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1 **Do acoustic characteristics of dysarthria in people with Parkinson's disease differ across languages?**

2 Serge Pinto, PhD,¹Rita Cardoso, SLP, MSc,^{2,3} Cyril Atkinson-Clement, MPsy, PhD,^{1,4} Isabel Guimarães,
3 SLP, PhD,^{3,5} Jasmin Sadat, PhD,¹Helena Santos, SLP, MSc,²Céline Mercier, SLP,^{1,6} Joana Carvalho, SLP,
4 MSc,² Marie-Charlotte Cuartero, MPsy, PhD,¹Pedro Oliveira, PhD,⁷ Pauline Welby, PhD,¹Sónia Frota,
5 PhD,⁸ Emilie Cavazzini, MPsy,¹Marina Vigário, PhD,⁸ Alban Letanneux, PhD,⁹ Marisa Cruz, PhD,⁸
6 Coralie Brulefert, SLP,¹Morgane Desmoulin, SLP,¹ Isabel Pavão Martins, MD, PhD,¹⁰ Rui Rothe-
7 Neves, PhD,¹¹ François Viallet, MD, PhD,^{1,6} Joaquim J. Ferreira, MD, PhD,^{2,3}

8 ¹ Aix Marseille Univ, CNRS, LPL, Aix-en-Provence, France

9 ² CNS - Campus Neurológico Sénior, Torres Vedras, Portugal

10 ³ Instituto de Medicina Molecular (IMM), Faculdade de Medicina, University of Lisbon, Portugal

11 ⁴ Precision Imaging Beacon, School of Medicine, University of Nottingham, UK

12 ⁵ Alcoitão Health School of Sciences, Speech Therapy Department, Alcabideche, Portugal

13 ⁶ Neurology Department, Centre Hospitalier Intercommunal du Pays d'Aix, Aix-en-Provence, France

14 ⁷ Université Jean Moulin, Lyon 3, France

15 ⁸ Center of Linguistics, School of Arts and Humanities, University of Lisbon, Portugal

16 ⁹ ESPE Université Paris-Est Créteil, Laboratoire CHArt-UPEC (EA 4004), Bonneuil-sur-Marne, France

17 ¹⁰ Language Research Laboratory, Neurology Department, University of Lisbon, Portugal

18 ¹¹ Laboratório de Fonética, Universidade Federal de Minas Gerais (UFMG), Belo Horizonte, Brasil

19 **Corresponding author:**

20 Serge Pinto, Ph.D.

21 Laboratoire Parole et Langage (LPL), UMR 7309 - CNRS / Aix-Marseille Université

22 5 avenue Pasteur, 13100 Aix-en-Provence, France

23 +33 4 13 55 36 23 serge.pinto@univ-amu.fr

24 **Keywords:** Parkinson's disease; Dysarthria; Cross-language; Medical treatment; Portuguese; French

25 **Abstract**

26 **Purpose:** Cross-language studies suggest more similarities than differences in how dysarthria affects
27 the speech of people with Parkinson’s disease (PwPD) who speak different languages. In this study,
28 we aimed to identify the relative contribution of acoustic variables to distinguish PwPD from controls
29 who spoke varieties of two Romance languages, French and Portuguese.

30 **Method:** This bi-national, cross-sectional, and case-controlled study included 129 PwPD and 124
31 healthy controls who spoke French or Portuguese. All participants underwent the same clinical
32 examinations, voice/speech recordings, and self-assessment questionnaires. PwPD were evaluated
33 *off* and *on* optimal medication. Inferential analyses included Disease (controls vs. PwPD) and
34 Language (French vs. Portuguese) as factors, and random decision forest algorithms identified
35 relevant acoustic variables able to distinguish participants: i) by language (French vs. Portuguese) and
36 ii) by clinical status (PwPD *on* and *off* medication vs. controls).

37 **Results:** French-speaking and Portuguese-speaking individuals were distinguished from each other
38 with over 90% accuracy by five acoustic variables (the mean F0 and the shimmer of the sustained
39 vowel /a/ production, the oral diadochokinesis performance index, the relative SPL and the relative
40 SPL_SD of the text reading). A distinct set of parameters discriminated between controls and PwPD:
41 for men, maximum phonation time and the oral diadochokinesis speech proportion were the most
42 significant variables; for women, variables calculated from the oral diadochokinesis were the most
43 discriminative.

44 **Conclusions:** Acoustic variables related to phonation and voice quality distinguished between
45 speakers of the two languages. Variables related to pneumophonic coordination and articulation rate
46 were the more effective in distinguishing PwPD from controls. Thus, our research findings support
47 that respiration and diadochokinesis tasks appear to be the most appropriate to pinpoint signs of

48 dysarthria, which are largely homogeneous and language-universal. In contrast, identifying language-
49 specific variables with the speech tasks and acoustic variables studied was less conclusive.

50 **Introduction**

51 People with Parkinson’s disease (PwPD) face several impairments of voice and speech, referred to as
52 hypokinetic dysarthria (Darley et al., 1969a, 1969b). The key features of speech in PwPD are
53 monopitch, reduced stress, monoloudness, imprecise consonants, inappropriate silences, short
54 rushes of speech, harsh and breathy voice, low pitch, and variable rate (Darley et al., 1969a, 1969b).
55 An additional and potential marker of dysarthria in PwPD is reduced loudness or hypophonia (Becker
56 et al., 2002; Canter, 1963; Fox & Ramig, 1997; Hlavnička et al., 2017; Ho et al., 1999; Liotti et al.,
57 2003; Rusz et al., 2013).

58 Dysarthria is a complex symptom resulting from multiple factors (for a review, see Sapir, 2014). The
59 particular language a person speaks is a key variable that may influence how listeners perceive
60 dysarthric speech. Much of the literature on dysarthria in PD focuses on English or a few other
61 languages, leading to a predominant English-centered perspective in the field and leaving aside
62 thousands of other world languages, which is an issue in various disciplines (García et al., 2023).
63 Studies examining the impact of speech difficulties from a cross-language perspective are increasing
64 in number, providing arguments in favor of language-universal and language-specific aspects of
65 dysarthric speech (Levy & Moya-Galé, 2023; Moya-Galé et al., 2023). For example, as it is mentioned
66 as a critical component of communication deficits in people with motor speech disorders, speech
67 rhythm could affect communication as a language-specific feature (Liss et al., 2013). So far,
68 researchers have discovered more similarities than differences in how dysarthria affects the speech
69 and/or intelligibility of PwPD in different languages. For instance, similarities were found between
70 dysarthric English and Chinese speakers with cerebral palsy or Parkinson’s disease (Whitehill, 2010).
71 Dysarthria in Cantonese-speaking PwPD seems also perceptually very similar to that of English and
72 Japanese-speaking PwPD (Whitehill et al., 2003). These examples support language-universal aspects
73 of dysarthria in PwPD. Recent studies have developed automatic acoustic approaches to determine
74 common variables for patient identification across different languages (Favaro et al., 2023; Moreno-

75 Acevedo et al., 2023; Scimeca et al., 2023). Studies have not found language-specific differences
76 between controls and PwPD in a broad range of acoustic parameters in Czech, American English,
77 German, French, and Italian – languages that were found to differ in several acoustic parameters.
78 Classic dysfunctions of PD voice and speech (monopitch, prolonged pauses, and imprecise
79 consonants) were thus automatically detected across the six languages (Rusz et al., 2021). This aligns
80 with previous findings for Spanish, German, and Czech (Orozco-Arroyave et al., 2016) when running
81 an automatic segmentation of utterances in isolated words, diadochokinesis, sentences, or read
82 texts. Following the same type of automatic speech analysis, deficits in morphological processing
83 were also similar in the same set of languages studied (Eyigoz et al., 2020). Perceptual studies have
84 also provided arguments for language-universal aspects of dysarthria in PwPD: raters can
85 discriminate speech between controls and PwPD, independently of the language spoken by the
86 raters, *i.e.*, Dutch or non-Dutch listeners (Verkhodanova, Coler, Jonkers, Timmermans, et al., 2022).
87 This classification capacity can be interpreted as non-native listeners perceptually focusing on
88 “speech rate, presence of phonation deficiency reflected by maximum phonation time measurement,
89 and centralization of the vowels” (Verkhodanova, Coler, Jonkers, Timmermans, et al., 2022, page 16),
90 rather than the content of the message (Verkhodanova, Coler, Jonkers, & Lowie, 2022).

91 Alongside these similarities, García et al. reported that linguistic idiosyncrasies have also been found
92 in speech in PwPD (García et al., 2023). Many possible reasons point to language-specific differences
93 in the assessment and impact of dysarthria in PwPD, all of which rely on particular properties of a
94 given language (Miller & Lowit, 2014). For example, differences between Cantonese and Mandarin
95 speakers may highlight possible language-specific aspects of dysarthria, which could be attributed to
96 the distinct phonologies of the two languages (Whitehill, 2010). A study comparing American English
97 and Korean-speaking PwPD indicated that while acoustic vowel space was the main contributor to
98 speech intelligibility, two additional variables (voice onset time and articulation rate) also
99 contributed to intelligibility in Korean (Kim & Choi, 2017). As it comes to a higher cognitive level,
100 word processing in PD was shown to be impaired for action verbs but not for concrete nouns in

101 French (Boulenger et al., 2008); a selective action-verb deficit was noted in Spanish speakers (García
102 et al., 2018) but not in speakers of Danish (Møller et al., 2023). This was explained primarily by
103 differences in vocabulary and syntax between the two languages and in linguistic context (García &
104 Ibáñez, 2023).

105 In the FraLusoPark project (Pinto et al., 2016), a large set of clinical, patient-reported, and acoustic
106 measures was integrated into the construction of a database that included speech productions from
107 PwPD speaking varieties of two Romance languages, Metropolitan French (from France) and European
108 Portuguese (from Portugal). French and Portuguese share certain vocabulary and grammar features,
109 which might reduce the relevance of a cross-linguistic comparison. However, they differ substantially
110 in phonetics and phonology, making the comparison between the two languages interesting in
111 searching for acoustic variables more sensitive to PD in one language than in the other.

112 French is usually described as a language with fixed stress as it has a primary stress regularly assigned
113 to the final full syllable of the last lexical item of a stress group. A secondary stress, which is non-final
114 and optional, is more generally assigned to the first syllable of a content word (Di Cristo, 1998).
115 Implementing these stresses implies pitch prominence and primary stress, but not secondary stress, is
116 also manifested by temporal cues. Thus, French intonation is generally characterized by a fundamental
117 frequency (F0) rise on the last syllable of a phrase that is not utterance-final; an optional early, or initial,
118 rise may occur somewhere before the late, or final, rise (Welby, 2006). Authors usually agree that there
119 is an early rise and a late rise, although some disagreement appears to be related to the structure of
120 such rises. A prosodic grouping higher than the word is often reported (Welby, 2006).

121 Unlike French, Portuguese is a language with variable stress. Lexical stress may fall within the last three
122 syllables of a word, and the stressed syllable can distinguish between words as, *e.g.*, in “*número*”
123 *number* versus “*numero*” / *number* (Mateus & de Andrade, 2002). The correlates of stress in
124 Portuguese combine prosodic with vowel quality cues. The main prosodic correlates are temporal cues,
125 not pitch prominence (Delgado-Martins, 1986). Primary stress is signaled by vowel quality cues: unlike

126 stressed vowels, unstressed vowels are reduced (Mateus & de Andrade, 2002). Given that pitch is not
127 an acoustic correlate of stress in that language, Portuguese intonation differs substantially from French
128 intonation. In Portuguese, intonational pitch movements signal the most prominent syllable in the
129 utterance, which is typically in the utterance-final word (Frota, 2014).

130 Compared to French, Portuguese is a language with a rather lax articulation and presents various
131 phonetic modifications, *e.g.*, plosives may be spirantized, and the articulation of unstressed vowels is
132 often undershot. Moreover, unlike in French, the syllable cannot be taken as the timing unit in
133 Portuguese since phonetic syllables may be blended through the collapse of weak vowels in connected
134 speech. Indeed, the rhythm of Portuguese has been described to be mixed and not syllable-based as
135 in French (Frota & Vigário, 2001). One could argue that Portuguese-speaking PwPD are trained to
136 preserve word stress, because it is important to word meaning. In contrast, French-speaking PwPD
137 would have no reason to preserve this dimension since stress cannot lead words to change meaning
138 in French. Furthermore, intonational patterns in French are more phrase-based, marking prosodic
139 groupings higher than the word, whereas in Portuguese they delimit the utterance. If PwPD preserve
140 these contrasting patterns, then sequences of melodic rises and falls would be more common in French
141 than in Portuguese. Alternatively, an equally impaired melodic curve across PwPD could be defined by
142 the speech characteristic of monopitch in PD.

143 The aims of the current study were, on the one hand, to identify relevant acoustic variables that would
144 distinguish French-speaking versus Portuguese-speaking individuals, while controlling for gender
145 (men/women), group (controls/PwPD), and medication state (on/off). On the other hand, we aim to
146 identify the acoustic variables that distinguish controls from PwPD, with analyses performed by
147 gender, language, and medication states. For this purpose, we used a classificatory analysis to identify
148 the separate contribution of each acoustic variable when distinguishing groups with the highest
149 accuracy. Because of the above-mentioned language-related specificities, we expected some acoustic
150 variables to differ between French-speaking and Portuguese-speaking controls.

151 As mentioned previously, we established for PwPD two alternative a priori hypotheses based upon two
152 different perspectives (Pinto et al., 2017): (i) according to a disease-based account, these differences
153 could disappear in PwPD since dysarthric signs could be language-universal, constant and
154 homogeneous; (ii) from a more language-specific account, these differences could be exacerbated in
155 one specific language due to articulatory specificities that could be more vulnerable in one language
156 as compared to the other. In the latter case, we would expect different impacts of dysarthria in PwPD's
157 communication according to their language, and we hypothesized that this would be reflected in our
158 patient cohorts in terms of intelligibility and the psychosocial impact of dysarthria.

159 **Method**

160 ***Study design***

161 FraLusoPark is a bi-national, cross-sectional, and case-controlled study with PwPD and healthy
162 controls speaking varieties of two Romance languages, namely Metropolitan French (from France)
163 and European Portuguese (from Portugal). The reported study protocol (Pinto et al., 2016) was
164 approved by the local ethics committees (*France: Comité de Protection des Personnes, Sud*
165 *Méditerranée 1; Portugal: Ethics Committee of the Lisbon Academic Medical Centre*) and registered
166 under the reference NCT02753192 on <https://clinicaltrials.gov/>. The study was conducted following
167 the ethical standards of the Declaration of Helsinki (World Medical Association Declaration of
168 Helsinki, 2013). PwPD and controls were included in the study after providing their written informed
169 consent.

170 ***Participants***

171 PwPD were recruited either in France (N=64; Neurology Department, Centre Hospitalier du Pays
172 d'Aix, Aix-en-Provence, France) or in Portugal (n=84; Movement Disorders Unit, Hospital de Santa
173 Maria, Lisbon, and Campus Neurológico Sénior [CNS], Torres Vedras, Portugal). PwPD met the UK
174 Parkinson's Disease Brain Bank Criteria (Gibb & Lees, 1988) for diagnosing idiopathic PD. All

175 participants were right-handed and native speakers of French or Portuguese (French-Portuguese
176 bilinguals were excluded from the study). Two groups of healthy volunteers (N=68 in France, n=74 in
177 Portugal), age- and gender-matched with the PwPD, were also included in the study as controls.
178 Exclusion criteria for participants were the following: illiteracy; non-native French/Portuguese
179 speakers or French-Portuguese bilinguals; participants under tutorship or guardianship, or any other
180 administrative or legal dependence; consent withdrawn; cognitive deficits, severe depression,
181 dementia, psychosis (including medication-induced) or behavioral, neurological, medical, or
182 psychological disorders that could have interfered with evaluations (clinically assessed by the
183 neurologists during participant screening). For PwPD, additional exclusion criteria included non-
184 idiopathic PD, deep brain stimulation, and severe motor impairment impeding participation in the
185 study. To gauge speech changes at various stages of the disease, the PwPD were initially recruited
186 (Pinto et al., 2016) to reflect a large spectrum of disease severity according to disease duration and
187 the modified Hoehn & Yahr stage (Goetz et al., 2004). Since the primary aim of our study was to
188 assess PwPD speaking two languages in parallel, we did not separate PwPD into subgroups for our
189 analyses. All participants underwent the same non-invasive examinations. PwPD were assessed
190 twice, *off* and *on* medication, respectively: (i) at least twelve hours after withdrawal from all PD
191 medications and (ii) between 45-60 minutes after administration of the patient's usual morning dose
192 of medication. The levodopa-equivalent doses (LED) for this intake were calculated according to
193 reported protocols (Jost et al., 2023; Schade et al., 2020; Tomlinson et al., 2010).

194 ***Clinical examinations***

195 The Movement Disorders Society Unified Parkinson's Disease Rating Scale – MDS-UPDRS (Goetz et
196 al., 2008) – was used for the neurological assessment: the motor part (section 3) was performed
197 twice with the PwPD, *off* and *on* medication. During the *on-medication* state, the non-motor (section
198 1.A) and motor complication (section 4) parts of the MDS-UPDRS were administered, along with the

199 Montreal Cognitive Assessment – MoCA (Nasreddine et al., 2005) – and the Clinical Global
200 Impression of Dysarthria Severity – CGI-S scale (Busner & Targum, 2007).

201 The Frenchay Dysarthria Assessment, version 2 – FDA-2 (Enderby & Palmer, 2008) – was performed
202 to assess oromotor function. Speech intelligibility was rated following the instructions of the FDA-2
203 (Enderby & Palmer, 2008). Word and sentence sets were adapted into French (Ghio et al., 2020) and
204 Portuguese (Cardoso et al., 2017). More specifically, the general procedure was as follows: ten words
205 (out of 101 for French, 109 for Portuguese) and ten sentences (out of 50 for French, 60 for
206 Portuguese) were randomly selected from the sets and presented to the participants, who read them
207 aloud. The speech/language pathologists/therapists (SLP/Ts) who carried out the FDA-2 assessment
208 rated the correct words and sentences on the spot; they also rated intelligibility based on a short
209 conversation with the participant. The scoring for the words and sentences was: 0 = fewer than 5
210 words/sentences understood correctly; 1 = five to six words/sentences; 2 = seven to nine
211 words/sentences; 3 = ten words/sentences understood with some effort; 4 = ten words/sentences
212 easily understood. The scoring for the conversation was: 0 = unintelligibility; 1 = some words
213 understood; 2 = severely distorted (the patient can be understood half the time and has to repeat
214 often); 3 = abnormal but intelligible (the patient has to repeat occasionally); 4 = normal. The speech
215 intelligibility score we used here refers to the sum of these three assessments (maximum score = 3
216 tasks*4 = 12 for normal intelligibility; minimum score = 3 tasks*0 = 0 for unintelligible speech).

217 The overall assessment of the control participants was like that of the PwPD (except MDS-UPDRS
218 section 4).

219 ***Patient-reported outcome measures***

220 Self-assessments were used to obtain information on the functional impact of the patient's
221 speech/communication impairment and to provide patient-reported outcome measures (PROMs).
222 The first set of questionnaires assessed the general quality of life and the psychosocial impact of

223 dysarthria: the 39-item Parkinson's Disease Questionnaire - PDQ-39 (Peto et al., 1995), adapted into
224 European French and Portuguese; and the Dysarthria Impact Profile - DIP (Walshe et al., 2009),
225 adapted into European French (Atkinson-Clement et al., 2019; Letanneux et al., 2013) and
226 Portuguese (Cardoso et al., 2018). A second set assessed the patient's self-evaluation of their voice
227 and speech: the 30-item Voice Handicap Index - VHI-30 (Jacobson et al., 1997), adapted into
228 European French (Woisard et al., 2004) and Portuguese (Guimaraes et al., 2017; Guimarães &
229 Abberton, 2004); and the Patient Global Impression of dysarthria Severity - PGI-S (Hurst & Bolton,
230 2004). All self-evaluations were administered with PwPD on medication and with controls.

231 ***Acoustic recording procedure***

232 Acoustic data were collected in quiet rooms in the neurology wards of university hospitals in Aix-en-
233 Provence, France, and Lisbon, Portugal, using specialized equipment (EVA2© system, SCLab, Aix-en-
234 Provence, France; <http://www.sqlab.fr/>; a Marantz PMD661 MKII recorder, USA; and a DPA 4288
235 CORE Directional Flex Headset microphone). The distance between the participant's mouth and the
236 head-mounted microphone was kept consistent across participants to range from three to five
237 centimeters. It was positioned at an angle of 45°-90° to the side of the lip angle, as recommended.
238 No sound-treated recording booths were available in the neurological wards. The noise floor was not
239 measured, but the experimental rooms were specifically chosen to prevent noise pollution from
240 affecting the audio signals. Two researchers specialized in movement disorders in each country
241 carried out the overall protocol: two specialized SLP/Ts in Portugal, one specialized SLP/T, and a
242 specialized psycholinguist in France. The researchers were not blind to medication conditions (*off* or
243 *on*). All participants were instructed to perform speech tasks at a comfortable volume and pitch to
244 avoid straining their voices. The researchers all used the same instructions from the shared case
245 report form to present the tasks to the participants. Participants were recorded while performing
246 non-speech movements and speech tasks to allow several acoustic parameters to be calculated. The
247 non-speech movement tasks included: (i) the maximally-sustained vowel /a/; (ii) production of a 3-

248 second sustained vowel /a/; and (iii) an oral diadochokinesis (DDK), namely the sequential motion
249 rate task requiring the repetition of the tri-syllable pseudo-word /pataka/at the fastest rate possible.
250 The speech task involved: (iv) reading aloud French (Fougeron & Smith, 1993, 1999) and Portuguese
251 (Cruz-Ferreira, 1995, 1999) versions of Aesop’s fable “*The North Wind and the Sun.*”

252 ***Acoustic recording pre-processing***

253 The audio files were segmented, annotated, and analyzed with Praat software (Boersma & Weenink,
254 2018) to calculate the dependent variables (**Table 1**).

255 *TABLE 1 ABOUT HERE*

256 The maximum phonation time (MPT) was estimated from the maximally sustained vowel, as it is an
257 efficient indicator of the coordination between the phonatory and respiratory systems. The
258 participants were instructed to sustain the vowel /a/ twice at a comfortable voice amplitude and
259 pitch level after maximum inspiration (Midi et al., 2008). The longer duration was selected from the
260 two trials.

261 Pre-processing parameters for the 3-second sustained vowel /a/ production included a sampling at
262 standard spectrum Praat settings (view range: 0-5000 Hz), F0 settings at 60-400 Hz (Rusz et al., 2011),
263 a cross-correlation Praat method for pitch/voice analysis, the window defined in most stable
264 segments, regardless of its location, and window length with at least 110 cycles (2-sec window if
265 possible). The beginning (onset) and final (offset) of steady vowels are subject to changes in
266 aerodynamic and muscular parameters, resulting in elevated jitter and shimmer values.
267 Consequently, the most stable regions of the voice signals are usually selected for acoustic analysis
268 (Olszewski et al., 2011). In our analyses, we discarded 200 ms from the onset and offset of the
269 vowels. Periodicity (*i.e.*, fundamental frequency, or F0) was calculated by averaging the mean F0
270 across the 3 trials of the vowel for each participant (Yu et al., 2007). Jitter (short-term, cycle-to-cycle
271 variability in vocal fold vibration frequency) and shimmer (short-term, cycle-to-cycle variability in

272 vocal fold vibration amplitude) represent measures of altered stability of the steady vowel: low jitter
273 and shimmer values are associated with an ability to maintain periodic vibration (Baken & Orlikoff,
274 2000; Olszewski et al., 2011). The harmonic-to-noise ratio (HNR) is the ratio between the signal's
275 total energy and the noise components' energy: the lower the HNR, the more noise in the voice;
276 higher HNR values are associated with normal voices. HNR is evaluated as the ratio of the inharmonic
277 (1500–4500 Hz) to the harmonic (70–4500 Hz) spectral energy (Olszewski et al., 2011).

278 In the oral DDK task, from which sequential motion rate can be calculated (Kent, 2015; Pierce et al.,
279 2013), participants repeated a tri-syllable pseudoword, which provided data to measure several
280 variables involved in oromotor articulatory control (Gadesmann & Miller, 2008; Lowit et al., 2018). In
281 this task, participants repeat the syllables as quickly as possible for 30 seconds at a comfortable pitch
282 and volume (Midi et al., 2008). The syllables for the DDK task were used to assess three major
283 articulators, *i.e.*, the lips and the tip and dorsum of the tongue (Ziegler, 2002). Segmentation was
284 conducted to place cursors on the audio file at the beginning and end of sound sequences to exclude
285 silent pauses (mainly inspirations) from the total duration of the task to determine the speech
286 proportion (= speech duration/total duration). The other measures performed were the following:
287 articulatory rate (= syllable number/speech duration), an oral DDK performance index (DDKi), defined
288 as speech proportion/number of sound sequences, and the variation of inter-vowel intervals (VIVI),
289 calculated as the inter-vowel duration SD/inter-vowel duration mean.

290 For the reading task, the automatic detection of speech utterances was done using the same Praat
291 script used for the DDK task. A specific Praat script (ProsodyPro) was then applied to extract and
292 calculate speech duration, mean fundamental frequency (F0) and F0 standard deviation (F0_SD).
293 Relative sound level pressure (SPL) and relative SPL standard deviation (SPL_SD) were calculated in
294 Praat using the averaging method (mean dB unit) for the above-mentioned time selection.

295

296 **Statistical analyses**

297 Data analyses were performed using the R statistical software package (R Core Team, 2013). Where
298 appropriate, demographic, and clinical data were compared using ANOVAs and generalized linear
299 models (men/women ratio). Multiple comparisons were adjusted using Tukey corrections, and the
300 threshold for significance was set at $p \leq 0.05$. To determine the importance of acoustic data for
301 identifying language and disease differences between groups, we used random forest models
302 combined with permutations (rfPermute package). This approach generated decision trees ($n=5,000$)
303 using a subsample of the data (i.e., the individuals) and the predictors (i.e., the acoustic variables),
304 and identified the best cut-off values that provided the highest classification accuracy for each tree.
305 The relative importance, or mean decrease accuracy (MDA), was then calculated after normalization
306 as follows:

307
$$\frac{\mu(DA)}{\sigma(DA)}$$

308 where $\mu(DA)$ represents the mean decrease accuracy of trees (MDA) and $\sigma(DA)$ represents the
309 standard deviation of the decrease accuracy of trees. In other words, the importance of one
310 predictor (i.e., one acoustic variable) is determined by calculating the difference in accuracy between
311 the decision trees that consider this predictor in comparison to trees that do not. Finally, 1,000 new
312 random forests were built using permutations (i.e., by randomizing the predictors' values),
313 generating a null distribution and therefore yielding p-values. The p-values are calculated by
314 comparing the MDA of the proper random forest to the MDA of the 1,000 permuted random forests.
315 A p-value of 0.05 means that the proper MDA is higher than 95% of the permuted MDA.

316

317

318

319 **Results**

320 ***Population description***

321 **Table 2** summarizes the participant characteristics. Identification of exclusion criteria led us to
322 exclude some participants from the analysis: seven PwPD and eight controls in France, and ten PwPD
323 and nine controls in Portugal (the criteria included severe cognitive and depressive symptoms [n=12],
324 a neurological history such as essential tremor or vascular accident [n=13], medication-induced
325 hallucinations [n=1], no Parkinson’s disease medication [n=2], oromotor history/inconvenient dental
326 apparatus [n=2], French-Portuguese bilinguals [n=1], study withdrawal [n=2], and missing data [n=1]).
327 The two participant cohorts we studied did not differ in age, disease duration, or LED medication for
328 the *on*-medication state (**Table 2.A**). However, the Portuguese-speaking participants were slightly
329 younger than the French-speaking ($p<0.05$), and the man/woman ratio was more unbalanced in the
330 French-speaking PwPD.

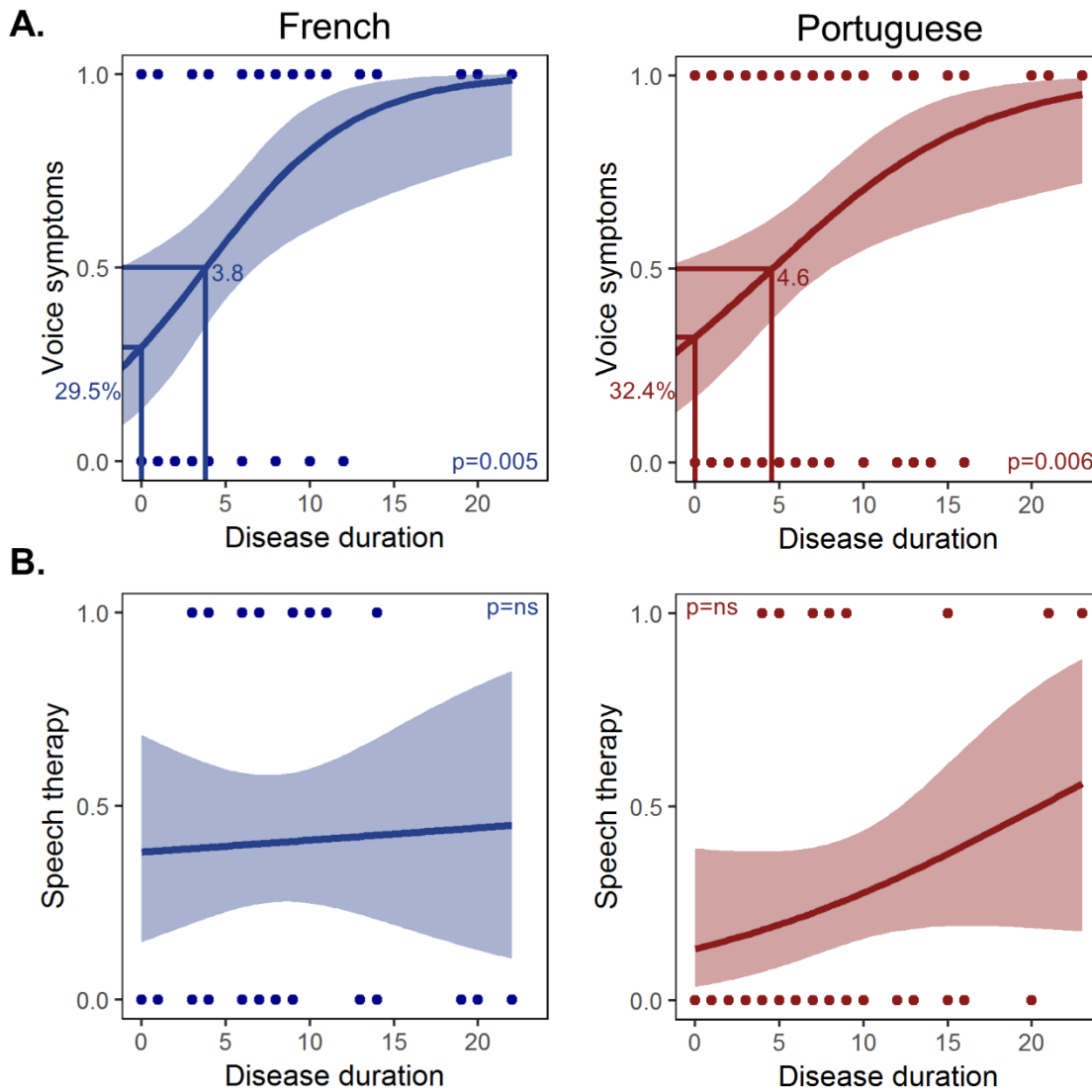
331 *TABLE 2 ABOUT HERE*

332 Logistic regressions revealed that disease duration predicted the occurrence of voice/speech
333 complaints in both French-speaking ($p=0.005$) and Portuguese-speaking ($p=0.008$) PwPD: at the
334 diagnosis, the models estimated that 29.5% (French-speaking) and 34.8% (Portuguese-speaking)
335 PwPD already had an impairment, which increased over time to become a concern for half of the
336 PwPD after four years of the disease’s progression (3.8 years for French-speaking PwPD, 4.6 years for
337 Portuguese-speaking PwPD; **Figure 1.A**). Nevertheless, disease duration did not predict involvement
338 in speech therapy in either language group (**Figure 1.B**).

339 *FIGURE 1 ABOUT HERE*

340

341



342

343 **Clinical assessments**

344 By including 'Disease' as a fixed factor of our statistical analyses, all clinical assessments (CGI-S, FDA-
 345 2, MDS-UPDRS and MoCA) demonstrated significant ($p < 0.001$) differences between PwPD and
 346 controls (**Table 2.B**). With 'Language' as the fixed factor, no differences were found between French-
 347 speaking and Portuguese-speaking participants for the CGI-S and part 4 of the MDS-UPDRS (PwPD-
 348 only comparison). Significant differences were revealed for both neurological (MDS-UPDRS parts 1.A
 349 and 3; $p < 0.001$) and speech (FDA-2; $p < 0.05$) assessments. A 'Disease' and 'Language' factor
 350 interaction ($p < 0.001$) was displayed *on* medication for the MDS-UPDRS motor evaluation, explained
 351 by significantly different scores ($p < 0.001$) between French-speaking and Portuguese-speaking PwPD,

352 as well as French-speaking and Portuguese-speaking controls. For the FDA-2, scores were similar for
353 the PwPD in the two language groups, both *off* ($p=0.8512$) and *on* ($p=0.4017$) medication;
354 assessments of controls were significantly different ($p<0.001$), mainly driven by ‘Disease’ and
355 ‘Language’ factor interactions ($p<0.001$). The MoCA scores also differed significantly ($p<0.001$)
356 between language groups, with Portuguese-speaking participants presenting lower scores than
357 French-speaking participants; however, no interaction was found between ‘Disease’ and ‘Language’
358 factors.

359 ***Patient-reported outcome measures***

360 All PROMs (MDS-UPDRS parts 1.B [non-motor daily-living activities] and 2 [motor daily-living
361 activities], PDQ-39, PGI-S, DIP, and VHI-30) were significantly ($p<0.01$) different between PwPD and
362 controls (**Table 2.C**). No differences were found between the two groups of language speakers,
363 except for the DIP ($p<0.05$) for which Portuguese-speaking participants displayed lower scores than
364 the French-speaking; no interaction was found between ‘Disease’ and ‘Language’ factors. A marginal
365 interaction ($p=0.049$) between factors was found for the MDS-UPDRS part 1.B; scores were similar
366 for the PwPD ($p=0.19$) and the control participants ($p=0.85$) of the two language groups.

367 *TABLE 3 ABOUT HERE*

368 ***Acoustic parameters***

369 **Table 3** summarizes the acoustic data of the studied population. Classificatory analyzes on language
370 (**Table 4**) revealed that French-speaking and Portuguese-speaking controls could be accurately
371 distinguished (94.8% for men and 97% for women), as well as PwPD either *off* (90.9% for men; 94.5%
372 for women) or *on* medication (90.9% for men 92.7% for women). Interestingly, three types of
373 patterns emerged:

374 i) *some acoustic variables distinguished French-speaking and Portuguese-speaking individuals,*
375 *regardless of gender or population: the mean F0 (except for men PwPD on medication) and the*
376 *shimmer of the vowel /a/, the oral DDKi (except for men controls), the relative SPL and relative*
377 *SPL_SD of the text reading;*

378 ii) *one variable could significantly discriminate French-speaking and Portuguese-speaking men,*
379 *regardless of the population (controls or PwPD, off and on medication): the F0_SD of the*
380 *reading task;*

381 iii) *and some variables distinguished French-speaking and Portuguese-speaking individuals for*
382 *specific populations: for men PwPD on medication, the mean harmonic-to-noise ratio (HNR) of*
383 *the vowel /a/; for women controls, the reading task duration; and for women PwPD off*
384 *medication, the oral DDK speech proportion.*

385 *TABLE 4 ABOUT HERE*

386 When distinguishing PwPD from controls, analyses were performed for each gender, language, and
387 medication state (**Table 5**). Altogether, the models led to significant general accuracy that was
388 generally higher for the French cohort (61.2% to 75%) than for the Portuguese cohort (59.7% to
389 70.1%). While no acoustic variable was able to distinguish PwPD from controls regardless of gender,
390 language, or medication status, three scenarios were also observed here:

391 i) *some variables distinguished PwPD from controls regardless of language: the oral DDK*
392 *speech proportion, except for women on medication; the maximum phonation time (MPT),*
393 *both for men PwPD off and on medication (together with French-speaking women on*
394 *medication); the mean jitter of the vowel /a/ was found to be discriminatory for men PwPD,*
395 *off medication for French-speaking individuals, and on medication for Portuguese-speaking*
396 *PwPD;*

397 ii) some variables distinguished French-speaking PwPD from controls: the mean F0 and the
398 mean HNR of the vowel /a/ for men *on* medication; the F0_SD of the reading task for men *off*
399 medication; and the oral DDKi for women, both *off* and *on* medication;

400 iii) some variables distinguished PwPD from controls for Portuguese-speaking individuals: the
401 reading task duration for men *off* medication and women both *off* and *on* medication; the oral
402 DDK articulatory rate for women *off* medication; the oral DDKi for men *off* medication; and the
403 F0_SD of the reading task for women *on* medication.

404 *TABLE 5 ABOUT HERE*

405 **Discussion**

406 As expected, French-speaking and Portuguese-speaking control participants, both men and women,
407 could be discriminated between by five acoustic variables - the mean F0 and the shimmer of the
408 vowel /a/ production, the oral DDKi, the relative SPL and the relative SPL_SD of the reading task -
409 with an accuracy of over 94%. Differences in acoustic variables between speakers of the two
410 languages were not exacerbated in PwPD compared to controls. Therefore, acoustic signs of
411 dysarthria appear to be language-universal, constant and homogeneous: for both French-speaking
412 and Portuguese-speaking men, the main variables were the maximum phonation time and the oral
413 DDK speech proportion, while jitter was less prominent; for women, it was the oral DDK speech
414 proportion. In contrast, the identification of language-specific variables that were more affected in
415 one language than the other was less conclusive in the speech tasks and acoustic variables studied
416 here.

417 ***Voice quality markers for language comparisons***

418 The importance of a specific predictor (i.e., one acoustic variable) was determined by calculating the
419 difference in accuracy between the decision trees that consider this predictor in comparison to trees

420 that do not. The identified acoustic variables contributed the most to the specified comparison, with
421 statistical significance. Comparison of acoustic variables between French-speaking and Portuguese-
422 speaking controls, both men and women (**Table 4**), showed that differences between languages
423 appeared to be related mostly to phonation and voice quality (mean F0 and shimmer of the
424 sustained vowel /a/ production; relative SPL and relative SPL_SD for the reading task). These
425 differences were also observed for PwPD, both *off* and *on* medication, suggesting that the French vs.
426 Portuguese discrimination based upon these variables was disease-independent. One variable from
427 the oral DDK task, the DDKi, also participated in the language distinction for most of the participants
428 and the reading task duration for women controls only.

429 To some extent, this is consistent with early (e.g., Hanley et al., 1966) and more recent (e.g., Tucker
430 & Wright, 2020) approaches to studying acoustic differences among languages. Hanley et al. (1966)
431 conducted an experimental comparison of acoustic variables in three languages (American English,
432 American Spanish, and Japanese), using reading and spontaneous speech tasks, observing different
433 continuums of languages between tasks and acoustic variables (including F0, SPL, and variabilities of
434 both). This study is an early example of the research development during the 20th century of using
435 acoustic metrics to complement the description of and compare the world's languages, a research
436 area that has been topical as of late in various fields, such as linguistics (e.g. Tucker & Wright, 2020),
437 eco-anthropology (e.g., Maddieson, 2018), and machine learning modeling (e.g., HaCohen-Kerner &
438 Hagege, 2015). Within these fields, the question arises as to which dimensions of languages are
439 shared with others and which differ; here, whether indicators of voice quality are language-specific
440 (Tucker & Wright, 2020). In a study addressing this question, the comparison of acoustic variables
441 (mean F0, F0_SD, HNR, jitter, shimmer) between three languages (German, Italian, Polish) confirmed
442 the “hypothesis of intercultural or/and interlanguage differences in voice quality” (page 654) while
443 showing that different parameters predominate in different languages (Wagner & Braun, 2003).

444 Our descriptive data contribute to this theoretical framework: F0 and shimmer appear higher in
445 Portuguese-speaking individuals, who also produced lower relative SPL and variation (SPL_SD) in the
446 reading task compared to the French-speaking cohort. F0_SD differences between languages for men
447 also showed that French-speaking individuals had lower variability than Portuguese-speaking ones.
448 The question remains as to how these interlanguage differences can be integrated in the case of
449 PwPD. First, while acoustic variables are important in distinguishing controls from PwPD (see below
450 for a discussion of this comparison), these variables are less appropriate for a cross-language
451 comparison between French-speaking and Portuguese-speaking PwPD; this could be the case (or not)
452 for other language comparisons, depending on the degree of similarity between their acoustic
453 dimensions. Following this conceptualization, cross-language comparisons may lead to as many
454 differences as languages compared, impeding generalization. This remark also underscores the
455 absolute necessity of including control groups. Secondly, particular differences in patterns of specific
456 acoustic variables (**Table 4**) may contribute to specific interpretations. For instance, when
457 considering PwPD *off* medication (namely the pathological state), the oral DDK speech proportion
458 appeared to be a variable contributing to the distinction between French-speaking and Portuguese-
459 speaking women PwPD. This result, in conjunction with the above-mentioned contributions of the
460 oral DDKi and the duration of the reading task to the distinction between French-speaking and
461 Portuguese-speaking populations, suggests that the temporal organization of speech production may
462 reflect the specificities between languages to a lesser extent. Finally, a single acoustic parameter –
463 the HNR - made a significant contribution to separating French-speaking and Portuguese-speaking
464 men PwPD *on* medication. Due to the erratic effect of medication on PD voice quality and the
465 confounding factors in this comparison (language, gender, pathology, medication), it is difficult at
466 this point to retain any robust interpretation able to disentangle language specificity rather than a
467 medication effect. Still, these points altogether suggest that acoustic variables may be language-
468 dependent, at least to some extent.

469 ***Speech tasks for studying language-universal acoustic markers of dysarthria in PwPD***

470 When designing our study protocol (Pinto et al., 2016), we initially planned to report in a primary
471 analysis the main results of the project on the acoustic, prosodic, clinical, and patient-reported
472 measures. We adjusted this plan by focusing on the present article on acoustic, clinical, and PROM
473 measures since some data on prosodic patterns have been already reported (Cavazzini et al., 2018;
474 Frota et al., 2021; see also below). We had determined in the study protocol three a priori
475 hypotheses: “(1) global acoustic features are altered similarly in French and Portuguese PwPD; (2)
476 language-specific prosodic patterns are altered differently in French and Portuguese PwPD, and (3)
477 the impact of speech disorders on intelligibility and quality of life depends on the cultural and
478 linguistic environment” (Pinto et al., 2016, page 3). We discuss our findings within this framework.

- 479 • *“Global acoustic features are altered similarly in French and Portuguese individuals with PD”*

480 Recent studies have brought some insights in favor of a cross-language approach for studying
481 dysarthric speech (Kim & Choi, 2017; Liss et al., 2013; Whitehill, 2010). Perceptual studies in
482 particular point to more similarities than differences in how dysarthria affects the speech and/or
483 intelligibility of PwPD in different languages (Orozco-Arroyave et al., 2016; Ruzs et al., 2021; Whitehill
484 et al., 2003). According to a disease-based account (Pinto et al., 2017) this would imply that the signs
485 of dysarthria in PwPD are constant and homogeneous across languages, and generally independent
486 of language specificities. We indeed found this to be true for the following variables, suggesting that
487 they may be language-universal: mean F0 and shimmer of the sustained vowel /a/ production;
488 relative SPL and relative SPL_SD for the reading task. Our findings show altogether that acoustic
489 variables related to pneumo-phonetic discoordination and generally associated with non-speech tasks
490 (MPT, oral DDK), are the most accurate way to pinpoint dysarthria dimensions at the
491 (neuro)physiological level. MPT is a good indicator of the coordination between the phonatory and
492 respiratory systems as it is an aerodynamic measure of vocal function related to glottic efficiency
493 (Hirano et al., 1968; Maslan et al., 2011). In our study, MPT has been clearly identified as a strong
494 contributor to discrimination between men controls and men PwPD. From a disease-related

495 perspective, this result concurs with the forward-symptom progression of dysarthria (Critchley, 1981;
496 Selby, 1968), which begins with changes in the respiratory system. From a physiological point of
497 view, the gender-related trend (*i.e.*, only for men) has also been largely demonstrated (e.g., Knuijt et
498 al., 2019). Regarding gender differences, it is noteworthy that no variable should be considered
499 reliable enough to distinguish PwPD from controls when considering French-speaking women, both
500 *off* and *on* medication, as well as Portuguese-speaking women *on* medication since PD accuracy
501 values (**Table 5**) were not significant when calculating the random forest decision models (French-
502 speaking women *off* medication: $p=0.31453$; French women *on* medication: $p=0.68547$; Portuguese-
503 speaking women *on* medication: $p=0.12794$). As with oral DDK, this task requires voluntary control
504 of exhalation during phonation, and in our case under time pressure. We found no significant
505 involvement of oral DDK measures related to rhythmicity (articulatory rate, VIVI) to distinguish PwPD
506 from controls, which could have been expected (Lowit et al., 2018). Still, the DDK speech proportion
507 and the performance index contributed to this comparison. Our findings agree with the report that a
508 diadochokinesis task appears to be more appropriate than a reading task to evaluate speech in PwPD
509 in cross-language comparisons (Orozco-Arroyave et al., 2016).

510

- 511 • *“Language-specific prosodic patterns are altered differently in French versus Portuguese*
512 *individuals with PD”*

513 Medication effects reported in two separate investigations - one in each language groups - yielded
514 results on the prosodic patterns produced by the different groups in our cohort. For French-speaking
515 individuals (Cavazzini et al., 2018), we reported participants' prosodic patterns when reading
516 sentences with a list of items, which provided well-defined prosodic features. We hypothesized that
517 PwPD who experienced difficulties in producing all of the F0 rises required would preserve at least
518 the late rise (essential in conveying the information that the element was a "non-final element of a
519 list") rather than the optional early rise (low functional load here). Our hypothesis was confirmed,

520 with the most severely affected PwPD tending to produce smaller tonal patterns with the expected
521 prosodic phrasing – a variety observed in controls and other PwPD. As regards medication effects,
522 the *on*-medication state appeared to influence the prosodic pattern variety in PwPD positively. From
523 the Portuguese side (Frota et al., 2021), we investigated nuclear contours (i.e., the most prominent
524 pitch movement within the utterance) and intonational phrasing to establish the ability of PwPD to
525 use the prosodic categories and structures of Portuguese. Data were reported from a subgroup of
526 our cohort using speech materials designed to elicit specific prosodic patterns, including diverse
527 sentence types, pragmatic meanings, and prosodic phrasings. Overall, PwPD showed a decreased
528 ability to use nuclear contours and prosodic phrasing. Medication improved intonation regardless of
529 disease duration but did not help with dysprosodic phrasing. In turn, disease duration and motor
530 fluctuations affected phrasing patterns but did not impact intonation. As previously mentioned (Frota
531 et al., 2021; Rusz et al., 2021), only a few studies have investigated the phonetic (and acoustic)
532 parameters from a more functional perspective, such as Thies et al. (2020) and Tykalova et al. (2014).
533 In line with our study protocol, we will conduct the planned subsequent prosodic analyzes and
534 expand our knowledge on this point.

- 535 • *“The impact of speech disorders on intelligibility and quality of life depends on the cultural*
536 *and linguistic environment”*

537 Intelligibility scores for French-speaking and Portuguese-speaking controls on the one hand, and
538 French-speaking and Portuguese-speaking PwPD on the other hand, did not differ (**Table 2**). French-
539 speaking PwPD scores were slightly lower than Portuguese-speaking PwPD’, and suggested no effect
540 of medication – contrary to Portuguese-speaking PwPD who experienced an improvement on
541 medication to some extent. Over the last two decades, numerous studies have focused on the effects
542 of medication (mainly L-dopa) on dysarthria in PwPD, finding only mitigated effects, ranging from no
543 effect in the early stage of PD (*e.g.*, Skodda et al., 2010) to improvement in advanced PwPD (*e.g.*, De
544 Letter, Santens, De Bodt, et al., 2007; De Letter, Santens, Estercam, et al., 2007); the question

545 remains a subject of study (Fabbri et al., 2017). Furthermore, intelligibility has been shown to have a
546 modest and limited influence on functional communication (Barnish et al., 2017). Therefore, even if
547 PwPD intelligibility is generally preserved, when combined with a mild voice impairment, PwPD can
548 experience an alteration in their ability to communicate. Speech intelligibility depends on both the
549 speaker and the listener (Kim, 2016; Lansford et al., 2016), and it is worth remembering that
550 clinicians are expert listeners who may understand patients' speech better than naive listeners (e.g.,
551 for Portuguese-speaking speakers, Carvalho et al., 2021).

552 Although clinical examinations do not always correlate with patient self-assessments (Pawlukowska
553 et al., 2018), our study found a high degree of agreement between disease severity impressions from
554 both clinicians (CGI-S) and patients (PGI-S), which strongly discriminated PwPD from controls,
555 similarly across the two Portuguese-speaking and French-speaking groups. It should be
556 acknowledged that self-assessment of speech requires patients to consider more general dimensions
557 of speech, which can be language or culturally dependent and are not assessed by the clinician
558 focusing on the assessment of speech motor control. All other PROMs (DIP, MDS-UPDRS parts 1.B
559 and 2, PDQ-39, and VHI-30) also distinguished significantly between PwPD and controls, and similarly
560 across the two languages, except for the DIP – Portuguese-speaking participants reporting
561 significantly more severe speech symptoms than French-speaking participants. This finding suggests
562 that the psychosocial impact of dysarthria could be a parameter that reports aspects of the
563 culturally-supported social network and/or language. However, it should be noted that the cognitive
564 profile of the Portuguese-speaking participants was significantly lower than that of the French-
565 speaking PwPD, which may have contributed to the difference. Also, since culture-dependent
566 aspects are not specific to dysarthria in PwPD, they could also underlie a cultural difference in dealing
567 with presbyphonia (Kosztyła-Hojna et al., 2023). However, this culturally relevant factor remains
568 speculative at this stage as it was not tested in the current study.

569 ***Are there any language specificities in acoustic markers in dysarthria in PwPD?***

570 Identifying language-specific variables that were more affected in PwPD in one language than the
571 other was less conclusive with the speech tasks and acoustic variables studied here. In this sense, our
572 findings contribute to the debate raised by previous work on assessing specific impacts on speech
573 impairment according to the patient's spoken language. For instance, unique and specific measures
574 affected by dysarthria depending on the language have been reported in Swedish and Australian
575 English-speaking patients with multiple sclerosis (Hartelius et al., 2003). The recent comparison
576 between American English-speaking and Korean-speaking PwPD demonstrated that different
577 variables involved intelligibility impairment depending on the language (Kim & Choi, 2017). We found
578 that some acoustic variables were language-specific and more affected in one language than the
579 other, depending on the patient's gender and medication state. The French vs. Portuguese speaker
580 comparison (**Table 4**) showed that for men PwPD *on* medication, the mean HNR was specifically
581 discriminative.

582 In contrast, the oral DDK speech proportion was specific for women PwPD *off* medication. This can be
583 cross-checked with the patient vs. control comparison (**Table 5**), which demonstrates that for French-
584 speaking men, some voice quality variables were discriminative either *on* medication (the mean F0
585 and, as seen for the other comparison, the mean HNR of the vowel /a/) or *off* medication (the F0_SD
586 of the reading task). This could be related to the fact that language-specific acoustic variables
587 distinguishing speakers of the two languages were mainly related to phonation and voice quality.

588 Additionally, for French-speaking women (*off* and *on* medication) and Portuguese-speaking men and
589 women, significant variables were mainly temporal/rhythmic, calculated from the oral DDK and the
590 reading task duration, and connected to pneumo-phonetic coordination. However, interpretative
591 speculation would be hazardous here since the accuracy of the classificatory analyses was borderline.

592 These findings also raise questions regarding the potential need for language-specific tasks for
593 speech assessment and therapy. So far, language-universal findings have been identified as
594 important for assessing and managing dysarthria in PwPD by speech and language

595 pathologists/therapists (SLP/T) unfamiliar with the language spoken by the patient. A study involving
596 Arabic-speaking patients showed no difference between the assessments made by Arabic-speaking
597 and (non-Arabic) Swedish-speaking SLP/T in the domains of respiration, phonation, articulation,
598 listener comprehension, and severity of dysarthria; a significant difference was found between
599 assessments in the “oromotor and velopharyngeal function” domain (Näsström & Schalling, 2020).
600 This result suggests that an assessment performed by an SLP/T speaking a language different than
601 the patient’s is possible to some extent. On the contrary, the ability to identify cultural aspects by
602 native SLP/Ts versus professionals who do not speak the language might contribute to fine-tune the
603 treatment of the patient. This can be considered within the framework provided by Levy and Moya-
604 Galé (2023), who propose a “hybrid approach” when it comes to cross-language treatment: while
605 some treatment targets such as vocal loudness may be language-universal and appropriate to use
606 regardless of the language spoken, it is also crucial to identify which aspects of speech intelligibility
607 are particularly affected in a given language to maximize treatment benefits (Levy & Moya-Galé,
608 2023).

609 ***The FraLusoPark project: strengths and weaknesses***

610 Dysarthria is often described as a late symptom that affects speech intelligibility and worsens with
611 disease progression (Müller et al., 2001). However, the early stages of dysarthria do not necessarily
612 refer to speech intelligibility alteration. In recent years, some studies have reported that dysarthria
613 is, in fact, a precocious symptom (Moreau et al., 2016) for which specific voice/speech dimensions
614 could be identified even in the prodromic phase of PD (Harel et al., 2004; Postuma et al., 2012). Our
615 results agree with an early emergence since we estimated that approximately 30% of our PwPD
616 experienced some voice/speech impairment at the time of the diagnosis (**Figure 1.A**). Along the same
617 lines, previous studies showed that even if a large majority of PwPD (more than 80%) report
618 increasing speech impairments with disease progression (Miller et al., 2010; Schalling et al., 2017),
619 PwPD do not systematically undergo speech/language therapy, as shown to some extent in our study

620 **(Figure 1.B)**. Fortunately, participation in speech/language therapy has increased in recent years; it
621 has been reported that up to 45% of PwPD have undergone speech therapy (Schalling et al., 2017).
622 On this point, recent literature reviews recall that while medication and neurostimulation have
623 mitigated effects on speech impairment (Brabenec et al., 2017), speech/language therapy can
624 significantly and consistently improve speech in PwPD (Atkinson-Clement et al., 2015).

625 In clinical trials, orofacial motor functions are typically assessed through qualitative judgments on
626 some items of the MDS-UPDRS or, more specifically, by a speech and language pathologist, *e.g.*,
627 using the FDA-2. We observed differing results from these scales in our study between the
628 Portuguese-speaking and the French-speaking control groups in clinical examinations (MDS-UPDRS,
629 MoCA, FDA-2). We question whether these differences may have resulted from the inappropriate
630 definition of inclusion criteria for the group, low sample size, or different levels of strictness of the
631 clinicians who performed evaluations, possibly leading to inter-rater variability. For the record and
632 future experiments, an approach using audio-video recordings of clinical assessments would allow
633 clinicians to conduct joint consortium scoring. Despite these limitations connected to its multicenter
634 design, our large cohort study protocol (Pinto et al., 2016) made it possible to develop (Cardoso et
635 al., 2017, 2018; Guimaraes et al., 2017) or use (Ghio et al., 2020) speech/voice evaluation tools
636 whose adaptation and validation were lacking in French and Portuguese, as well as providing insights
637 on medication modulation on prosodic features (Cavazzini et al., 2018; Frota et al., 2021).

638 To conclude, the acoustic variables related to pneumo-phonetic coordination and articulation rate
639 were the most relevant for discriminating between PwPD and controls. Maximum phonation time
640 and oral diadochokinesis tasks appear to be the most appropriate for detecting signs of dysarthria
641 that are largely homogeneous and language-universal. This result is quite in line with the automated
642 approach's objective to detect universal discriminatory variables in PwPD, regardless of the language
643 spoken (Rusz et al., 2021). Nevertheless, linguistic idiosyncrasies have also been found in the speech
644 of PwPD (García et al., 2023), suggesting that more refined tasks and protocols, as well as more

645 specific complementary analyses are needed to further our knowledge in this domain. Beyond the
646 implications of tuning dysarthria assessments to differences across languages, comparisons across
647 languages also have implications for SLP/T interventions. The identification of linguistic and/or
648 oromotor domains that are differentially affected depending on the language is critical to fine-tune
649 SLP/Ts management of target interventions to mitigate speech and language difficulties in PwPD
650 (Levy & Moya-Galé, 2023).

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667 **Data availability statement**

668 The datasets analyzed during the current study are available from the corresponding author upon
669 reasonable request. However, they cannot be released before the publication of subsequent
670 analyses conducted in the framework of the FraLusoPark project.

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1008

1009 **Figure caption**

1010 **Figure 1.** Relationships between disease duration and (A) self-perception of voice symptoms by the
1011 patients, and (B) their participation in speech/language therapy.

1012 Disease duration is reported in years on the x-axis. Logistic regressions were performed, based on
1013 yes/no answers from the PwPD during the anamnesis interview. At the disease onset (*i.e.*, disease
1014 duration = 0), significant correlations were reported between disease duration and self-reported voice
1015 symptoms: 29.5% of French-speaking PwPD ($p=0.005$) and 34.8% of Portuguese-speaking PwPD
1016 ($p=0.008$) reported a voice impairment (**A**). No relation ($p=ns$, non significant) between disease
1017 duration and participation in speech/language therapy was found (**B**).

Table 1. Functional PD signs related to the alteration of acoustic parameters calculated from the non-speech movement and speech tasks.

Non-speech and speech tasks	Calculated Parameters	Related (dys)functions
Sustained vowel /a/ production	1. Maximal Phonation Time (MPT), in seconds	<i>Pneumophonic discoordination</i>
<i>PRAAT script: get measurements.praat → original script created by Christan Kroos, Rikke Bundgaard-Nielsen, Michael Tyler. Modified by Mark Antoniou adapted by Jasmin Sadat. http://web.mit.edu/zqi/www/uploads/1/4/8/9/14891652/get_measurements.praat</i>		
Three-second sustenance of vowel /a/	2. Mean fundamental frequency (F0), in Hz 3. Jitter (cycle to cycle F0 variation), in % 4. Shimmer (cycle to cycle SPL variation), in dB 5. Harmonics-to-noise ratio (HNR), in %	<i>Dysphonia</i> <i>Roughness</i> <i>Breathiness</i> <i>Hoarseness</i>
<i>PRAAT script: get measurements.praat → original script created by Christan Kroos, Rikke Bundgaard-Nielsen, Michael Tyler modified by Mark Antoniou adapted by Jasmin Sadat. http://web.mit.edu/zqi/www/uploads/1/4/8/9/14891652/get_measurements.praat</i>		
Oral diadochokinesis (DDK)	6. Speech proportion (= speech duration/total duration of the session) 7. Articulatory rate (= syllable number/speech duration, in syllables/second) 8. Oral DDK performance Index (DDKi = speech proportion/number of breath groups) 9. Variation of inter-vowel intervals (VIVI = inter-vowel duration SD/inter-vowel duration mean)	<i>Pneumophonic discoordination</i> <i>Dysrhythmia</i> <i>Pneumophonic discoordination</i> <i>Dysrhythmia</i>
<i>Praat Script (Syllable Nuclei): Copyright (C) 2008, Nivja de Jong and Ton Wempe. https://sites.google.com/site/speechrate/Home/praat-script-syllable-nuclei-v2</i>		
Text read aloud	10. Speech duration, in seconds 11. Mean fundamental frequency (F0), in Hz 12. F0 standard deviation (F0_SD), in Hz 13. Relative sound pressure level (SPL), in dB 14. Relative SPL standard deviation (SPL_SD), in dB	<i>Bradylalia</i> <i>Pitch alteration</i> <i>Monopitch</i> <i>Hypophonia</i> <i>Monoloudness</i>
<i>Praat Script (Syllable Nuclei): Copyright (C) 2008, Nivja de Jong and Ton Wempe. https://sites.google.com/site/speechrate/Home/praat-script-syllable-nuclei-v2</i>		
<i>Praat Script (ProsodyPro) : Xu, Y. (2005-2010). ProsodyPro.praat. Available from: http://crdo.fr/crdo000723</i>		

MPT was performed twice, the longest duration was selected from the two trials for analyses. The three-second sustenance of vowel /a/ was performed three times, and voice parameters were calculated by averaging across the three trials of the vowel for each participant. The oral DDK task and the conversation were performed once.

Table 2. Description of the study cohort.

	French participants		Portuguese participants		Statistical comparisons by factor		
	HC	PD	HC	PD	Disease	Language	Interaction
<i>Screened</i>	N = 68	N = 64	N = 74	N = 84			
Retained for analyses	N = 60	N = 57	N = 64	N = 75			
A. Demographics and medication							
Age ± SD (years)	66.2 ± 7.2	69.1 ± 8.1	64.5 ± 11.4	65.9 ± 10.3	ns	*	ns
Men/Women	28/32	40/17	30/34	37/38	ns	ns	ns
Disease duration ± SD (years)	-	6.3 ± 5.1	-	7.1 ± 5.4	-	ns	-
LED ± SD (mg)	-	283.3 ± 139.5	-	273.1 ± 145.9	-	ns	-
B. Clinical assessments							
CGI-S	1.1 ± 0.3	3.3 ± 1.3	1.1 ± 0.4	2.5 ± 1.1	***	ns	ns
FDA-2							
<i>off</i> medication	100.8 ± 3.3	86.4 ± 11.1	95 ± 5	87.5 ± 7.8	***	*	***
<i>on</i> medication		89.4 ± 10.1		91.3 ± 6.5	***	*	***
Intelligibility (<i>off</i>)	11.9 ± 0.3	10.9 ± 1.3	11.9 ± 0.5	11 ± 1.4	***	ns	ns
Intelligibility (<i>on</i>)		10.8 ± 1.7		11.5 ± 0.9	***	*	**
MDS-UPDRS							
Part 1.A	1.1 ± 1.1	2.1 ± 1.7	2.3 ± 2.3	3.4 ± 2.9	***	***	ns
Part 3 – <i>off</i> medication	1.2 ± 1.9	25.6 ± 14.2	11.6 ± 7.5	40.4 ± 15.9	***	***	ns
Part 3 – <i>on</i> medication		12.2 ± 9.1		31.5 ± 13.7	***	***	***
Part 4	-	3.1 ± 3.5	-	4.1 ± 3.9	-	ns	-
MoCA	26.7 ± 1.9	25.3 ± 2.9	24.9 ± 3.2	23.6 ± 3.3	***	***	ns
C. Patient-reported self-evaluations							
PGI-S	1 ± 0	2.6 ± 1.4	1.1 ± 0.3	2.2 ± 1.2	***	ns	ns
DIP	192.8 ± 21.7	179 ± 27.3	181 ± 21.9	176.3 ± 22.4	**	*	ns
MDS-UPDRS							
Part 1.B	3.5 ± 2.9	9.5 ± 4.1	4.1 ± 3.1	8.2 ± 4.6	***	ns	*
Part 2	0.7 ± 1.4	11.5 ± 6.2	1.2 ± 2.6	12.4 ± 8.6	***	ns	ns
PDQ-39	11.9 ± 11.3	38.6 ± 20.6	14.2 ± 14.1	42.4 ± 24.3	***	ns	ns
VHI-30	3.2 ± 4.8	22.7 ± 22.9	4.3 ± 7.4	19.8 ± 19.3	***	ns	ns

ANOVAs main effects: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$. CGI-S, clinical global impression of dysarthria severity (note: missing data for 47 French controls and 20 French patients); DIP, Dysarthria Impact Profile; FDA-2, Frenchay Dysarthria Assessment, version 2; HC, healthy controls; LED, levodopa-equivalent dose; MDS-UPDRS, Movement Disorders Society-Unified Parkinson's Disease Rating Scale; MoCA, Montreal Cognitive Assessment; *off*, without medication (at last 12 hours of medication withdrawal); *on*, with medication (at least 45 minutes following usual morning dose medication intake); PD: Parkinson's disease; PDQ-39, 39-Item Parkinson's Disease Questionnaire; PGI-S, patient global impression of dysarthria severity; SD: standard deviation; VHI-30, 30-Item Voice Handicap Index.

Table 3. Acoustic data of non-speech and speech tasks in healthy controls (A) and patients with Parkinson’s disease (B).

A. Healthy controls	Men		Women	
	French	Portuguese	French	Portuguese
MPT	21.81 ± 7.56	24.19 ± 8.85	15.04 ± 5.01	15.85 ± 7.54
/a/ - Mean F0	104.67 ± 15.14	123.85 ± 27.66	172.01 ± 27.34	211.49 ± 48.79
/a/ - Mean HNR	20.59 ± 5.33	20.59 ± 4.82	24.65 ± 3.47	23.62 ± 5.20
/a/ - Jitter	0.39 ± 0.24	0.51 ± 0.43	0.28 ± 0.14	0.43 ± 0.35
/a/ - Shimmer	2.67 ± 1.69	4.80 ± 2.85	1.33 ± 0.59	2.96 ± 1.48
DDK - Art. rate	5.88 ± 0.84	5.89 ± 0.85	5.29 ± 0.85	5.32 ± 0.72
DDK - Speech prop.	0.95 ± 0.02	0.95 ± 0.03	0.93 ± 0.03	0.94 ± 0.04
DDK - Index	0.14 ± 0.06	0.28 ± 0.26	0.12 ± 0.05	0.16 ± 0.07
DDK - VIVI	27.56 ± 7.52	25.60 ± 7.01	29.14 ± 8.20	24.24 ± 5.75
Text - Duration	39.93 ± 5.30	39.07 ± 4.06	39.29 ± 5.49	44.16 ± 8.73
Text - Mean F0	123.14 ± 18.81	125.39 ± 21.53	194.05 ± 23.23	190.83 ± 25.02
Text - F0_SD	24.31 ± 6.65	37.18 ± 18.44	37.74 ± 9.67	37.61 ± 9.26
Text - Rel. SPL	70.75 ± 6.99	66.11 ± 3.24	70.23 ± 6.13	66.81 ± 2.94
Text - Rel. SPL_SD	15.19 ± 1.65	10.81 ± 1.77	15.39 ± 1.29	11.51 ± 2.10

B. PD patients	Men				Women			
	French		Portuguese		French		Portuguese	
	off	on	off	on	off	on	off	on
MPT	14.51 ± 5.75	16.09 ± 6.37	16.26 ± 6.69	16.79 ± 6.76	11.51 ± 6.27	10.79 ± 4.78	15.83 ± 10.23	16.48 ± 9.03
/a/ - Mean F0	118.43 ± 27.56	122.94 ± 25.71	129.91 ± 25.38	133.55 ± 23.49	164.94 ± 24.17	179.69 ± 20.65	194.85 ± 44.14	199.29 ± 41.85
/a/ - Mean HNR	20.14 ± 6.47	21.88 ± 2.67	19.59 ± 5.69	20.42 ± 5.95	24.39 ± 2.89	24.98 ± 3.18	22.88 ± 4.55	23.65 ± 5.08
/a/ - Jitter	0.49 ± 0.29	0.38 ± 0.20	0.67 ± 0.63	0.64 ± 0.75	0.30 ± 0.14	0.33 ± 0.24	0.42 ± 0.35	0.41 ± 0.22
/a/ - Shimmer	2.26 ± 0.85	2.23 ± 1.24	4.69 ± 3.40	4.71 ± 3.14	1.36 ± 0.50	1.52 ± 0.89	2.81 ± 1.87	2.92 ± 2.00
DDK - Art. rate	5.49 ± 0.71	5.41 ± 0.87	5.44 ± 0.82	5.54 ± 0.81	5.47 ± 0.60	5.54 ± 0.66	5.47 ± 1.15	5.39 ± 0.81
DDK - Speech prop.	0.91 ± 0.04	0.89 ± 0.07	0.90 ± 0.08	0.91 ± 0.05	0.86 ± 0.10	0.90 ± 0.06	0.92 ± 0.06	0.93 ± 0.05
DDK - Index	0.10 ± 0.05	0.09 ± 0.05	0.13 ± 0.06	0.15 ± 0.07	0.07 ± 0.04	0.09 ± 0.07	0.19 ± 0.16	0.16 ± 0.07

DDK - VIVI	26.73 ± 7.15	29.34 ± 11.28	23.27 ± 6.23	24.90 ± 5.65	28.56 ± 9.29	27.03 ± 6.96	23.74 ± 6.04	24.76 ± 6.31
Text - Duration	40.57 ± 6.09	39.41 ± 5.47	45.45 ± 15.40	45.72 ± 14.89	42.51 ± 5.65	41.15 ± 11.69	44.01 ± 11.01	43.52 ± 9.61
Text - Mean F0	122.27 ± 22.91	133.84 ± 34.56	127.62 ± 22.59	129.40 ± 21.03	188.11 ± 20.68	178.15 ± 28.13	180.00 ± 26.43	184.91 ± 23.90
Text - F0_SD	19.45 ± 5.19	21.43 ± 6.27	32.65 ± 13.16	34.77 ± 13.23	31.71 ± 7.95	30.21 ± 10.35	36.64 ± 11.08	32.18 ± 9.02
Text - Rel. SPL	70.36 ± 6.31	71.79 ± 5.77	64.75 ± 3.37	65.16 ± 3.78	68.88 ± 7.63	68.58 ± 7.61	65.91 ± 4.04	66.07 ± 3.23
Text - Rel. SPL_SD	16.03 ± 1.89	1.04 ± 2.08	11.86 ± 1.76	11.70 ± 2.26	15.66 ± 1.04	15.98 ± 1.59	11.58 ± 2.01	11.78 ± 1.89

Non-speech movement tasks included: (i) the sustained vowel /a/ production, which allowed the calculation of the maximum phonation time (MPT, in seconds); (ii) the 3-seconds sustenance of the vowel /a/, which allowed the calculation of the mean fundamental frequency (F0, in hertz - Hz), jitter (%), shimmer (in decibels - dB), and the harmonics-to-noise ratio (HNR, in %); and (iii) an oral diadochokinesis (DDK), which provided the calculation of the speech proportion, the articulatory rate (in syllables/second), the oral DDK performance index, and the variation of inter-vowel intervals (VIVI). The connected speech task involved: (iv) reading aloud of short text, which allowed the calculation of the speech (text) duration, the mean F0 (Hz), the mean F0 standard deviation (F0_SD, Hz), the relative sound pressure level (rel. SPL, dB) and the relative SPL standard deviation (rel. SPL_SD, dB). *off*, without medication (at last 12 hours of medication withdrawal); *on*, with medication (at least 45 minutes following usual morning dose medication intake).

Table 4. Contribution of acoustic parameters for distinguishing French and Portuguese individuals.

	Men			Women		
	HC	PD <i>off</i>	PD <i>on</i>	HC	PD <i>off</i>	PD <i>on</i>
MPT	-0.94%	-4.59%	3.24%	-3.82%	5.98%	10.88%
/a/ - Mean F0	19.78% *	10.19% *	9.55%	33.91% **	22.06% **	20.59% *
/a/ - Mean HNR	0.71%	3.38%	17.27% *	5.41%	4.93%	6.42%
/a/ - Jitter	7.18%	6.89%	6.56%	8.26%	4.46%	9.99%
/a/ - Shimmer	22.62% *	34.64% ***	32.53% ***	46.95% ***	35.35% ***	23.23% **
DDK - Articulatory rate	-5.44%	-2.68%	-2.47%	2.34%	-1.44%	-2.73%
DDK - Speech proportion	1.45%	-3.85%	-2.79%	5.51%	16.78% *	11.86%
DDK - Index	13.66%	13.02% *	26.64% **	15.28% *	27.64% **	27.29% ***
DDK - VIVI	-4.24%	7.09%	2.37%	10.51%	10.18%	-3.66%
Text - Duration	-6.06%	-0.25%	7.25%	17.60% *	0.91%	0.18%
Text - Mean F0	-0.95%	0.38%	3.35%	-4.29%	11.34%	3.54%
Text - F0_SD	29.89% **	48.15% ***	46.53% ***	-2.56%	0.03%	-0.27%
Text - Relative SPL	44.67% ***	42.03% ***	37.74% **	33.85% ***	12.48% *	25.47% **
Text - Relative SPL_SD	63.33% ***	68.26% ***	63.09% ***	66.14% ***	52.46% ***	50.89% ***
French accuracy (p-value)	92.9% (<i><0.00001</i>)	95.0% (<i><0.00001</i>)	92.5% (<i><0.00001</i>)	93.8% (<i><0.00001</i>)	100% (<i><0.00001</i>)	94.1% (<i><0.00001</i>)
Portuguese accuracy (p-value)	96.7% (<i><0.00001</i>)	86.5% (<i><0.00001</i>)	89.2% (<i><0.00001</i>)	100% (<i><0.00001</i>)	92.1% (<i><0.00001</i>)	92.1% (<i><0.00001</i>)
General accuracy (p-value)	94.8% (<i><0.00001</i>)	90.9% (<i><0.00001</i>)	90.9% (<i><0.00001</i>)	97.0% (<i><0.00001</i>)	94.5% (<i><0.00001</i>)	92.7% (<i><0.00001</i>)

Data are expressed as mean decrease accuracy (in %) for each acoustic variable, and according to participant sex (men, women) and population state (controls, PD patients *off* medication, PD patients *on* medication). The French and Portuguese accuracy refers to the capacity of the random forest models to identify respectively a French participant as an actual French person, and a Portuguese participant as an actual Portuguese individual. The general accuracy refers to the same capacity for the whole group of participants (*i.e.*, French and Portuguese participants). Data can be interpreted in the following manner: the higher the percentage, the more important is the variable in the random forest models that aim at discriminating French and Portuguese individuals. For example, for men controls, the mean decrease accuracy of the vowel

/a/ mean F0 is 19.78%, which means that if the vowel /a/ mean F0 was removed from the set of variables analyzed here, the accuracy of discriminating French and Portuguese participants would decrease by 19.78%; demonstrating – and confirmed by the p-value of the comparison – that this acoustic variable is of importance for such discrimination. Significant mean decrease accuracy are highlighted in grey and as follows: *: $0.01 < p < 0.05$; **: $0.001 < p < 0.01$; ***: $p < 0.001$.

Table 5. Contribution of acoustic parameters for distinguishing PD patients and controls.

	French				Portuguese			
	Men		Women		Men		Women	
	<i>off</i>	<i>on</i>	<i>off</i>	<i>on</i>	<i>off</i>	<i>on</i>	<i>off</i>	<i>on</i>
MPT	43.79% ***	34.42% ***	13.16%	18.02% *	33.84% **	28.44% **	0.11%	1.94%
/a/ - Mean F0	10.62%	24.91% **	1.66%	-0.43%	-2.04%	6.33%	-0.37%	-2.27%
/a/ - Mean HNR	4.90%	15.83% *	-8.35%	-11.70%	-1.83%	-2.96%	6.66%	-5.34%
/a/ - Jitter	23.46% **	-2.16%	-7.20%	-9.37%	4.73%	16.19% *	-5.58%	-2.25%
/a/ - Shimmer	12.19%	-1.53%	-7.20%	-9.09%	-5.20%	-4.35%	7.83%	-1.26%
DDK - Articulatory rate	3.85%	1.78%	-3.70%	-4.34%	3.36%	-5.32%	18.94% *	4.15%
DDK - Speech proportion	26.50% **	29.87% **	21.35% *	10.57%	28.87% **	17.74% *	20.32% *	7.98%
DDK - Index	6.92%	8.06%	20.92% *	21.80% *	31.62% **	12.96%	2.87%	-1.88%
DDK - VIVI	-2.30%	-9.77%	0.07%	-3.51%	11.99%	2.18%	2.07%	-5.63%
Text - Duration	-8.73%	-10.99%	2.23%	-0.39%	16.92% *	13.47%	14.59% *	21.12% *
Text - Mean F0	1.08%	-3.09%	-10.86%	-9.21%	-7.69%	-7.24%	3.24%	-10.94%
Text - F0_SD	22.77% **	10.02%	4.42%	12.04%	-0.96%	1.22%	-5.87%	22.09% *
Text - Relative SPL	12.67%	0.72%	-1.33%	-5.09%	7.54%	13.12%	3.47%	2.21%
Text - Relative SPL_SD	3.78%	7.18%	2.04%	-4.12%	4.52%	6.28%	0.99%	8.37%
HC accuracy (p-value)	75.0% (0.00001)	67.9% (0.01785)	68.8% (0.01003)	71.9% (0.00350)	66.7% (0.02139)	56.7% (0.18080)	70.6% (0.00452)	61.8% (0.06072)
PD accuracy (p-value)	75.0% (0.00001)	70.0% (0.00321)	52.9% (0.31453)	41.2% (0.68547)	73.0% (0.00128)	62.2% (0.04943)	65.8% (0.01677)	57.9% (0.12794)
General accuracy (p-value)	75.0% (0.00001)	69.1% (0.00046)	63.3% (0.02219)	61.2% (0.04272)	70.1% (0.00026)	59.7% (0.04322)	68.1% (0.00065)	59.7% (0.03818)

Data are expressed as mean decrease accuracy (in %) for each acoustic variable, and according to language (French, Portuguese), participant sex (men, women) and medication state (*off*, *on* medication). The HC and PD accuracy refers to the capacity of the random forest models to identify respectively a HC as an actual HC, and a patient as an actual PD patient. The general accuracy refers to the same capacity for the whole group of participants (*i.e.*, HC and PD patients). Data can be interpreted in the following manner: the higher the percentage, the more important is the variable in the random forest models that aim at discriminating PD patients from HC. For example,

for French PD patients off medication, the mean decrease accuracy of MPT is 43.79%, which means that if MPT was removed from the set of variables analyzed here, the accuracy of discrimination PD patients from HC would decrease by 43.79%; demonstrating – and confirmed by the p-value of the comparison – that MPT is of great importance for such discrimination. Significant mean decrease accuracy are highlighted in grey and as follows: *: $0.01 < p < 0.05$; **: $0.001 < p < 0.01$; ***: $p < 0.001$.