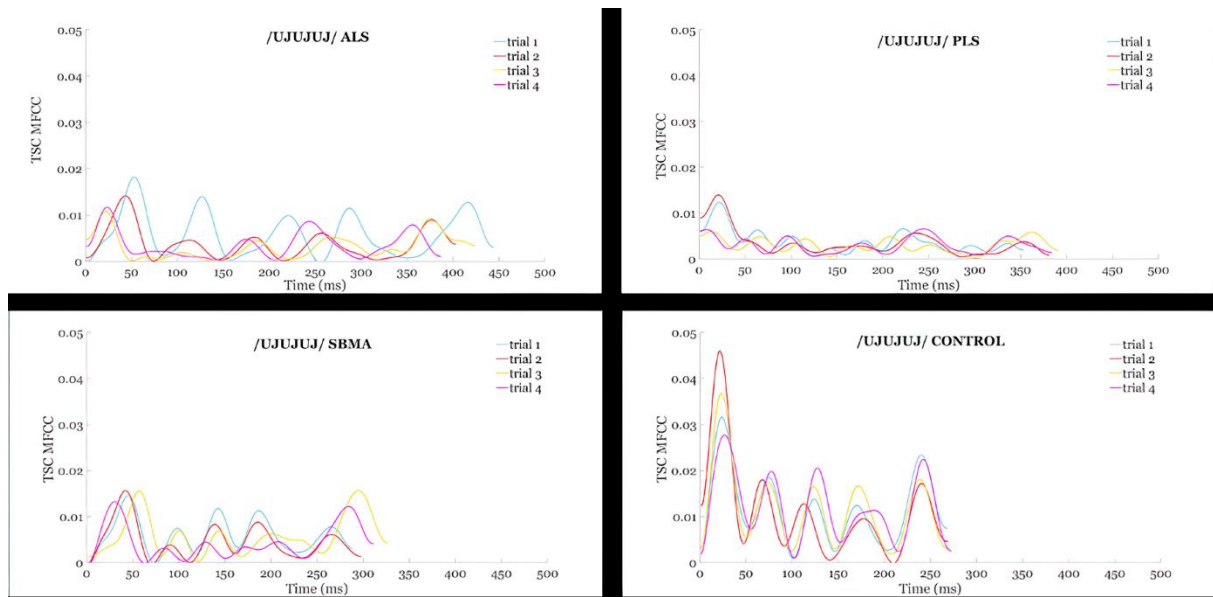
216

217 ***Acoustic data analysis***

218 All sound files were resampled to 16 KHz. Audio based segmentation and annotation
219 of each sequence were manually performed in Praat (Praat: Doing Phonetics by Computer,

220 2020). To compute the amount of acoustic change produced over the utterance Mel
221 Frequency Cepstral Coefficients (MFCCs) were calculated as follows. First, the spectra were
222 calculated over 25 ms time frames sliding over time in 2 ms steps. To target the frequencies
223 relevant for vocal tract shape changes, only the spectral coefficients between 300 and 8000
224 Hz were considered. The trimmed frequency scale was then converted into a Mel frequency
225 scale, which approaches the filter characteristics of the human ear (O'Shaughnessy, 1987).
226 Next, the spectra were log-transformed and submitted to a Discrete Cosine Transformation
227 (Davis & Mermelstein, 1980), resulting in a set of coefficients. Because the 1st coefficient
228 contains information about the overall average spectral energy, this coefficient was
229 disregarded and only the 2nd to 13th coefficient were considered. Next the differences between
230 coefficients 2-13 in two consecutive windows were calculated and squared; information about
231 the direction of change is thus removed and only the magnitude of energy change is
232 preserved. Finally, these difference values were summed (see also Slis et al., 2021). This
233 method results in values of total squared changes of mel frequency cepstral coefficients,
234 referred to as TSC_MFCCs. Plotting all TSC_MFCCs, a contour resulted, consisting of
235 increasing and decreasing TSC_MFCC values as illustrated in Figure 1, which presents the
236 contours of the degree of acoustic change during a /ujujuj/ sequence, produced four times by
237 a talker of each group.

238



239

240 Maxima in this contour aligns with the part of the speech production, during which the most
 241 vocal tract shape change is observed, i.e., during the transition from a vowel to a glide or
 242 glide to a vowel. Minima align with the part during which the vocal tract shape is relatively
 243 steady, i.e., during the steady state of the speech production.

244

245

246 ***Derived metrics***

247 The complete TSC_MFCC contour was delimited from the steady part of the first
 248 segment (i.e., the first valley) to the steady part of the last segment (i.e., the last valley). Next,
 249 three measures were extracted ([see also Slis et al., 2021](#)) :

250 - MEAN: the mean of the complete TSC_MFCC values capturing the average amount of
 251 acoustic change over time during the sequence. It is expected to lower with decreased
 252 acoustic contrastiveness between the successive segments, for example during a
 253 hypoarticulated sequence with little vocal tract changes.

254 - VARCO: the coefficient of variation of the complete contour determined the degree of
 255 variability of the acoustic changes over the sequence. In other words, it aimed to capture the
 256 stability in the acoustic contrasts, resulting from repeated successive syllables of the

257 sequence. The value is expected to be lower if the successive elements of the sequence are
258 articulated the same way and to increase with instability in the articulation over the
259 successive elements.

260 - eventDUR: to capture differences in articulation rate, maximum and minimum
261 velocity values in the contour were automatically determined by a peak-picking algorithm in
262 MATLAB. Values were then manually checked. Each interval duration from each valley to
263 the next was then computed. These intervals included the acoustic transition between one
264 segment to the next in the /ajajaj/, /ujujuj/, /wiwiwi/ sequences since valleys in the
265 TSC_MFCC contour occur where there is little acoustic changes before and after each
266 transition.

267

268 ***Statistical analysis***

269 Main effects of SPEAKER CONDITION (CONTROLS, ALS, PLS and SBMA) and
270 SEQUENCE TYPE (/aj/, /uj/, /wi/) as well as the interaction between the two were examined,
271 using linear mixed effect models (LMM) for the three acoustic metrics (MEAN, VARCO,
272 eventDUR). Because measurements were based on 4 repetitions of a sequence for each
273 speaker, speakers were considered as random effect variables. When findings of the LMM
274 models revealed statistically main or interaction effects, post hoc comparisons were
275 performed applying Tukey adjustments for multiples comparisons. The critical alpha level for
276 all tests was set to $p < .05$.

277 To assess the possible relationship between the dysarthria severity and the dependent
278 variables, individual linear regressions for each pathological condition (ALS, PLS, SBMA)
279 were used. Since the perceptual score is measured by participant and is the same for the 12
280 sequences (3 sequences * 4 repetitions) for each participant, we decided to create a unique
281 variable by combining the values of the 12 sequences to avoid convergence issues. Hence,
282 speakers were not considered as random effect variables. Because normality and/or
283 homogeneity assumptions were frequently rejected, we did not consider standard error and t-

284 values which can be biased in such cases with potential misleading p values. Confidence
285 intervals for the linear regression slopes, estimated by using a bootstrap approach, were used
286 to test the null hypothesis. The linear association between the dysarthria severity level and
287 the dependent variables was considered statistically significant when the 95% confidence
288 interval excluded the value of 0.

289 For each analysis, values below the first percentile and over the 99th percentile were
290 removed for each dependent variable. Residuals normality assumptions were checked using
291 Shapiro-Wilk test and quantile-quantile plots. The residual homogeneity assumption was
292 checked visually by plotting the standardized residuals as a function of the corresponding
293 fitted values. Because data were unbalanced and there was an interaction effect between the
294 independent variables, a type III sum of squares methodology was used to assess
295 significance, and a p-value of <.05 for two-sided test was considered significant.

296 All statistical analyses were done using R (version 4.0.2). Linear mixed effect models
297 were fitted using the lmer function of the lme4 (Bates et al., 2015) and the lmerTest packages
298 (Kuznetsova et al., 2017). P values were computed using Kenward-Roger 's approximation of
299 the degree of freedom. Post-hoc comparisons were done using the emmeans function of the
300 emmeans package (Lenth, 2020), and confidence intervals of slope were estimated using the
301 Boot function of the car package (Fox and Weisberg, 2019).

302

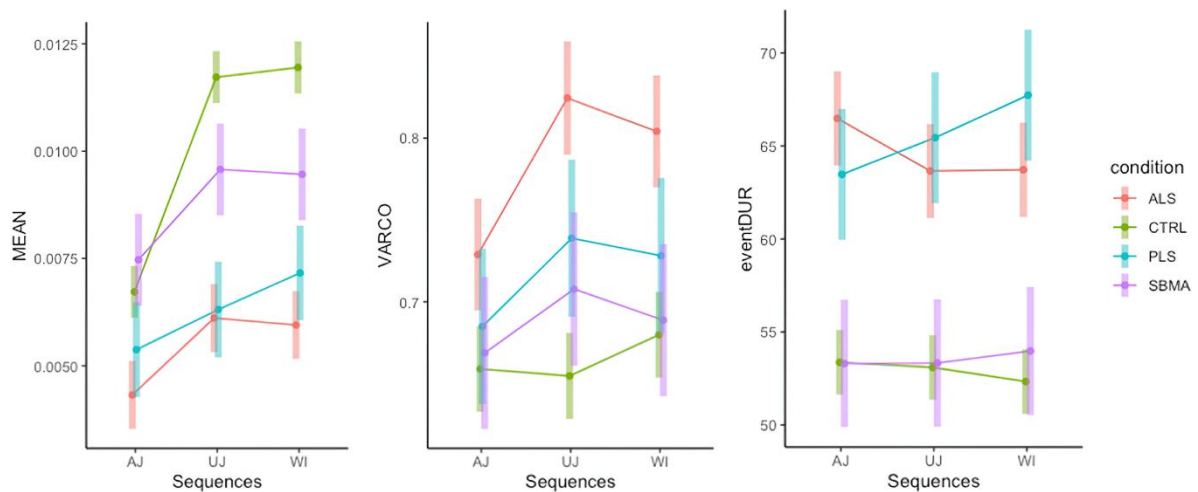
303 **Results**

304 SPEAKER CONDITION (CONTROL¹, ALS, PLS and SBMA) and SEQUENCE TYPE

¹ Variables were compared between the controls from Geneva and from Paris with the talker's origin as fixed effect. No statistical differences were found between them, excluding a potential regional differences effect. They were thus grouped in a single control population in the analyses.

305 Figure 2 presents the condition averages for the three measures MEAN, VARCO and eventDUR
 306 across all sequences.

307



308

309 *i. MEAN*

310 A significant main effect was found for SPEAKER CONDITION and SEQUENCE TYPE (see
 311 Table 2). Overall, MEAN acoustic change was significantly smaller for ALS and PLS compared
 312 with SBMA (respectively $p < .001$ and $p < .01$) and controls ($p < .001$). No significant
 313 difference was found between ALS and PLS ($p = .5$) and between SBMA and controls ($p = .1$).
 314 Overall, the sequence /ajajaj/ elicited significantly smaller MEAN acoustic change than
 315 /ujujuj/ and /wiwiwi/ ($p < .0001$). No significant difference was found between /ujujuj/ and
 316 /wiwiwi/ ($p = .3$).

317 The interaction between SPEAKER CONDITION x SEQUENCE TYPE was significant. During the
 318 production of /ajajaj/, the MEAN acoustic change for ALS speakers was significantly smaller
 319 than for CONTROL and SBMA speakers, and the MEAN acoustic change for PLS speakers was
 320 significantly smaller compared to SBMA speakers (see Table 3). No significant difference was
 321 found between ALS and PLS, CONTROL and PLS, and CONTROL and SBMA (ALS < SBMA
 322 & controls; PLS < SBMA).

323 During the production of /ujujuj/ and /wiwiwi/, the MEAN acoustic change for ALS
324 and PLS speakers was significantly smaller than for CONTROL and SBMA and the MEAN
325 acoustic change of SBMA speakers was significantly smaller than that of CONTROL (ALS &
326 PLS < SBMA < CONTROL). No significant difference was found between the two conditions
327 ALS and PLS.

328 As shown in Table 4, all the groups showed a larger degree of acoustic change over the back-
329 front/rounded-unrounded sequences compared to /ajajaj/. Only for speakers with PLS, the
330 sequence /wiwiwi/ elicited significantly greater MEAN acoustic change than the sequence
331 /ujujuj/.

332 ii. *VARCO*

333 A main effect was found for SPEAKER CONDITION and SEQUENCE TYPE (see Table 2).
334 ALS showed higher VARCO values than CONTROL ($p < .0001$), PLS ($p = .04$) and SBMA ($p =$
335 $.001$). The sequences /ujujuj/ and /wiwiwi/ resulted in greater VARCO than the sequence
336 /ajajaj/ ($p < .0001$).

337 The SPEAKER CONDITION x SEQUENCE TYPE interaction was significant. As shown in
338 Table 5, a significantly greater VARCO in the ALS condition compared to CONTROL across the
339 three sequences /ajajaj/, /ujujuj/ and /wiwiwi/ was observed. During the /ujujuj/
340 production, ALS speakers also showed greater VARCO compared to the PLS and the SBMA
341 speakers, and PLS speakers had significantly greater VARCO than CONTROL speakers (ALS >
342 PLS & SBMA; PLS > CONTROL). Finally, during the production of the sequence /wiwiwi/,
343 ALS speakers also showed greater VARCO compared to the SBMA.

344 As shown in Table 6, for both PLS and ALS, the alternating back-front/rounded-unrounded
345 sequences induced more irregularity in the successive articulation than the open-close
346 /ajajaj/. It is shown in the VARCO for /ujujuj/ and /wiwiwi/ for ALS and for /ujujuj/ in PLS.
347 In SBMA, no difference in VARCO is found according to the sequence.

348

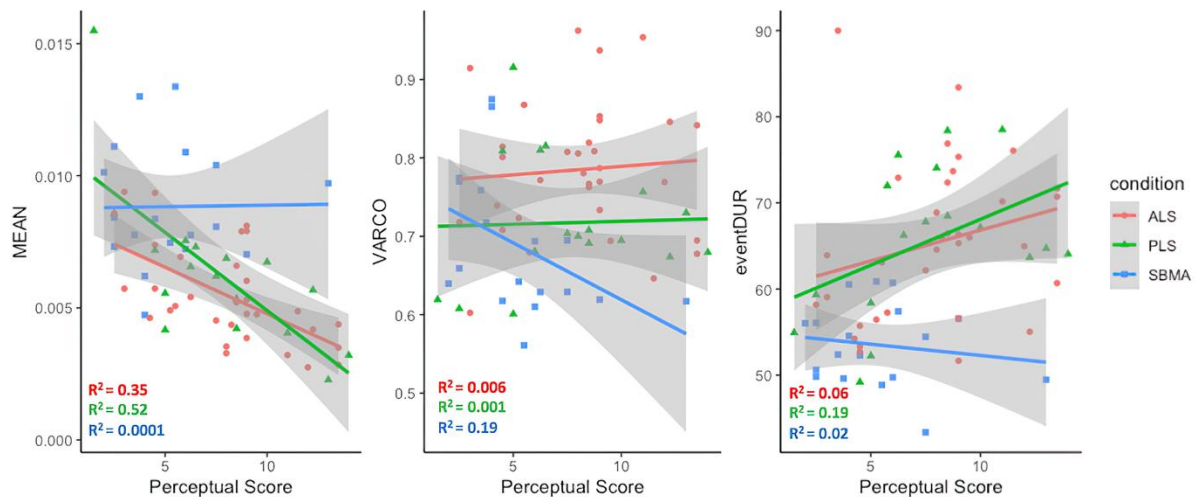
349 iii. *eventDUR*

350 A significant effect was found for SPEAKER CONDITION, for SPEAKER CONDITION x
351 SEQUENCE TYPE interaction, but not for SEQUENCE TYPE (see Table 2). As shown in Table 7 and
352 8, ALS and PLS speakers are slower than both SBMA and CONTROL speakers for all
353 sequences. Again, the back-front/rounded-unrounded sequences differed from the /ajajaj/
354 sequence for the ALS speakers, with longer eventDUR for /ajajaj/ compared with /ujujuj/ and
355 /wiwiwi/. For speakers with PLS, the /wiwiwi/ sequence showed longer eventDUR values
356 than /ajajaj/. For CONTROL and speakers with SBMA, eventDUR values did not change
357 according to SEQUENCE TYPE.

358 ***Relationship between metrics and dysarthria severity***

359 Relations between the acoustic measurements and dysarthria severity (expressed in a
360 perceptual score taken as a discrete quantitative variable) are shown in Figure 3. Table 9
361 displays the findings of the linear regression analyses for each pathological condition.

362



363

364 The linear association between dysarthria severity and MEAN was statistically significant only
365 in ALS and PLS. MEAN acoustic change decreases when dysarthria severity increases. The
366 linear association between the dysarthria severity and VARCO was statistically significant only
367 in SBMA. As shown in Figure 3, there was an apparent decrease in VARCO with dysarthria

368 severity in SBMA. However, this trend was mainly due to sparse distribution of the mild
369 dysarthric speakers ($PS < 5$), with some speakers showing a high VARCO, similar to that of
370 ALS speakers. No linear association was found between dysarthria severity and eventDUR in
371 any condition. In ALS and PLS, three clusters appear in the distribution (Figure 3): mild
372 dysarthric speakers ($PS < 7$) showed eventDUR around 50-65 ms, moderate dysarthric
373 speakers ($7 < PS < 11$) showed longer eventDUR between 65-85 ms with a few speakers
374 between 70 and 85 ms, but a few speakers with more severe dysarthria ($11 < PS < 13$) showed
375 eventDUR that were shorter (< 70 ms) than the moderate dysarthric speakers.

376

377 **Discussion**

378 The current study explored the use of an acoustic measure, which indirectly captured
379 vocal tract shape changes, to differentiate flaccid, spastic, and mixed spastic flaccid
380 dysarthria subtypes associated with SBMA, PLS and ALS respectively. Several findings
381 indicate that the tool is efficient in describing articulatory differences between the three
382 dysarthria subtypes and the following sections discuss for each dysarthria subtype how the
383 results of mean acoustic change, variability and duration inform on these distinctions.

384

385 ***Flaccid dysarthria in SBMA***

386 For flaccid dysarthria in SBMA, involving LMN system, it was hypothesized that
387 temporal aspects of speech were reduced compared to controls as a consequence of motor
388 weakness or as a strategy to compensate for this weakness (Duffy, 2019). Studying
389 articulatory impairments in SBMA was novel in this research, as they have already been
390 reported in LMN involvement due to other origins before (Duffy, 2019). No hypotheses were
391 formulated concerning the amount and the variability of the acoustic change, as well as the
392 relation between dysarthria severity and the outcome measures.

393

394 ***Mean acoustic change***

395 Compared to speech of non-dysarthric speakers, the speech of patients with SBMA
396 showed a lower amount of acoustic energy change, suggesting diminished possibilities to
397 change the vocal tract shape. As stated earlier, the acoustic changes, measured by the MFCCs,
398 capture changes between the successive vocal tract configurations required to produce the
399 three-syllable sequences. A reduced amount of acoustic energy change was thus interpreted
400 as a sign of hypoarticulation during the vowel glide and glide vowel sequences. Interestingly,
401 signs of hypoarticulation were only found in the productions of the sequences/ujujuj/ and
402 /wiwiwi/. These sequences specifically involve back-front tongue movements and rounded-
403 unrounded lip movements. The marked amyotrophy and weakness of the tongue described in
404 SBMA, causing swallowing problems (Banno et al., 2017; Mano et al., 2014) possibly explain
405 why the alternating front-back movements of the tongue required for these sequences were
406 difficult to achieve for the speakers with SBMA. Despite the reported jaw weakness in SBMA
407 resulting in cases of jaw dropping (Larsen & Smith, 2005; Sumner & Fischbeck, 2002),
408 speakers in the current study managed to preserve acoustic spectral energy changes during
409 /ajajaj/. The observation that speakers with SBMA showed a tendency for larger values of
410 acoustic energy change than the other groups during productions requiring jaw movements
411 (Figure 2), suggests a jaw aperture overshoot during /ajajaj/ resulting from poor control; this
412 interpretation is merely speculative and must be considered as an interesting line of future
413 research, exploring the behavior of the jaw in speakers with SMBA.

414 The amount of acoustic change did not decrease with increased perceptually assessed
415 dysarthria severity for this group of speakers with pure flaccid dysarthria. Compared to the
416 other populations, there was a large diversity in speaker specific patterns, as shown in Figure
417 3, which was not related to severity. Different possible explanations for this result are
418 proposed. First, the findings might have been influenced by the way severity was assessed.
419 The Perceptual Score indicated a composite measure of severity, not only related to
420 articulatory dimensions. Therefore, the severity of dysarthria might have been rated on other
421 prominent altered speech dimensions, such as voice quality or nasal resonance, which are
422 particularly affected in SBMA (Tanaka et al., 2014, 2019). Second, it is speculated that the

423 decrease of acoustic change was not affected by severity progression in this population
424 because our sample did not cover the same range of severity as the other populations. Indeed,
425 SBMA patients usually present mild levels of dysarthria and this was reflected in our
426 population; only 5 moderate (vs. 13 mild) dysarthric patients were recruited.

427

428 ***Variability***

429 Poor lingual mobility did not seem to be related to the stability of vocal tract shape
430 changes. Indeed, except for a few speakers, SBMA speakers showed similar low variability
431 values as controls and PLS speakers. Recall that the VARCO measure captures the articulatory
432 stability of the successive syllables in the sequence. It was speculated that one of the reasons
433 for this stability was due to the slow progression of this disease, allowing patients to find
434 compensatory adjustments. This idea was supported by the high VARCO profiles of some of
435 the mildest dysarthric SBMA speakers, while all speakers with more progression in the
436 dysarthria (PS>5) achieved to produce more stable acoustic patterns (Figure 3).

437

438 ***Duration***

439 Our findings do not support the notion that tongue weakness results in slow speech
440 rate in flaccid dysarthria associated with SBMA as suggested in the literature for flaccid
441 dysarthria due to other etiologies (Duffy, 2019). Speakers with pure flaccid dysarthria in
442 SBMA showed the same temporal patterns as controls in all sequences possibly related to the
443 fact that the group of SBMA patients were mildly dysarthric (PS<7).

444

445 ***Spastic and spastic-flaccid dysarthria in PLS and ALS***

446 ***Mean acoustic change***

447 Based on previous studies stated earlier on articulatory impairments in ALS and other
448 pathologies involving pure UMN dysfunction, it was expected that speakers with ALS and

449 PLS showed a reduction in the degree of acoustic energy changes, implicating smaller vocal
450 tract shape changes and thus hypoarticulation. This was indeed the case: speakers with
451 dysarthria associated with ALS and PLS both displayed a comparable low amount of acoustic
452 change, which was even lower than observed for speakers with SBMA. For both groups the
453 acoustic energy differences declined with dysarthria severity, and confirmed the findings on
454 progressively reduced tongue movement range in speakers with ALS (Kuruvilla et al., 2012;
455 Lee et al., 2018; Lee & Bell, 2018).

456 Compared to flaccid dysarthric speakers and non-dysarthric speakers, the back-front
457 sequences /ujujuj/ and /wiwiwi/ were especially affected, which is in agreement with the
458 previous kinematic studies demonstrating a reduced articulatory range of tongue movements
459 detected in the anterior-posterior dimension in ALS patients (Lee & Bell, 2018). Compared to
460 speakers with pure flaccid dysarthria associated with SBMA, however, both speakers with
461 mixed spastic-flaccid and pure spastic dysarthria also displayed significant reduced acoustic
462 energy changes in the sequence /ajajaj/. It is speculated that the absence of hypoarticulation
463 in the /ajajaj/ sequence for the SBMA speakers is caused by the fact that for this sequence,
464 compensation is still possible to achieve the appropriate opening and closing movements.
465 Muscle weakness associated with LMN involvement only affects isolated muscles but the
466 spasticity typically associated with UMN involvement affects patterns of movements and
467 coordination between them (Duffy, 2019). Impaired movement patterns and coordination
468 probably explain the lower values of mean energy change in dysarthric speakers with UMN
469 involvement. It is speculated that the similarities, found between dysarthric speakers
470 associated with ALS and PLS, are originating as a consequence of their shared UMN
471 involvement. Although studies have shown that the jaw displayed exaggerated range of
472 movement in ALS (Kuruvilla et al., 2012; Lee et al., 2018, 2020; Lee & Bell, 2018; Yunusova
473 et al., 2008), it seemed that this compensation was not achieved by the ALS and PLS
474 speakers in this study. A possible interpretation explaining the lack of compensation by ALS
475 and PLS speakers, is that these speakers may present jaw spasticity resulting in reduced
476 range of jaw movements (for a review on spasticity, see Synnot et al., 2017).

477

478 **Variability**

479 Whereas speakers with spastic and mixed dysarthria set themselves apart from
480 speakers with flaccid dysarthria and non-dysarthric speakers regarding the amount of
481 acoustic energy change, they can be separated from each other further in terms of variability
482 of acoustic energy change. While similar patterns of mean acoustic energy change was shown
483 in speakers with spastic and mixed dysarthria, speakers with mixed dysarthria showed a
484 much higher degree of variability overall, especially caused by the /ujujuj/ sequence. This
485 great variability observed in patients with ALS is likely multifactorial. First, the well-known
486 fatigue in ALS (Beukelman et al., 2011) might have contributed to higher variability and
487 second, the fact that the progression of this disease is very fast compared with PLS, prevents
488 speakers from establishing solid compensatory strategies, likely resulting in more variability.
489 Finally, because both the UMN and LMN systems are affected in ALS resulting in mixed
490 dysarthria, we speculate that productive compensation strategies are more difficult to
491 achieve.

492

493 **Duration**

494 Based on the literature cited in introduction which demonstrated impaired temporal
495 aspects in speech production, in ALS as well as in other pathologies involving pure UMN
496 dysfunction, we expected slower sequence production in mixed and spastic dysarthria. Our
497 results indeed confirmed that both spastic and mixed dysarthric speakers showed longer
498 segment duration in the vowel-glide sequences than the controls and speakers with flaccid
499 dysarthria. These results are comparable to those of Mefferd (2015) and Lee et al. (2018),
500 who found respectively that the duration of the diphthong /ai/ in the word “kite”, and /wi/ in
501 the word “whip” was prolonged for speakers with mixed dysarthria. Interestingly, the current
502 findings showed an interaction in the sense that the duration values for /wiwiwi/ were higher
503 than /ajajaj/ for the spastic dysarthric speakers while the opposite was found for the mixed
504 dysarthric speakers (/ajajaj/ > /wiwiwi/). It is speculated that the slower duration of the

505 sequence /ajajaj/ for speakers associated with ALS was caused by the fact that the jaw is
506 especially affected in this disease, maybe because both UMN and LMN are involved. The
507 exact reason for this finding, however, is not clear and the authors cannot provide a
508 satisfactory explanation for this interaction.

509 Both in ALS and PLS, speakers with more severe dysarthria showed a slower speech
510 rate than speakers with milder dysarthria. The lack of association, however, between the
511 temporal aspects and the severity in this study is contradictory to our expectation. Indeed, a
512 link between severity and slow rate has been described in the literature, particularly in ALS
513 (for instance Allison et al., 2019; Lee et al., 2018; Lee & Bell, 2018). A possible explanation of
514 the lack of association in this study is that 8 patients with ALS and PLS, judged with more
515 severe dysarthria ($11 < PS < 13$), demonstrated shorter eventDUR than patients who were
516 judged less dysarthric ($7 < PS < 10$). Further, one patient with ALS judged with mild dysarthria,
517 showed the longest eventDUR. While speech rate and intelligibility are usually employed as
518 severity indices in ALS (Ball et al., 2002; Green et al., 2013; Kuruvilla et al., 2012; Lee et al.,
519 2018), we used a generalized rating of speech with five dimensions of speech (intelligibility,
520 prosody, voice quality, naturalness and articulatory precision) making speech rate less
521 important as a determining factor. It is possible that the severity of dysarthria of each patient
522 was judged according to different dimensions, not specifically related to temporal aspects.

523

524 **Limitation of the study**

525 One of the factors that complicates studies like the current one is that the rate of
526 disease progression varies considerably across these diseases. ALS can be a very fast
527 progressive disease, leaving little time to develop compensation strategies, whereas PLS and
528 SBMA are typically very slow in the speed of progression. Since the dysarthria characteristics
529 may not only be related to UMN or LMN involvement, but also to the presence or absence of
530 compensation strategies, our findings need to be considered with caution. In addition, our
531 findings regarding the relation between severity and the outcome measures studied here

532 likely differ from studies using severity indices such as speech rate or intelligibility. Finally,
533 more balanced sample size across dysarthria severity continuum in each subtype would
534 provide stronger conclusions about the relation between severity and the outcome measures.

535

536 **Clinical implications and conclusion**

537 The acoustic parameters used in this study partially differentiated among the
538 dysarthria subtypes in relation to MNDs: smaller vocal tract shape changes from one
539 articulatory configuration to the next were shown in flaccid dysarthria but to a less extent
540 than in spastic and spastic-flaccid dysarthria. These latter showed similar acoustic patterns.
541 We speculate that these similarities are due to their common spastic component. Yet, crucial
542 differences between spastic and spastic-flaccid dysarthria were found in the stability of the
543 acoustic patterns. In spastic-flaccid dysarthria, these patterns were much more variable,
544 suggesting articulatory instability of the successive syllables in the sequence. The method
545 used in the current study forms a promising clinical tool as a diagnostic marker of
546 diminished vocal tract shape changes, interpreted as hypoarticulation here, even at mild
547 stage of dysarthria progression, and as an objective monitoring indicator of the disease
548 progression in the bulbar territory in ALS and PLS. Though, future research goals which are
549 interesting to pursue are investigating more in depth the relation between the current
550 acoustic measures and articulatory patterns to better understand articulatory deficiencies in
551 MNDs. Because this method does not require advanced instrumentation, the acoustic
552 measures used in this study are well-suited to assess vocal tract shape changes in a clinical
553 setting. We are currently working on integrating this method in the MonPaGe assessment
554 tool (Laganaro et al., 2021; Pernon et al., 2020).

555

556 **Acknowledgments**

557 This research was funded by Assistance Publique – Hôpitaux de Paris, Délégation de
558 la Recherche Clinique et de l'Innovation (DRCI) (awarded to the first author) and by the

559 Swiss National Science Foundation, Sinergia program (CRSII5_173711, 10.2017-9.2020). The
560 authors are thankful to the participants for taking part in this project. The authors would also
561 like to thank François Salachas, Nadine Le Forestier, Pierre-François Pradat, Timothée
562 Lenglet, Maria Del Mar Amador, Adèle Hesters, Giorgia Querin for supporting patients'
563 recruitment and Michaela Pernon, Claire Della Vedova and Speech'n Co colleagues for their
564 help in this project. We thank the reviewers of the manuscript for their inspiring comments.

565

566 **References**

567 Allison, K. M., Yunusova, Y., & Green, J. R. (2019). Shorter Sentence Length Maximizes
568 Intelligibility and Speech Motor Performance in Persons With Dysarthria Due to
569 Amyotrophic Lateral Sclerosis. *American Journal of Speech-Language Pathology*, 28(1),
570 96–107. https://doi.org/10.1044/2018_AJSLP-18-0049

571 Atsuta, N., Watanabe, H., Ito, M., Banno, H., Suzuki, K., Katsuno, M., Tanaka, F., Tamakoshi,
572 A., & Sobue, G. (2006). Natural history of spinal and bulbar muscular atrophy (SBMA): A
573 study of 223 Japanese patients. *Brain: A Journal of Neurology*, 129(Pt 6), 1446–1455.
574 <https://doi.org/10.1093/brain/awl096>

575 Auzou, P., & Rolland-Monnoury, V. (2006). *BECD: Batterie d'évaluation clinique de la*
576 *dysarthrie*

577 Ball, L. J., Beukelman, D. R., & Pattee, G. L. (2002). Timing of speech deterioration in people
578 with amyotrophic lateral sclerosis. *Journal of Medical Speech-Language Pathology*, 10(4),
579 231–235

580 Banno, H., Katsuno, M., Suzuki, K., Tanaka, S., Suga, N., Hashizume, A., Mano, T., Araki, A.,
581 Watanabe, H., Fujimoto, Y., Yamamoto, M., & Sobue, G. (2017). Swallowing markers in
582 spinal and bulbar muscular atrophy. *Annals of Clinical and Translational Neurology*, 4(8),
583 534–543. <https://doi.org/10.1002/acn3.425>

584 Bates, D., Maechler, M., Bolker, B., Walker, S. (2015). Fitting Linear Mixed-Effects Models

585 Using lme4. *Journal of Statistical Software*, 67(1), 1-48.
586 <https://doi.org/10.18637/jss.v067.i01>

587 Bede, P., & Finegan, E. (2018). Revisiting the pathoanatomy of pseudobulbar affect:
588 Mechanisms beyond corticobulbar dysfunction. *Amyotrophic Lateral Sclerosis and*
589 *Frontotemporal Degeneration*, 19(1-2), 4-6.
590 <https://doi.org/10.1080/21678421.2017.1392578>

591 Bede, P., & Pradat, P.-F. (2019). Editorial: Biomarkers and Clinical Indicators in Motor
592 Neuron Disease. *Frontiers in Neurology*, 10. <https://doi.org/10.3389/fneur.2019.01318>

593 Beukelman, D., Fager, S., & Nordness, A. (2011). Communication Support for People with
594 ALS. *Neurology Research International*, 2011, 714693. <https://doi.org/10.1155/2011/714693>

595 Brooks, B. R., Miller, R. G., Swash, M., Munsat, T. L., & World Federation of Neurology
596 Research Group on Motor Neuron Diseases. (2000). El Escorial revisited: Revised criteria for
597 the diagnosis of amyotrophic lateral sclerosis. *Amyotrophic Lateral Sclerosis and Other*
598 *Motor Neuron Disorders: Official Publication of the World Federation of Neurology,*
599 *Research Group on Motor Neuron Diseases*, 1(5), 293-299

600 Cedarbaum, J. M., Stambler, N., Malta, E., Fuller, C., Hilt, D., Thurmond, B., & Nakanishi, A.
601 (1999). The ALSFRS-R: A revised ALS functional rating scale that incorporates assessments
602 of respiratory function. BDNF ALS Study Group (Phase III). *Journal of the Neurological*
603 *Sciences*, 169(1-2), 13-21

604 Charcot, J.-M., & Joffroy, A. (1869). Deux cas d'atrophie musculaire progressive : Avec
605 lésions de la substance grise et des faisceaux antéro-latéraux de la moelle épinière. V. Masson

606 Clark, H. M., Duffy, J. R., Whitwell, J. L., Ahlskog, J. E., Sorenson, E. J., & Josephs, K. A.
607 (2014). Clinical and imaging characterization of progressive spastic dysarthria. *European*
608 *Journal of Neurology*, 21(3), 368-376. <https://doi.org/10.1111/ene.12271>

609 Darley, F. L., Aronson, A. E., & Brown, J. R. (1969a). Clusters of deviant speech dimensions
610 in the dysarthrias. *Journal of Speech and Hearing Research*, 12(3), 462-496

611 Darley, F. L., Aronson, A. E., & Brown, J. R. (1969b). Differential Diagnostic Patterns of
612 Dysarthria. *Journal of Speech, Language, and Hearing Research*, 12(2), 246–269.
613 <https://doi.org/10.1044/jshr.1202.246>

614 Darley, F. L., Aronson, A. E., & Brown, J. R. (1975). *Motor Speech Disorders*. Saunders

615 DePaul Roxanne & Brooks Benjamin R. (1993). Multiple Orofacial Indices in Amyotrophic
616 Lateral Sclerosis. *Journal of Speech, Language, and Hearing Research*, 36(6), 1158–1167.
617 <https://doi.org/10.1044/jshr.3606.1158>

618 Duffy, J. R. (2019). *Motor speech disorders e-book: Substrates, differential diagnosis, and*
619 *management*. Elsevier Health Sciences

620 Finegan, E., Chipika, R. H., Li Hi Shing, S., Doherty, M. A., Hengeveld, J. C., Vajda, A.,
621 Donaghy, C., McLaughlin, R. L., Pender, N., Hardiman, O., & Bede, P. (2019). The clinical
622 and radiological profile of primary lateral sclerosis: A population-based study. *Journal of*
623 *Neurology*, 266(11), 2718–2733. <https://doi.org/10.1007/s00415-019-09473-z>

624 Fox, J. & Weisberg, W. (2019). An {R} Companion to Applied
625 Regression, Third Edition. Thousand Oaks CA: Sage. URL:
626 <https://socialsciences.mcmaster.ca/jfox/Books/Companion/>

627 Goldstein, L. (2019). The Role of Temporal Modulation in Sensorimotor Interaction.
628 *Frontiers in Psychology*, 10. <https://doi.org/10.3389/fpsyg.2019.02608>

629 Gordon, P. H., Cheng, B., Katz, I. B., Pinto, M., Hays, A. P., Mitsumoto, H., & Rowland, L. P.
630 (2006). The natural history of primary lateral sclerosis. *Neurology*, 66(5), 647–653.
631 <https://doi.org/10.1212/01.wnl.0000200962.94777.71>

632 Green, J. R., Yunusova, Y., Kuruvilla, M. S., Wang, J., Pattee, G. L., Synhorst, L., Zinman, L.,
633 & Berry, J. D. (2013). Bulbar and speech motor assessment in ALS: Challenges and future
634 directions. *Amyotrophic Lateral Sclerosis and Frontotemporal Degeneration*, 14(7–8), 494–
635 500. <https://doi.org/10.3109/21678421.2013.817585>

636 Hashizume, A., Banno, H., Katsuno, M., Hijikata, Y., Yamada, S., Inagaki, T., Suzuki, K., &

637 Sobue, G. (2017). Quantitative Assessment of Swallowing Dysfunction in Patients with Spinal
638 and Bulbar Muscular Atrophy. *Internal Medicine (Tokyo, Japan)*, *56*(23), 3159–3165.
639 <https://doi.org/10.2169/internalmedicine.8799-16>

640 Hirose, H., Kiritani, S., & Sawashima, M. (1982). Patterns of Dysarthric Movement in
641 Patients with Amyotrophic Lateral Sclerosis and Pseudobulbar Palsy. *Folia Phoniatica et*
642 *Logopaedica*, *34*(2), 106–112. <https://doi.org/10.1159/000265636>

643 Ince, P. G., Lowe, J., & Shaw, P. J. (1998). Amyotrophic lateral sclerosis: Current issues in
644 classification, pathogenesis and molecular pathology. *Neuropathology and Applied*
645 *Neurobiology*, *24*(2), 104–117. <https://doi.org/10.1046/j.1365-2990.1998.00108.x>

646 Kennedy, W. R., Alter, M., & Sung, J. H. (1968). Progressive proximal spinal and bulbar
647 muscular atrophy of late onset. A sex-linked recessive trait. *Neurology*, *18*(7), 671–680

648 Kent, R. D., Weismer, G., Kent, J. F., Vorperian, H. K., & Duffy, J. R. (1999). Acoustic studies
649 of dysarthric speech: Methods, progress, and potential. *Journal of Communication*
650 *Disorders*, *32*(3), 141–180, 183–186; quiz 181–183, 187–189

651 Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation
652 Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, *15*(2), 155–163.
653 <https://doi.org/10.1016/j.jcm.2016.02.012>

654 Kuruvilla, M. S., Green, J. R., Yunusova, Y., & Hanford, K. (2012). Spatiotemporal coupling
655 of the tongue in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing*
656 *Research: JSLHR*, *55*(6), 1897–1909. [https://doi.org/10.1044/1092-4388\(2012/11-0259\)](https://doi.org/10.1044/1092-4388(2012/11-0259))

657 Kuruvilla-Dugdale, M., & Chuquilin-Arista, M. (2017). An investigation of clear speech effects
658 on articulatory kinematics in talkers with ALS. *Clinical Linguistics & Phonetics*, *31*(10), 725–
659 742. <https://doi.org/10.1080/02699206.2017.1318173>

660 Kuruvilla-Dugdale, M., & Mefferd, A. (2017). Spatiotemporal movement variability in ALS:
661 Speaking rate effects on tongue, lower lip, and jaw motor control. *Journal of Communication*
662 *Disorders*, *67*, 22–34. <https://doi.org/10.1016/j.jcomdis.2017.05.002>

663 Kuznetsova, A., Brockhoff, P.B., Christensen RHB (2017). lmerTest Package: Tests in Linear
664 Mixed Effects Models. *Journal of Statistical Software*, 82 (13), 1-26.
665 <https://doi.org/10.18637/jss.v082.i13>

666 Laganaro, M., Fougeron, C., Pernon, M., Levêque, N., Borel, S., Fournet, M., Catalano
667 Chiuvé, S., Lopez, U., Trouville, R., Ménard, L., Burkhard, P. R., Assal, F., & Delvaux, V.
668 (2021). Sensitivity and specificity of an acoustic- and perceptual-based tool for assessing
669 motor speech disorders in French: The MonPaGe-screening protocol. *Clinical Linguistics &*
670 *Phonetics*, 1–16. <https://doi.org/10.1080/02699206.2020.1865460>

671 Langmore Susan E. & Lehman Mark E. (1994). Physiologic Deficits in the Orofacial System
672 Underlying Dysarthria in Amyotrophic Lateral Sclerosis. *Journal of Speech, Language, and*
673 *Hearing Research*, 37(1), 28–37. <https://doi.org/10.1044/jshr.3701.28>

674 Larsen, K., & Smith, T. A. (2005). ["Jaw drop" as an atypical manifestation of Kennedy's
675 disease]. *Ugeskrift for Laeger*, 167(35), 3310–3311

676 Lee, J., & Bell, M. (2018). Articulatory Range of Movement in Individuals With Dysarthria
677 Secondary to Amyotrophic Lateral Sclerosis. *American Journal of Speech-Language*
678 *Pathology*, 1. https://doi.org/10.1044/2018_AJSLP-17-0064

679 Lee, J., Bell, M., & Simmons, Z. (2018). Articulatory Kinematic Characteristics Across the
680 Dysarthria Severity Spectrum in Individuals With Amyotrophic Lateral Sclerosis. *American*
681 *Journal of Speech-Language Pathology*, 27(1), 258–269.
682 https://doi.org/10.1044/2017_AJSLP-16-0230

683 Lee, J., Rodriguez, E., & Mefferd, A. (2020). Direction-Specific Jaw Dysfunction and Its
684 Impact on Tongue Movement in Individuals With Dysarthria Secondary to Amyotrophic
685 Lateral Sclerosis. *Journal of Speech, Language, and Hearing Research*, 63(2), 499–508.
686 https://doi.org/10.1044/2019_JSLHR-19-00174

687 Lenth, R. (2020). emmeans: Estimated Marginal Means, aka Least-Squares Means. R
688 package version 1.5.1. <https://CRAN.R-project.org/package=emmeans>

689 Logroscino, G., Traynor, B. J., Hardiman, O., Chio', A., Couratier, P., Mitchell, J. D.,
690 Swingler, R. J., Beghi, E., & EURALS. (2008). Descriptive epidemiology of amyotrophic
691 lateral sclerosis: New evidence and unsolved issues. *Journal of Neurology, Neurosurgery,*
692 *and Psychiatry*, 79(1), 6–11. <https://doi.org/10.1136/jnnp.2006.104828>

693 Mano, T., Katsuno, M., Banno, H., Suzuki, K., Suga, N., Hashizume, A., Araki, A., Hijikata, Y.,
694 Tanaka, S., Takatsu, J., Watanabe, H., Yamamoto, M., & Sobue, G. (2015). Head Lift Exercise
695 Improves Swallowing Dysfunction in Spinal and Bulbar Muscular Atrophy. *European*
696 *Neurology*, 74(5–6), 251–258. <https://doi.org/10.1159/000431088>

697 Mano, T., Katsuno, M., Banno, H., Suzuki, K., Suga, N., Hashizume, A., Araki, A., Watanabe,
698 H., Tanaka, S., Yamamoto, M., & Sobue, G. (2014). Tongue pressure as a novel biomarker of
699 spinal and bulbar muscular atrophy. *Neurology*, 82(3), 255–262.
700 <https://doi.org/10.1212/WNL.0000000000000041>

701 Mefferd, A. (2015). Articulatory-to-Acoustic Relations in Talkers With Dysarthria: A First
702 Analysis. *Journal of Speech, Language, and Hearing Research: JSLHR*, 58(3), 576–589.
703 https://doi.org/10.1044/2015_JSLHR-S-14-0188

704 Mefferd, A. S., & Dietrich, M. S. (2020). Tongue- and Jaw-Specific Articulatory Changes and
705 Their Acoustic Consequences in Talkers With Dysarthria due to Amyotrophic Lateral
706 Sclerosis: Effects of Loud, Clear, and Slow Speech. *Journal of Speech, Language, and*
707 *Hearing Research: JSLHR*, 1–12. https://doi.org/10.1044/2020_JSLHR-19-00309

708 Mefferd, A. S., Green, J. R., & Pattee, G. (2012). A novel fixed-target task to determine
709 articulatory speed constraints in persons with amyotrophic lateral sclerosis. *Journal of*
710 *Communication Disorders*, 45(1), 35–45. <https://doi.org/10.1016/j.jcomdis.2011.09.002>

711 Mefferd, A. S., Pattee, G. L., & Green, J. R. (2014). Speaking rate effects on articulatory
712 pattern consistency in talkers with mild ALS. *Clinical Linguistics & Phonetics*, 28(11), 799–
713 811. <https://doi.org/10.3109/02699206.2014.908239>

714 Miyata, M., Kakeda, S., Hashimoto, T., Korogi, Y., & Adachi, H. (2019). The facial nerve

715 atrophy with spinal and bulbar muscular atrophy patients (SBMA): Three case reports with
716 3D fast imaging employing steady-state acquisition (FIESTA). *Journal of the Neurological*
717 *Sciences*, 406, 116461. <https://doi.org/10.1016/j.jns.2019.116461>

718 O'Shaughnessy, D. (1987). *Speech Communications: Human and Machine* (1st edition).
719 Addison-Wesley

720 Ozawa, Y., Shiromoto, O., Ishizaki, F., & Watamori, T. (2001). Symptomatic differences in
721 decreased alternating motion rates between individuals with spastic and with ataxic
722 dysarthria: An acoustic analysis. *Folia Phoniatrica et Logopaedica: Official Organ of the*
723 *International Association of Logopedics and Phoniatrics (IALP)*, 53(2), 67–72.
724 <https://doi.org/10.1159/000052656>

725 Pedroso, J. L., Vale, T. C., Barsottini, O. G., Oliveira, A. S. B., & Espay, A. J. (2018). Perioral
726 and tongue fasciculations in Kennedy's disease. *Neurological Sciences: Official Journal of*
727 *the Italian Neurological Society and of the Italian Society of Clinical Neurophysiology*,
728 39(4), 777–779. <https://doi.org/10.1007/s10072-017-3170-8>

729 Pernon, M., Lévêque, N., Delvaux, V., Assal, F., Borel, S., Fougeron, C., Trouville, R., &
730 Laganaro, M. (2020). MonPaGe, un outil de screening francophone informatisé d'évaluation
731 perceptive et acoustique des troubles moteurs de la parole (dysarthries, apraxie de la parole.
732 *Rééducation Orthophonique*, 281, 171

733 Portnoy, R. A., & Aronson, A. E. (1982). Diadochokinetic syllable rate and regularity in
734 normal and in spastic and ataxic dysarthric subjects. *The Journal of Speech and Hearing*
735 *Disorders*, 47(3), 324–328. <https://doi.org/10.1044/jshd.4703.324>

736 Praat: *Doing Phonetics by Computer*. (n.d.). Retrieved October 12, 2020, from
737 <https://www.fon.hum.uva.nl/praat/>

738 Praline, J., Guennoc, A.-M., Malinge, M.-C., de Toffol, B., & Corcia, P. (2008). Pure bulbar
739 motor neuron involvement linked to an abnormal CAG repeat expansion in the androgen
740 receptor gene. *Amyotrophic Lateral Sclerosis: Official Publication of the World Federation*

741 of *Neurology Research Group on Motor Neuron Diseases*, 9(1), 40–42.
742 <https://doi.org/10.1080/17482960701553915>

743 Pringle, C. E., Hudson, A. J., Munoz, D. G., Kiernan, J. A., Brown, W. F., & Ebers, G. C.
744 (1992). Primary lateral sclerosis. Clinical features, neuropathology and diagnostic criteria.
745 *Brain: A Journal of Neurology*, 115 (Pt 2), 495–520.
746 <https://doi.org/10.1093/brain/115.2.495>

747 Querin, G., Bede, P., Marchand-Pauvert, V., & Pradat, P.-F. (2018). Biomarkers of Spinal and
748 Bulbar Muscle Atrophy (SBMA): A Comprehensive Review. *Frontiers in Neurology*, 9, 844.
749 <https://doi.org/10.3389/fneur.2018.00844>

750 Rong, P., Loucks, T., Kim, H., & Hasegawa-Johnson, M. (2012). Relationship between
751 kinematics, F2 slope and speech intelligibility in dysarthria due to cerebral palsy. *Clinical*
752 *Linguistics & Phonetics*, 26(9), 806–822. <https://doi.org/10.3109/02699206.2012.706686>

753 Rong, P., Yunusova, Y., Richburg, B., & Green, J. R. (2018). Automatic extraction of
754 abnormal lip movement features from the alternating motion rate task in amyotrophic lateral
755 sclerosis. *International Journal of Speech-Language Pathology*, 1–14.
756 <https://doi.org/10.1080/17549507.2018.1485739>

757 Rong, P., Yunusova, Y., Wang, J., & Green, J. R. (2015). Predicting Early Bulbar Decline in
758 Amyotrophic Lateral Sclerosis: A Speech Subsystem Approach. *Behavioural Neurology*,
759 2015, 183027. <https://doi.org/10.1155/2015/183027>

760 Roy, N., Leeper, H. A., Blomgren, M., & Cameron, R. M. (2001). A Description of Phonetic,
761 Acoustic, and Physiological Changes Associated With Improved Intelligibility in a Speaker
762 With Spastic Dysarthria. *American Journal of Speech-Language Pathology*, 10(3), 274–290.
763 [https://doi.org/10.1044/1058-0360\(2001/025\)](https://doi.org/10.1044/1058-0360(2001/025))

764 Schölderle, T., Staiger, A., Lampe, R., Strecker, K., & Ziegler, W. (2016). Dysarthria in Adults
765 With Cerebral Palsy: Clinical Presentation and Impacts on Communication. *Journal of*
766 *Speech, Language, and Hearing Research*, 59(2), 216–229.

767 https://doi.org/10.1044/2015_JSLHR-S-15-0086

768 Shellikeri, S., Green, J. R., Kulkarni, M., Rong, P., Martino, R., Zinman, L., & Yunusova, Y.
769 (2016). Speech Movement Measures as Markers of Bulbar Disease in Amyotrophic Lateral
770 Sclerosis. *Journal of Speech, Language, and Hearing Research*, 59(5), 887–899.
771 https://doi.org/10.1044/2016_JSLHR-S-15-0238

772 Slis, A., Lévêque, N., Fougeron, C., Pernon, M., Assal, F., & Lancia, L. (2021). Analysing
773 spectral changes over time to identify articulatory impairments in dysarthria. *The Journal of*
774 *the Acoustical Society of America*, 149(2), 758–769. <https://doi.org/10.1121/10.0003332>

775 Stipancic, K. L., Palmer, K. M., Rowe, H. P., Yunusova, Y., Berry, J. D., & Green, J. R. (2021).
776 “You Say Severe, I Say Mild”: Toward an Empirical Classification of Dysarthria Severity.
777 *Journal of Speech, Language, and Hearing Research: JSLHR*, 1–18.
778 https://doi.org/10.1044/2021_JSLHR-21-00197

779 Sumner, C. J., & Fischbeck, K. H. (2002). Jaw drop in Kennedy’s disease. *Neurology*, 59(9),
780 1471–1472

781 Synnot, A., Chau, M., Pitt, V., O’Connor, D., Gruen, R. L., Wasiak, J., Clavisi, O., Pattuwege,
782 L., & Phillips, K. (2017). Interventions for managing skeletal muscle spasticity following
783 traumatic brain injury. *Cochrane Database of Systematic Reviews*.
784 <https://doi.org/10.1002/14651858.CD008929.pub2>

785 Tanaka, S., Banno, H., Katsuno, M., Suzuki, K., Suga, N., Hashizume, A., Mano, T., Araki, A.,
786 Watanabe, H., Adachi, H., Tatsumi, H., Yamamoto, M., & Sobue, G. (2014). Distinct acoustic
787 features in spinal and bulbar muscular atrophy patients with laryngospasm. *Journal of the*
788 *Neurological Sciences*, 337(1–2), 193–200. <https://doi.org/10.1016/j.jns.2013.12.010>

789 Tanaka, S., Hashizume, A., Hijikata, Y., Yamada, S., Ito, D., Nakayama, A., Kurita, K., Yogo,
790 H., Banno, H., Suzuki, K., Yamamoto, M., Sobue, G., & Katsuno, M. (2019). Nasometric
791 Scores in spinal and bulbar muscular atrophy—Effects of palatal lift prosthesis on dysarthria
792 and dysphagia. *Journal of the Neurological Sciences*, 407, 116503.

793 <https://doi.org/10.1016/j.jns.2019.116503>

794 Tomik, B., & Guiloff, R. J. (2010). Dysarthria in amyotrophic lateral sclerosis: A review.
795 *Amyotrophic Lateral Sclerosis*, 11(1–2), 4–15. <https://doi.org/10.3109/17482960802379004>

796 Tomik, B., Partyka, D., Sulek, A., Kurek-Gryz, E. A., Banach, M., Ostrowska, M., Zaremba, J.,
797 Figlewicz, D. A., & Szczudlik, A. (2006). A phenotypic-genetic study of a group of Polish
798 patients with spinal and bulbar muscular atrophy. *Amyotrophic Lateral Sclerosis: Official*
799 *Publication of the World Federation of Neurology Research Group on Motor Neuron*
800 *Diseases*, 7(2), 72–79. <https://doi.org/10.1080/17482960600664839>

801 Turner, M. R., Barohn, R. J., Corcia, P., Fink, J. K., Harms, M. B., Kiernan, M. C., Ravits, J.,
802 Silani, V., Simmons, Z., Statland, J., van den Berg, L. H., Delegates of the 2nd International
803 PLS Conference, & Mitsumoto, H. (2020). Primary lateral sclerosis: Consensus diagnostic
804 criteria. *Journal of Neurology, Neurosurgery, and Psychiatry*.
805 <https://doi.org/10.1136/jnnp-2019-322541>

806 Yunusova, Y., Graham, N. L., Shellikeri, S., Phuong, K., Kulkarni, M., Rochon, E., Tang-Wai,
807 D. F., Chow, T. W., Black, S. E., Zinman, L. H., & Green, J. R. (2016). Profiling Speech and
808 Pausing in Amyotrophic Lateral Sclerosis (ALS) and Frontotemporal Dementia (FTD). *PLOS*
809 *ONE*, 11(1), e0147573. <https://doi.org/10.1371/journal.pone.0147573>

810 Yunusova, Y., Green, J. R., Greenwood, L., Wang, J., Pattee, G. L., & Zinman, L. (2012).
811 Tongue Movements and Their Acoustic Consequences in Amyotrophic Lateral Sclerosis.
812 *Folia Phoniatrica et Logopaedica*, 64(2), 94–102. <https://doi.org/10.1159/000336890>

813 Yunusova, Y., Green, J. R., Lindstrom, M. J., Ball, L. J., Pattee, G. L., & Zinman, L. (2010).
814 Kinematics of disease progression in bulbar ALS. *Journal of Communication Disorders*,
815 43(1), 6–20. <https://doi.org/10.1016/j.jcomdis.2009.07.003>

816 Yunusova, Y., Green, J. R., Lindstrom, M. J., Pattee, G. L., & Zinman, L. (2013). Speech in
817 ALS: Longitudinal Changes in Lips and Jaw Movements and Vowel Acoustics. *Journal of*
818 *Medical Speech-Language Pathology*, 21(1), 1–13.

819 Yunusova, Y., Plowman, E. K., Green, J. R., Barnett, C., & Bede, P. (2019). Clinical Measures
820 of Bulbar Dysfunction in ALS. *Frontiers in Neurology*, 10.
821 <https://doi.org/10.3389/fneur.2019.00106>

822 Yunusova, Y., Weismer, G., Westbury, J. R., & Lindstrom, M. J. (2008). Articulatory
823 Movements During Vowels in Speakers With Dysarthria and Healthy Controls. *Journal of*
824 *Speech Language and Hearing Research*, 51(3), 596. [https://doi.org/10.1044/1092-](https://doi.org/10.1044/1092-4388(2008/043))
825 [4388\(2008/043\)](https://doi.org/10.1044/1092-4388(2008/043)

826 Ziegler, W., & von Cramon, D. (1986). Spastic dysarthria after acquired brain injury: An
827 acoustic study. *The British Journal of Disorders of Communication*, 21(2), 173–187.
828 <https://doi.org/10.3109/13682828609012275>

829

830

831 Figure legends

832 Figure 1 Examples of contours showing the amount of acoustic change over time during the
833 production of the /ujujuj/ sequence, repeated four times by a speaker of each group. Peaks in
834 the TSC_MFCC are coinciding with maximum acoustic change, expected to occur during the
835 transition from vowel to glide and from glide to vowel.

836 Figure 2 MEAN, VARCO and eventDUR as a function of sequences. Dispersion bars around
837 the mean values represent confidence intervals.

838 Figure 3 Relationships between the three acoustic measures (MEAN, VARCO, eventDUR) and
839 the dysarthria severity (indexed by the perceptual score taken as a discrete quantitative
840 variable) for the three dysarthric populations. Shaded areas indicate 95% confidence interval
841 of regression estimates. R^2 is the coefficient of determination.

842

843

Group	N (M/F)	Age Mean (SD) [Range]	ALSFRS-R Bulbar Subscore Mean (SD)	Perceptive Score (BECD) Mean (SD)	Dysarthria subtype
ALS	20/13	63.67 (10.90) [36-86]	9.00 (1.32)	8.05 (3.11)	Mixed flaccid-spastic
PLS	10/7	67.18 (8.18) [55-88]	8.94 (1.25)	7.65 (3.56)	Spastic
SBMA	18/0 ²	63.56 (12.28) [43-85]	9.33 (1.19)	5.29 (2.75)	Flaccid
CONTROLS	29/41	58.10 (20.02) [23-90]	NA	NA	NA

851 Table 1 Cohort description in terms of distribution across sex (N(M/F): number of male
852 and female speakers), age (mean, standard deviation (SD) and range), ALSFRS bulbar
853 subscores, used to assess bulbar involvement (mean and standard deviation), PS scores, used to
854 assess the dysarthria severity (mean and standard deviation) and dysarthria subtypes. Note.
855 ALSFRS-R: ALS Functional Rating Scale-Revised; BECD: Batterie d'Evaluation Clinique de la
856 Dysarthrie.

857

858

859

860

861

862

863

² SBMA is a male, X-linked recessive disease

	MEAN				VARCO				eventDUR			
	X2	p	Eta2 (partial)	90% CI	X2	p	Eta2 (partial)	90% CI	X2	p	Eta2 (partial)	90% CI
CONDITION	116.41	< .001***	0.48	0.38-0.56	44.17	< .001***	0.26	0.15-0.36	93.60	< .001***	0.40	0.30-0.49
SEQUENCE	470.16	< .001***	0.26	0.23-0.29	31.62	< .001***	0.02	0.01-0.04	1.56	.45	2.01e-04	0.00-0.00
CONDITION : SEQUENCE	267.06	< .001***	0.17	0.14-0.19	28.94	< .001***	0.02	0.01-0.03	34.16	< .001***	4.37e-03	0.00-0.01

864 Table 2 LMM results for the fixed effects “SPEAKER CONDITION” and “SEQUENCE TYPE” and its interaction
865 for MEAN, VARCO and eventDUR.*** indicates a significance $p < .001$. Effect sizes are measured by Eta
866 squared and confidence intervals are at a level of 90%.

867

868

869

870

871

872

873

874

875

876

877

878

879

880

881

882

883

884

885

886

887

888

	MEAN								
	AJ			UJ			WI		
	ESTIMATE (SE)	t RATIO	p	ESTIMATE (SE)	t RATIO	p	ESTIMATE (SE)	t RATIO	p
ALS-CONTROL	-0.002 (0.0005)	-4.76	< .0001	-0.005 (0.0005)	-11.10	< .0001	-0.005 (0.0005)	-11.89	< .0001
ALS-PLS	-0.001 (0.0006)	-1.53	.42	-0.0001 (0.0006)	-0.28	.99	-0.001 (0.0006)	-1.76	.29
ALS-SBMA	-0.003 (0.0006)	-4.67	< .0001	-0.003 (0.0006)	-5.13	< .0001	-0.003 (0.0006)	-5.21	< .0001
CONTROL -PLS	0.001 (0.0006)	2.11	.15	0.005 (0.0006)	8.43	< .0001	0.004 (0.0006)	7.52	< .0001
CONTROL -SBMA	-0.0007 (0.0006)	-1.20	.62	0.002 (0.0006)	3.45	< .01	0.002 (0.0006)	3.99	< .001
PLS-SBMA	-0.002 (0.0007)	-2.69	.03	-0.003 (0.0007)	-4.17	< .001	-0.002 (0.0007)	-2.95	.01

889

890 *Table 3 Estimate, standard error (SE), t and p values for condition's comparisons for the*
891 *metric MEAN acoustic change.*

892

893

894

895

896

897

898

899

900

901

902

903

904

905

906

907

908

		ESTIMATE	SE	t.RATIO	p
ALS	AJ-UJ	-0.0017	0.0002	-7.511	< .0001
	AJ-WI	-0.0016	0.0002	-6.881	< .0001
	UJ-WI	0.00016	0.0002	0.685	.77
CONTROL	AJ-UJ	-0.0049	0.0001	-27.596	< .0001
	AJ-WI	-0.0052	0.0001	-28.656	< .0001
	UJ-WI	-0.0002	0.0001	-1.231	.43
PLS	AJ-UJ	-0.0009	0.0003	-2.766	.01
	AJ-WI	-0.0017	0.0003	-5.424	< .0001
	UJ-WI	-0.0008	0.0003	-2.526	.031
SBMA	AJ-UJ	-0.0021	0.0003	-6.631	< .0001
	AJ-WI	-0.0019	0.0003	-6.271	< .0001
	UJ-WI	0.0001	0.0003	0.360	.93

909

Table 4 Estimate, SE, t and p values for the sequence's comparisons for the metric

910 *MEAN.*

911

912

913

914

915

916

917

918

919

920

921

922

923

924

925

926

	VARCO								
	AJ			UJ			WI		
	ESTIMATE (SE)	t RATIO	<i>p</i>	ESTIMATE (SE)	t RATIO	<i>p</i>	ESTIMATE (SE)	t RATIO	<i>p</i>
ALS-CONTROL	0.06 (0.02)	3.21	< .001	0.16 (0.02)	7.69	< .0001	0.12 (0.02)	5.68	< .0001
ALS-PLS	0.04 (0.02)	1.48	.45	0.08 (0.03)	2.85	.02	0.07 (0.02)	2.55	.05
ALS-SBMA	0.06 (0.02)	2.05	.17	0.11 (0.02)	3.94	< .001	0.11 (0.02)	3.94	< .001
CONTROL-PLS	-0.02 (0.02)	-0.94	.78	-0.08 (0.02)	-3.03	.01	-0.04 (0.02)	-1.75	.29
CONTROL-SBMA	-0.01 (0.02)	-0.36	.98	-0.05 (0.02)	-1.94	.21	-0.01 (0.02)	-0.33	.98
PLS-SBMA	0.01 (0.03)	0.48	.96	0.03 (0.03)	0.91	.79	0.03 (0.03)	1.16	.64

927 *Table 5 Estimate, SE, t and p values for the condition's comparisons for the metric VARCO.*

928

929

930

931

932

933

934

935

936

937

938

939

940

941

942

943

944

945

946

		ESTIMATE	SE	t.RATIO	p
ALS	AJ-UJ	-0.095	0.0155	-6.159	< .0001
	AJ-WI	-0.075	0.0153	-4.927	< .0001
	UJ-WI	0.02035	0.0156	1.305	.39
CONTROL	AJ-UJ	-0.0042	0.0118	0.358	.93
	AJ-WI	-0.0209	0.0117	-1.781	.17
	UJ-WI	-0.02512	0.0118	-2.123	.08
PLS	AJ-UJ	-0.0539	0.0215	-2.510	.03
	AJ-WI	-0.0432	0.0212	-2.037	.10
	UJ-WI	-0.0107	0.0215	0.499	.87
SBMA	AJ-UJ	-0.0390	0.0212	-1.842	.15
	AJ-WI	-0.02	0.0209	-0.957	.60
	UJ-WI	0.019	0.0212	0.897	.64

947 *Table 6 Estimate, SE, t and p values for the sequence's comparisons for the metric*
948 *VARCO.*

949
950
951
952
953
954
955
956
957
958
959
960
961
962
963
964
965

966

	eventDUR								
	AJ			UJ			WI		
	ESTIMATE (SE)	t RATIO	p	ESTIMATE (SE)	t RATIO	p	ESTIMATE (SE)	t RATIO	p
ALS-CONTROL	13.11 (1.59)	8.26	< .0001	10.56 (1.58)	6.67	< .0001	11.38 (1.59)	7.16	< .0001
ALS-PLS	3 (2.24)	1.34	.53	-1.79 (2.24)	-0.80	.85	-4.00 (2.24)	-1.78	.28
ALS-SBMA	13.17 (2.20)	5.99	< .0001	10.32 (2.20)	4.69	< .0001	9.74 (2.21)	4.41	< .001
CONTROL-PLS	-10.10 (2.03)	-4.98	< .0001	-12.35 (2.03)	-6.08	< .0001	-15.39 (2.03)	-7.59	< .0001
CONTROL-SBMA	0.06 (1.98)	0.03	1.00	-0.23 (1.98)	-0.10	.99	-1.64 (1.99)	-0.82	.84
PLS-SBMA	10.17 (2.54)	4	< .001	12.11 (2.54)	4.77	< .0001	13.75 (2.54)	5.41	< .0001

967 *Table 7 Estimate, SE, t and p values for the condition's comparisons for the metric eventDUR.*

968

969

970

971

972

973

974

975

976

977

978

979

980

981

982

983

984

985

986

987

		ESTIMATE	SE	z.RATIO	p
ALS	AJ-UJ	2.8267	0.779	3.627	< .001
	AJ-WI	2.759	0.787	3.504	< .01
	UJ-WI	-0.067	0.784	-0.086	.99
CONTROL	AJ-UJ	0.2761	0.536	0.515	.86
	AJ-WI	1.0331	0.540	1.913	.13
	UJ-WI	0.7570	0.537	1.410	.34
PLS	AJ-UJ	-1.9699	1.085	-1.816	.16
	AJ-WI	-4.2537	1.078	-3.946	< .001
	UJ-WI	-2.2838	1.081	-2.113	.09
SBMA	AJ-UJ	-0.0266	1.053	-0.025	.99
	AJ-WI	-0.6747	1.068	-0.632	.80
	UJ-WI	-0.6481	1.068	-0.607	.82

988 *Table8 Estimate, SE, t and p values for the sequence's comparisons for the metric eventDUR.*

989

990

991

992

993

994

995

996

997

998

999

1000

1001

1002

1003

Variables	ALS	PLS	SBMA
	Lower bound CI < Slope estimate < Upper bound CI	Lower bound CI < Slope estimate < Upper bound CI	Lower bound CI < Slope estimate < Upper bound CI
MEAN	-0.0004 < -3.521e-04 < -0.0001	-0.0011 < -0.0005 < -0.0002	-0.0003 < 1.151e-05 < 0.0003
VARCO	-0.009 < 0.002 < 0.013	-0.015 < 0.0007 < 0.010	-0.028 < -0.014 < -0.004
eventDUR	-0.69 < 0.71 < 1.54	-0.13 < 1.06 < 2.49	-1.08 < -0.26 < 0.67

1004 *Table 9 Slope estimate and bootstrap bca (bias-corrected and accelerated) confidence intervals*
 1005 *(95%) of the relationship between dysarthria severity level and acoustic measures MEAN, VARCO*
 1006 *and DURATION for each pathological group. When confidence intervals do not contain the value*
 1007 *of 0, then Ho hypothesis about slope equality to 0 is rejected, and it was assumed that there*
 1008 *was evidence of a linear relationship between dysarthria severity of speech and variables*
 1009 *(bold figures).*

1010