Acoustic and Perceptual Correlates of Vowel Articulation in Parkinson's Disease With and Without Mild Cognitive Impairment: A Pilot Study

Michaela Strinzel[1(✉)], Vasilisa Verkhodanova[2], Fedor Jalvingh[3,4], Roel Jonkers[4], and Matt Coler[2]

[1] European Master in Clinical Linguistics, University of Groningen, Groningen, The Netherlands
michaela_strinzel@yahoo.de
[2] University of Groningen, Campus Fryslân, Leeuwarden, The Netherlands
v.verkhodanova@rug.nl, m.coler@rug.nl
[3] Geriatric Clinic Vechta, St. Marienhospital - Vechta, Vechta, Germany
f.c.jalvingh@rug.nl
[4] Center for Language and Cognition, University of Groningen, Groningen, The Netherlands
r.jonkers@rug.nl

Abstract. This pilot study investigates the added acoustic and perceptual effect of cognitive impairment on vowel articulation precision in individuals with Parkinson's Disease (PD). We compared PD patients with and without Mild Cognitive Impairments (MCI) to elderly healthy controls on various acoustic measurements of the first and second formants of the vowels /i, u, a:, ɪ, ʊ, a/, extracted from spontaneous speech recordings. In addition, 15 naïve listeners performed intelligibility ratings on segments of the spontaneous speech. Results show a centralization of vowel formant frequencies, an increased formant frequency variability and reduced intelligibility in individuals with PD compared to controls. Acoustic and perceptual effects of cognitive impairments on vowel articulation precision were only found for the male speakers.

Keywords: Parkinson's Disease · Hypokinetic dysarthria · Mild cognitive impairments · Vowel articulation · Acoustic analysis · Speech intelligibility

1 Introduction

Parkinson's Disease (PD) is a complex neurodegenerative disease that is characterized by motor impairments [1,5]. However, a growing body of research shows that non-motor symptoms are common and clinically significant features in PD as well. These non-motor symptoms include first and foremost Mild Cognitive Impairment (MCI) and dementia. Cognitive impairments are prevalent in

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approximately 30% of the individuals with PD [1,12] and have been found to significantly contribute to disability and reduced quality of life in PD patients. The pattern of cognitive deteriorations in PD is heterogeneous but typically comprises memory-based impairments, executive dysfunctions, visual-spatial impairments and attentional deficits [10]. Although there is evidence indicating a positive correlation between motor and cognitive symptoms [11], to the best of our knowledge no study has yet investigated which effect (if any) cognitive impairments have on speech motor disorders in PD.

Up to 90% of the individuals with PD manifest the speech motor disorder referred to as hypokinetic dysarthria. Apart from respiratory, phonatory and prosodic abnormalities a common feature of dysarthria in PD is imprecise vowel articulation. Individuals with PD are limited in the execution of articulatory movements. Accordingly, voluntary motions of lips, jaw and tongue tend to be smaller and slower than that of healthy controls [3]. A typical consequence is articulatory "undershooting" [3], i.e. the reduced ability to achieve a certain vowel target. As a result, vowels are produced more centralized and become less distinct from each other. This contributes to reduced speech intelligibility [8]. A common method to represent this phenomenon is with the vowel space area (VSA) based on F1/F2 values of the corner vowels. However, findings on the VSA have been inconsistent. While the VSA separated dysarthric from non-pathological speech in some studies [7], it yielded no significant differences in other studies [17,20]. Ratio based vowel measurements such as the F2 ratio of the vowels /i/ and /u/ or the vowel articulation index (VAI) [14,16] have been found to be more sensitive towards speech impairments and less sensitive towards interspeaker variability than the VSA [16,18]. Apart from vowel space metrics, measurements of formant frequency overlap and a speaker's relative stability of reaching a vowel target seem to account for speech intelligibility as well [8].

Speech motor control requires more attention in individuals with PD than in healthy individuals and it is more likely to deteriorate as the complexity of a verbal task increases [4,19]. Consequently, the characteristics of dysarthria differ depending on the type of verbal task that is performed [13,15]. In particular spontaneous speech shows significantly different phonetic features compared to non-spontaneous speech in individuals with PD [6]. Presumably due to the attention devoted to cognitive and linguistic processing, the control of articulatory movements decreases during spontaneous speech. A recent study by Rusz et al. [15] suggests that spontaneous speech is preferable to other speech tasks in detecting imprecise vowel articulation in Czech speakers with PD. Since acoustic studies on articulatory performance of PD during spontaneous speech are scarce we aimed to replicate Rusz et al.'s findings for German speakers. In addition, we were interested in whether cognitive impairments would influence vowel articulation precision in PD. One of the features of cognitive impairments in PD is a reduced attention capacity. We therefore hypothesize that the control of articulatory precision during spontaneous speech is more compromised in individuals with PD and additional cognitive impairments than in individuals with PD only. We expect this pattern to be reflected by acoustic vowel measurements.

This study addresses three research questions: (1) Are the results from Rusz. et al. replicable for German, i.e. is spontaneous speech sensitive enough to acoustically detect vowel articulation imprecision in PD? (2) Which acoustic measurement is the most efficient in separating dysarthric from non-pathological speech? (3) Does MCI in PD have an additional acoustic and/or auditory perceivable effect on vowel articulation precision in spontaneous speech?

2 Methods

2.1 Participants

A total of 23 German native speakers participated in this study. The participants were split into three groups. The first group included 8 individuals who were clinically diagnosed with idiopathic PD (hereafter PD group). None of these individuals exhibited cognitive impairments as assessed with the Minimal Mental State Examination (MMSE). The second group was comprised of 6 individuals clinically diagnosed with idiopathic PD and MCI (hereafter MCI group). The third group was made up of 9 elderly healthy controls (hereafter HC group) without a history of neurological disorders. Table 1 summarizes the demographic data of each group.

All participants gave their written informed consent to the speech task and the recording procedure.

Table 1. Summary of group demographics. Age and duration of disease are given in years

		PD	MCI	HC
Male: Female		5:3	4:2	5:4
Age	M	76	81.8	74
	SD	6	2.5	5.9
Duration of disease	M	12	5.7	-
	SD	4.1	2.4	-
MMSE	M	29	24.5	29.8
	SD	1	1.9	0.4

2.2 Speech Task and Recording Procedure

Participant monologues were audio-recorded during a conversational interview with open-ended questions on a familiar topic such as hobbies, daily routines, family or prior jobs. Recordings were made with a Zoom H2 Recorder with 16-bit quantization and a sampling frequency of 44.1 kHz. The recordings were administered in an identical manner for each participant.

2.3 Annotation

For each monologue the occurrence of the three corner vowels /a:, i, u/ and their respectively short or lax counterparts /a, ɪ, ʊ/ was manually segmented and annotated based on visual observation of the waveform and the wideband spectrogram in Praat [2]. All annotation work was done by the same trained German native speaker to keep segmentations and annotation consistent. Given the characteristics of continuous speech we established criteria according to which suitable vowels were selected:

1. Only vowels occurring in intelligible, phonated words were annotated.
2. Only vowels with a stable part of at least 40 ms were selected. This stable part was the central part of each vowel, starting at least one period after vowel onset and ending one period before vowel offset.
3. Vowels preceded by a voiced sound were only selected if that sound matched the respective vowel's place of articulation, to ensure that formant transitions and co-articulation did not affect the vowel.
4. Vowels immediately following nasals, glides or other vowels were not selected.

2.4 Acoustic Analysis

Acoustic measures were obtained with the speech-analysis software Praat [2]. Automatic scripts were run to determine the formant frequencies of F1 and F2 in Hertz (Hz) from the entire duration of the stable part of each selected vowel.

With the obtained formant frequencies we computed the following five vowel measurements: (1) vowel formant contrasts for each speaker, (2) F1 and F2 variability within each speaker, (3) the vowel space area (VSA), (4) the vowel articulation index (VAI) and (5) the F2 ratio of the vowels /i, ɪ/ and /u, ʊ/.

To measure the vowel contrast for each speaker individually, we run ANOVAs and subsequent *post hoc* comparisons with the dependent variables F1 and F2 frequencies and vowel as independent variable. This measurement serves as an index of whether the formant frequencies of different vowels are distinct or not. We expected F1 frequencies to differ between the vowels /a, a:/ and /i, ɪ, u, ʊ/ and F2 frequencies between /i, ɪ/ and /a, a:, u, ʊ/. Accordingly, we expressed this measurement as a ratio of expected contrasts to observed contrasts, with a ratio of 1.0 indicating full contrasts between vowels and a lower ratio indicating reduced vowel contrasts.

The F1 and F2 variabilities were computed for each speaker individually as the mean standard deviation of each vowel respectively. According to Kim et al. [8] this measurement reflects a speaker's relative stability of achieving vowel targets. For VSA, VAI and the F2 ratio the formant frequencies were averaged over vowel and speaker. VSA is expressed as the following formula [9]:

$$VSA = 0.5 \times |F1i \times (F2a - F2u) + F1a \times (F2u - F2i) + F1u \times (F2i - F2a)|. \quad (1)$$

The VAI calculation was based on that of Roy et al. [14]:

$$VAI = \frac{F1a + F2i}{F1i + F1u + F2a + F2u}. \quad (2)$$

2.5 Intelligibility Rating

As a rough measure of speech impairment severity, the intelligibility of each participant's speech was rated by 15 naïve listeners. The listeners were German native speakers, between 20 and 40 years of age who had no training in phonetics or background related to speech pathologies.

For the intelligibility ratings two words and two short phrases were randomly selected from each monologue resulting in 46 words and 46 phrases in total. Both words and phrases included at least one of the selected vowels. The listeners were instructed to rate the intelligibility of each word and phrase on a scale from 1 (very poor intelligibility) to 6 (very high intelligibility). No time restrictions were imposed on the rating tasks and listeners were allowed to listen to the words and phrases as many times as needed.

3 Results

Table 2 summarizes the results of the vowel measurements and averaged intelligibility rating scores for each group divided by gender. For the male groups we found the predicted pattern of vowel articulation precision: the MCI group yielded lower values for VSA, VAI, F2 ratio and formant frequency contrasts than the PD and the HC group. As expected, higher values were found in the formant frequency variabilities for the MCI group compared to the PD and HC group. The vowel measurement results of the female groups are more ambiguous: the female MCI group scored lowest only in the VAI. In all other measures, except for the F2-Contrast, the PD group performed poorest among the female participants.

Kruskal-Wallis rank sum tests for non-parametric data were conducted to determine group differences across the data. The overall comparison of individuals with PD (including both PD group and MCI group) and healthy controls yielded significant differences for the measurements VAI ($H(2) = 4.6$, $p < .05$) and F1-Contrast ($H(2)$, $p < .05$). When MCI was included as a factor subsequent *post hoc* tests showed a significant difference between the F2-Variability values of the MCI group and the healthy controls. To assess how this finding was related to gender differences, we ran separate analyses for the male and female participants.

All male participants' vowel measurements (except for the F1-Variability measures) confirm the expected pattern of decrease of vowel space, formant contrasts and stability of achieving vowel targets in the MCI group compared to the PD and HC group (see Fig. 1). This finding is further reflected by a lower intelligibility score for the MCI group. Kruskal-Wallis tests were run to assess the significance of the observed trend. Significant differences were found for the vowel measurements VAI ($H(2) = 6.2$, $p < .05$), F1-Contrast ($H(2) = 6$, $p < .05$) and F2-Variability ($H(2) = 8$, $p < .05$). Subsequent *post hoc* analyses revealed that differences between the MCI group and the HC group accounted for the significance. The PD group did not differ from the MCI or the HC group.

Table 2. Summary of vowel measurements for each group divided by gender, where F2-ratio is ratio of /i/ and /u/, F1-cntr and F2-cntr are F1 and F2 contrasts (as ratios), F1-var and F2-var are F1 and F2 variabilities (mean(sd)), I-scores is intelligibility scores

		Vowel measurements							I-Scores
	Group	VSA	VAI	F2-ratio	F1-cntr	F2-cntr	F1-var	F2-var	
Male	**HC M**	105105	0.86	1.76	1	0.93	50	162	5.2
	SD	63348	0.09	0.42	0	0.15	4.5	41	
	PD M	60707	0.74	1.43	0.83	0.7	48	139	4.1
	SD	76967	0.09	0.46	0.24	0.33	12	29	
	MCI M	42742	0.72	1.35	0.38	0.56	118	297	3.2
	SD	19217	0.04	0.12	0.49	0.36	116	95	
Female	**HC M**	246025	1.00	2.42	1	1	42	130	5.3
	SD	30710	0.04	0.23	0	0	5.5	31	
	PD M	194988	0.96	2.13	0.79	1	68	227	4.3
	SD	97948	0.11	0.57	0.36	0	36	44	
	MCI M	221496	0.94	2.39	1	1	48	167	4.1
	SD	89311	0.02	0.33	0	0	7.4	31	

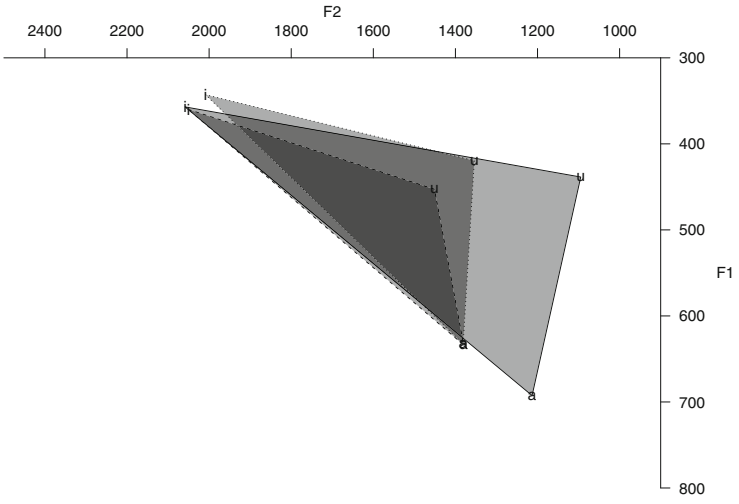

Fig. 1. Male vowel space areas. VSAs with dotted lines reflect the PD group, VSAs with scattered lines reflect the MCI group and solid lined VSAs the HC group

For the female participants, however, the pattern of vowel measurement results was less consistent (see Fig. 2). Although the intelligibility scores for the three female groups show the expected trend, with the MCI group being the least intelligible one, the PD group performed poorest in almost all vowel measurements (expect for VAI and F2-Contrast). Accordingly, the significant

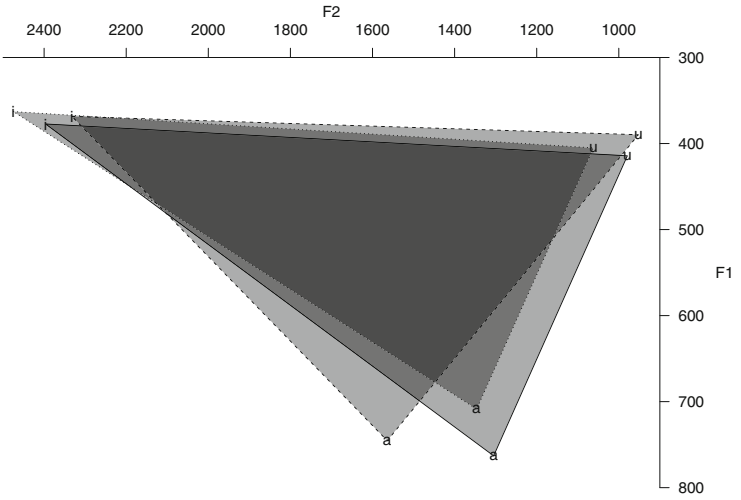

Fig. 2. Female vowel space areas. VSAs with dotted lines reflect the PD group, VSAs with scattered lines reflect the MCI group and solid lined VSAs the HC group

difference found for F2-Variability ($H(2) = 6.2$, $p < .05$) was between the PD group and the HC group. No difference was found for the MCI group.

Intelligibility ratings between groups differed as expected: the intelligibility of MCI group was rated lowest and the intelligibility of control participants highest. Kruskal-Wallis tests and subsequent *post hoc* tests showed significant differences ($p < .05$) between the HC and MCI group and between the HC and PD group. No correlation was found between intelligibility and vowel measures.

4 Discussion

The purposes of this pilot study were threefold: (1) we aimed to assess the utility of spontaneous speech as a task to detect imprecise vowel articulation often attested in PD-induced dysarthria, (2) we evaluated the sensitivity of different vowel measurement in detecting imprecise vowel articulation and (3) we investigated whether cognitive impairments affect vowel articulation in Parkinson's Disease.

The results are in line with a previous study by Rusz et al. [15], indicating that acoustic analysis of spontaneous speech is sensitive enough to separate impaired from non-pathological speech at the group level. Even with a small sample size as in this study, we were able to acoustically detect imprecise vowel articulation. Vowel measurements that proved to be most sensitive in this study were the vowel articulation index (VAI) and the F1-Contrast. While the first measurement is related to vowel space, the F1-Contrast is an index of how distinct a speaker's formant frequencies between different vowels are. Moreover, the separate analyses for men and women yielded significant effects of the F2-Variability

measurement, which reflects a speaker's steadiness in achieving vowel targets [8]. The effects of cognitive impairments on Parkinsonian speech, however, remain inconclusive. As speech motor control requires more attention capacity in individuals with PD than in healthy individuals, we expected individuals with PD and additional cognitive impairments to exhibit less precise vowel articulation than individuals with PD only, because of their reduced attention capacity. While vowel measurements and intelligibility rating showed the expected trend for male participants, the pattern of vowel measurements and intelligibility rating was less clear for the female speakers.

The lack of clarity could be attributable to in-group variation relative to the scarcity of data, especially among the female speakers. Although this study focused on vowel articulation precision, we stress that metrics of vowel articulation should not be treated as single parameter to differentiate dysarthric from healthy speech and to investigate the effects of cognitive decline. Thus, future research should include a larger sample size, more balanced sets of groups and further acoustic measurements to better understand the effects of cognitive impairment on speech motor control in PD.

5 Conclusion

With this pilot study we demonstrated the adequacy of acoustic analysis as a methodological approach to detect cognitive decline in PD. The main contribution of this study are primary data that indicate a potential, negative effect of cognitive impairment on the speech impairment dysarthria in individuals with PD. This effect is acoustically measurable and auditory perceivable.

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