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Towards a better characterization of Parkinsonian speech: a multidimensional acoustic study

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Abstract

This paper reports on a first attempt at adopting a new perspective in characterizing speech disorders in Parkinson's Disease (PD) based on *individual* patient profiles. Acoustic data were collected on 13 Belgian French speakers with PD, 6 male, 7 female, aged 45-81, and 50 healthy controls (HC) using the "MonPaGe" protocol (Fougeron *et al.*, LREC18). In this protocol, various kinds of linguistic material are recorded in different speech conditions, in order to assess multiple speech dimensions for each speaker. First, we compared a variety of voice and speech parameters across groups (HC vs. PD patients). Second, we examined individual profiles of PD patients. Results showed that as a group PD participants most systematically differed from HC in terms of speech tempo and rhythm. Moreover, the analysis of individual profiles revealed that other parameters, related to pneumophonatory control and linguistic prosody, were valuable to describe the speech specificities of several PD patients.

1. Introduction

Parkinson's disease (PD) is characterized by hypokinetic dysarthria, which entails a variety of speech impairments affecting the respiratory, phonatory and articulatory subsystems. Characterizing Parkinsonian speech is challenging for several reasons. First, the disease includes pervasive motor deficits (rigidity, bradykinesia, akinesia, tremor), with multiple consequences on all speech articulators (see [1] for a review of the potential relationships between the cardinal motor deficits in PD, their physiological correlates and associated phonation, articulation and prosody measures). Second, as is typical of neurodegenerative diseases, speech disorders associated with PD vary across stages of the disease, degenerate over time and may be diversely affected by treatment. Third, primary speech disorders in PD are not easy to disentangle from speech idiosynchrasies resulting from individual strategies to cope with the disease and its effects on speech motor systems.

As a result, apart from phonatory impairments which have been specified in some detail (i.e. breathy/hoarse voice, reduced loudness and restricted pitch variability, e.g. [2]), most of the recent literature has yielded either conflicting evidence or quite vague characterization of speech disorders in PD. For example, empirical data on tempo, rhythm, articulation rate and speech disfluencies lack consistency [3,4,5], so that PD is usually described as involving some "abnormalities of speech rate, and pause ratio" [6].

This paper reports on a first attempt at adopting another perspective in characterizing speech disorders in PD based on *individual* patient profiles. Our approach consists in collecting a large variety of acoustic parameters in order to: (i) characterize the speech of PD patients as a group (in comparison with healthy controls); (ii) examine the *relationships* between several acoustic indicators for given individuals or subgroups of patients. For example, one could ask whether the concept of "articulatory precision" unifies various aspects of the individual patients' productions (such as measures of organization of the vowels' system, slopes of F2 transitions, distributions of VOT in voiced vs. voiceless consonants) or whether there is a trade-off between them for a given individual, e.g. a trade-off between articulatory precision for vowel quality vs. consonant place of articulation or a trade-off between laryngeal and supra-laryngeal control.

The present paper is a first step towards this goal, in that both group tendencies and individual profiles of PD patients (i.e. between-speaker as well as within-speaker variation across tasks), are examined in a multidimensional acoustic study.

2. Material and methods

2.1. Speakers

Two groups of speakers participated in the study. The first group was composed of 13 patients diagnosed with PD. They were 6 male and 7 female speakers native of Belgian French, aged 45-81, with an average disease duration of 11 years. All PD participants had been receiving medication for several years at the time of the experiment; most of them still underwent speech therapy (see Table 1 for a summary of the characteristics of PD patients).

The second group of participants consisted in 50 healthy controls (HC), 25 female, 25 male, with no speech or language pathology by self-report. They were selected from a larger database of 405 healthy speakers [7], as the subset of 50 speakers who best matched the PD patients in terms of dialect, age and gender.

2.2. Linguistic material and speech tasks

The speech data were recorded using the "MonPaGe" protocol, which is designed for a quick although comprehensive assessment of the speech characteristics of patients presenting signs of motor speech disorders [7, 8].

In this protocol, various kinds of linguistic material are recorded in different speech conditions, in order to assess multiple speech dimensions for each speaker. The protocol consists of 8 modules and associated tasks: intelligibility: production of target words (from minimal pairs) in carrier

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sentences; articulation: repetition of pseudowords of varying phonetico-phonological complexity; prosody: production of fully voiced sentences in assertive vs. interrogative form; DDK: production of 7 oral diadochokineses of various structures; week: production of automated series of the days of the week; text: reading of a French text of 188 words; pneumophonatory control: production of sustained /a/, production of "heho" calls at 4 distinct levels of intensity; picture description task. The collected data are aimed at assessing intelligibility, articulatory precision, coarticulatory patterns, expressive and linguistic prosody, speech/articulation rate and fluency, voice quality and pneumo-phonatory control.

Table 1. *Characteristics of PD participants*

	Sex	Age	DD	OSP	H&Y	PDQ39	UPDRS
SV06	F	57	8	Y	2,5	7	22
SV14	F	69	/	N	2,5	25	22
SV04	F	72	19	Y	4	37	71
SV15	F	74	/	Y	4	57	50
SV08	F	75	/	N	2	22	23
SV13	F	79	9	Y	3	35	25
SV07	F	81	4	Y	1,5	4	9
SV10	M	45	2	N	2	22	17
SV18	M	58	16	Y	1,5	17	20
SV12	M	62	23	Y	3	12	31
SV05	M	65	12	Y	3	30	23
SV19	M	65	8	N	3	25	50
SV11	M	76	14	Y	2,5	13	19

DD: Duration of the disease (years). OSP: Ongoing Speech Therapy (Yes-No). H&Y: Score on the modified Hoehn & Yahr scale [14]. PDQ39: score on the PDQ-39 (%) [15]. UPDRS: total score on the UPDRS scale (/199) [16].

For the administration of the protocol, the computerized version of the MonPaGe was used. This application allows the prompting of the speech material/tasks in a set order, as well as the instant recordings of each production as a single audio file, indexed with the speaker's references. Speakers were seated in front of the computer and a trained experimenter administrated the protocol.

2.3. Acoustic and perceptual indicators

On the 7-8 minutes of recorded speech per speaker, a variety of acoustic measures and perceptual assessments were performed using Praat scripts adapted from the computerized version of MonPaGe. A total of 68 indicators were derived to be used as dependendent variables in statistical analyses, i.e. 60 acoustic parameters (e.g. vowel space area, maximum phonation time, mean intersyllabic interval over all DDK of CCV.CCV structure, etc.) and 8 perceptual parameters (e.g. proportion of pseudowords pronounced without phonological error, as judged by an expert; proportion of 12 judges correctly identifiying the intended modality in interrogative sentences, etc.). All these indicators are described in a table provided in the supplementary material.

3. Results

3.1. PD participants vs. Healthy controls

We first analyse the speech of PD patients as a group, in comparison with healthy controls. All the following statistical analyses were carried out using SPSS with Group (HC vs. PD) as the main between-subject factor.

3.1.1. Segmental articulation

In order to compare how efficient the production of vocalic and consonantal segments was across participants, a multivariate ANOVA was performed with Group as independent variable and three dependent variables: Phonological NoError Rate (the proportion of pseudowords produced without phonological errors – errors including distorsions, substitutions, deletions and insertions), Intelligibility Score (the number of target words out of 15 correctly identified by the experimenter in the intelligibility task) and PEW (the proportion of weeks produced with a missing or misplaced day). The MANOVA revealed that only Phonological NoError Rate was significantly lower in PD participants ($F_{1,55}$=5.15, p<.05). Between-speaker variability was larger among patients (see error bars in Fig.1, signalling here and henceforth 95% confidence intervals).

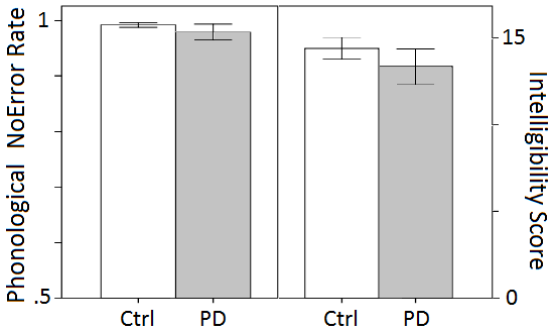

Figure 1. *Phonological NoError Rate and Intelligibility Score: Healthy controls vs. PD patients*

Concerning vowels, a repeated measures ANOVA was carried out with formant frequencies (mean values over the entire duration of 3 repetitions of each vowel embedded in C_(C) context) as dependent variables, Formant (1, 2, 3) and Vowel (i, E, a, O, u) as within-subject variables, and Group as between-subject variable. As expected, Formant and Vowel and the Formant*Vowel interaction yielded significant differences in formant frequencies, but crucially there was no effect of Group nor any significant interaction of Group with other factors. Each speaker's vowel space area (VSA, in KHz^2) was also computed as the area of the pentagon which 5 summits are the centroids of /i, E (the /e-ɛ/ archiphoneme), a, O (the /o-ɔ/ archiphoneme), u/. There was no significant difference in VSA between HC and PD participants (t_{55}=-.245, p=.89).

3.1.2. Pneumophonatory control

A multivariate ANOVA was conducted with Group as independent variable and a total of 12 dependent variables related with laryngeal function and voice quality, i.e. Maximum Phonation Time, Fundamental Frequency Mean and Standard Deviation (over 2 seconds of sustained /a/), HNR, shimmer, as well as the Acoustic Voice Quality Index (AVQI:[9]) and its 6 components (computed on speech samples made of 2 seconds of sustained /a/ + 2 fully voiced short sentences). Only HNR and the slope of the LTAS (one component of AVQI) turned out to be significantly different between HC and PD participants (HNR_aa: $F_{1,59}$=5.35, p<.05; Slope_AVQI: $F_{1,59}$=11.22, p<.05). These measures have been

found to be poorly to moderately correlated with perceived breathiness and hoarseness, respectively [10,11]. However, the absence of effect on AVQI or its CPPs component, which have proved adequately correlated with perceived grade of dysphonia [9,11], suggests that voice quality is preserved overall in our 13 PD patients.

In one of the tasks of the pneumophonatory control module, the speakers were asked to modulate the intensity of successive "ého" (ahoy) calls from the lowest to the highest in 4 distinct steps. Seven judges assessed how distinct the intensity steps were on a 3-point scale ("very well", "little" or "not at all" distinguished). Inter-rater agreement was fair (average Cohen's kappa : .38). Although the perceptual score (i.e., the mean proportion of judges responding "very well") was substantially larger for healthy controls than for PD patients, there was also large between-speaker variability in the latter group (Fig.2, right), so that eventually the group differences were not statistically significant (t_{60}=-1.36, p=.77).

3.1.3. Speech rate and fluency

Speech rate and fluency were assessed based on the intersyllabic interval (ISI, [12]). Mean ISI is close to the notion of speech rate: low ISI signals quick tempo and/or short silent pauses while high ISI is expected in slow speech. The standard deviation of ISI over an entire production gives an estimate of how much syllables undergo regular and irregular rythmic patterns (i.e. disfluencies, [13]). Mean_ISI and SD_ISI were computed over a similar sentence in the first and last paragraph of the text, as well as in the 7 DDK (CVCVCV: bababa, dedede, gogogo, badego; CCV.CCV: claclacla, tratratra, clatra).

A repeated measures ANOVA was performed with Mean_ISI as the dependent variable, Task (text vs. DDK) and Subtask (first vs. last, CV vs. CCV) as within-subject variables, and Group as the between-subject variable. There were significant effects of all main factors and all (2-way and 3-way) interactions between them on Mean_ISI. In summary, PD patients spoke at a significantly lower speech rate than healthy controls, the more so in the DDK, especially when they were of CCV.CCV structure (Fig.3, left).

Another repeated measures ANOVA was conducted, with SD_ISI as the dependent variable, Task (text vs. DDK) and Subtask (last vs. first, CV vs. CCV) as within-subject variables, and Group as the between-subject variable. The ANOVA revealed significant effects of Group and Subtask, as well as a significant interaction of Group*Task. Indeed, SD_ISI was larger for PD patients only in the DDK task (Fig.3, right). To sum up, Parkinsonian speech was slower in all (sub-)tasks, and more irregular when time pressure and motor complexity made the task more difficult.

3.1.4. Linguistic prosody

Linguistic prosody was tested by asking the speakers to pronounce two sentences ("Laurie l'a lu", "Mélanie vend du lilas") both in assertive and interrogative form. Eight judges listened to the 4 productions per speaker and judged whether the intended modality was assertive or interrogative. Inter-rater agreement was moderate overall (average Cohen's kappa: .61) and strong for interrogatives. A repeated measures ANOVA was performed with Perceptual Score (the proportion of judges correctly identifying the intended modality) as the dependent variable, Sentence (Laurie vs. Mélanie) and Modality (interrogative vs. assertive) as within-subject variables, and Group as the between-subject variable.

There were significant effects of Sentence ($F_{1,60}$=4.02, p=.05) and Modality ($F_{1,60}$=41.7, p<.001) but no effect of Group, alone or in interaction with other factors. The proportion of judges correctly identifying the intended modality was significantly smaller for interrogative than for assertive forms (Mean Perceptual Score: 54% vs. 97%) in both groups, meaning that all participants, HC and PD alike, performed quite poorly in interrogatives (Mean Perceptual Score: 70% vs. 51% respectively). However, these group tendencies may mask large interindividual differences. For example, in the case of "Mélanie vend du lilas" in its interrogative form (Fig.2, left), 7 out of 13 Parkinsonian performed at or above the mean performance of healthy controls, but the remaining 6 had a perceptual score of zero. Obviously, another perspective on the data is needed, which focusses on individual specificities of PD speakers.

3.1.5. Individual profiles

In order to examine interindividual differences among PD participants, the individual performances achieved for each acoustic and perceptual indicator were compared to those of the HC group. Specifically, PD participants' performances were categorized as "average" when they were within the range of HC mean ± 2 standard errors, and "below average" or "above average" accordingly when they fell out of that range. Table 2 summarizes the results of this analysis.

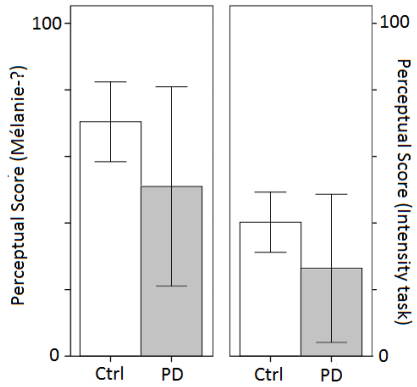

Figure 2. *Perceptual scores. Left: Mélanie-?. Right: Intensity task.*

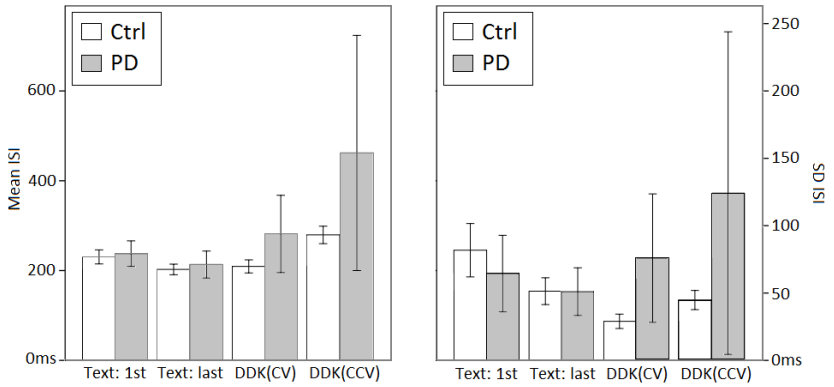

Figure 3. *ISI-related measures across tasks (text: 1st sentence; text: last sentence; DDK: CV.CV; DDK: CCV.CCV). Left: Mean_ISI. Right: SD_ISI over the entire DDK*

Table 2. *Individual performances of the 13 PD participants compared to the HC group for 25 indicators. See the text for the definition of performances as 'below average' (dark gray cells), 'average' (light gray cells) or 'above average' (white cells).*

	Healthy Controls			PD Participants												
Indicator	**-2SE**	**Mean**	**+2SE**	**SV04**	**SV05**	**SV06**	**SV07**	**SV08**	**SV10**	**SV11**	**SV12**	**SV13**	**SV14**	**SV15**	**SV18**	**SV19**
PhonNoErrorRate	.988	.992	.996	.99	.99	.97	.98	.98	1	.99	1	.99	.96	.91	.99	.96
IntelligibilityScore	13.78	14.40	15	13	11.5	11	15	11	15	11	15	14	13	15	14	15
PEW	.26	2.67	5.07	0	0	0	33.33	25	0	0	50	0	0	0	0	0
VSA	.27	.30	.33	.27	.36	.31	.33	.48	.28	.37	.2	.26	.39	.36	.13	.14
MPT	11.53	12.70	13.88	5.04	10.44	9.05	16.64	8.7	10.37	13.24	18.88	7.83	8.01	7.59	20.46	7.99
SDF0_aa	3.64	6.72	9.79	3.27	4.06	9.61	4.2	24.09	1.12	2.08	2.35	15.51	3.79	2.81	1.32	2.4
Shimmer_aa	3.68	4.47	5.25	4.26	3.74	3.97	4.75	5.12	1.27	1.16	4.07	3.9	2	5.17	2.19	5.63
HNR_aa	17.08	18.28	19.48	22.03	19.21	18.4	24.22	21.99	22.91	23.66	20.3	21.72	23.57	17.2	22.83	16.22
CPPs_AVQI	12.11	12.76	13.41	12.5	12.54	12.4	12.29	11.34	12.73	15.48	14.97	13.27	13.85	11.78	14.52	9.02
Slope_AVQI	-25.4	-23.9	-22.4	-31.9	-30.4	-27	-33.1	-23.1	-33.6	-22.8	-24.5	-3.5	-28.9	-31.9	-27.1	-32.5
Tilt_AVQI	-11.4	-11.1	-10.8	-10.2	-11.4	-10.3	-10.7	-12.4	-10.2	-10.7	-12.1	-10.8	-10.8	-10.6	-12	-9.6
AVQI	3.38	3.74	4.09	2.9	3.69	3.45	3.5	2.88	2.91	2.5	2.38	3.62	4.02	4.06	2.45	5.44
PercScore_Intensity	31.23	40.23	49.22	0	42.9	0	0	0	42.9	28.6	0	0	28.6	0	100	100
MeanISI_TxtLast	.19	.20	.21	.27	.16	.21	.22	.32	.2	.19	.14	.22	.2	.21	.22	.24
MeanISI_Txt1st	.22	.23	.25	.26	.16	.23	.27	.29	.27	.22	.16	.24	.3	.22	.2	.23
MnISI_DDK(CCV)	.26	.28	.30	.27	.46	.26	.25	.5	.39	.4	.18	.4	.35	1.74	.25	.35
MnISI_DDK(CV)	.19	.21	.22	.24	.31	.2	.18	.49	.23	.26	.14	.26	.21	.61		.23
SDISI_TxtLast	.04	.05	.06	.04	.04	.06	.05	.14	.05	.03	.04	.05	.03	.04	.07	.06
SDISI_Txt1st	.06	.08	.10	.05	.03	.07	.08	.08	.17	.03	.03	.04	.13	.04	.04	.03
SDISI_DDK(CCV)	.04	.04	.05	.06	.14	.05	.03	.05	.07	.12	.08	.04	.09	.71	.03	.05
SDISI_DDK(CV)	.02	.03	.03	.05	.1	.05	.02	.07	.04	.09	.05	.05	.03	.3		.07
PercScore(Lau_As)	97.75	98.98	100	100	100	100	100	100	100	100	100	100	100	100	12.5	100
PercScore(Lau_Int)	38.46	51.79	65.11	0	0	0	0	0	100	100	25	75	0	100	87.5	100
PercScore(Mel_As)	95.44	97.70	99.97	100	100	100	100	100	100	100	62.5	100	100	100	100	100
PercScore(Mel_Int)	58.48	70.41	82.34	0	100	0	0	0	0	100	75	100	0	100	87.5	100

Table 2 illustrates the fact that performances are heterogeneous among PD participants. Some of them perform poorly on a large number of indicators (e.g. SV04, SV08, SV19), while others typically perform quite well compared to the HC group (SV11, SV12, SV18), with no straightforward link to age or stage of the disease (Table 1). As a matter of fact, for the majority of PD participants the level of performances vary widely across the various indicators. A further step in the analysis, out of the scope of the present paper, will consist of examining the relationships between (groups of) acoustic indicators for given individuals. For example, SV10 exhibits very good performances for the articulation-related parameters (Phonological NoError Rate, Intelligibility Score, etc.), but performs systematically poorly on the indicators associated with speech rate and fluency. One could hypothesize that this PD patient preserves phonetic precision at the expense of speech tempo and rythm.

Finally, the analysis presented in Table 2 sheds light on the potential of a couple of indicators for future research. For example, Maximum Phonation Time and the perceptual score in the Intensity task yielded no statistically significant differences between HC and PD participants. It appears from Table 2 that a large majority of PD patients actually performed poorly on these indicators, but that this was hindered by the exceedingly good performances of a small minority.

4. Discussion and conclusion

In summary, the group analysis revealed some meaningful differences between PD and HC participants, mainly in terms of speech tempo and speech rythm. However, a large number of indicators did not prove statistically different, e.g. those associated with voice quality and the linguistic use of prosody. There might be a number of explanations: (i) some patients may exhibit only mild dysarthria at this stage (although dysarthria can appear at any stage of PD, it usually worsens as the disease progresses); (ii) some indicators may need further refinement (e.g. for articulatory precision in vowels, VSA data might be complemented with other measures related with the internal organization of vowel systems; indicators for coarticulatory patterns are currently under development, etc.); (iii) some speech disorders in PD might be better highlighted in spontaneous speech (here, the picture description task). Etc.

In any event, large interindividual variation was consistently observed among PD participants in the present study. Larger confidence intervals (Fig.2, Fig.3) may be due to the difference in group size, or to more intrinsic variation among patients, or both. Hence, we proposed here a first step towards adopting a novel approach focussed on speaker-specific deficits of individuals with PD. The analysis of individual profiles (Table 2) revealed that a couple of non statistically significant parameters related to pneumophonatory control and linguistic prosody were in fact valuable to describe the speech characteristics of several PD participants. Obviously, further work is needed in order to complete such an approach. Our current work involves full-scale analysis of the relationships between (groups of) speech indicators among individuals with PD, in relation with the patients' clinical profile (stage of the disease, consequences on daily life, specifics of past speech therapy, current medication and medication history, etc.).

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