Imprecise vowel articulation as a potential early marker of Parkinson's disease: Effect of speaking task

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The purpose of this study was to analyze vowel articulation across various speaking tasks in a group of 20 early Parkinson's disease (PD) individuals prior to pharmacotherapy. Vowels were extracted from sustained phonation, sentence repetition, reading passage, and monologue. Acoustic analysis was based upon measures of the first (F1) and second (F2) formant of the vowels /a/, /i/, and /u/, vowel space area (VSA), F2i/F2u and vowel articulation index (VAI). Parkinsonian speakers manifested abnormalities in vowel articulation across F2u, VSA, F2i/F2u, and VAI in all speaking tasks except sustained phonation, compared to 15 age-matched healthy control participants. Findings suggest that sustained phonation is an inappropriate task to investigate vowel articulation in early PD. In contrast, monologue was the most sensitive in differentiating between controls and PD patients, with classification accuracy up to 80%. Measurements of vowel articulation were able to capture even minor abnormalities in speech of PD patients with no perceptible dysarthria. In conclusion, impaired vowel articulation may be considered as a possible early marker of PD. A certain type of speaking task can exert significant influence on vowel articulation. Specifically, complex tasks such as monologue are more likely to elicit articulatory deficits in parkinsonian speech, compared to other speaking tasks.
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I. INTRODUCTION

Parkinson's disease (PD) is a neurological illness characterized by the progressive loss of dopaminergic neurons and is associated with a variety of motor and non-motor deficits (Hornykiewicz, 1998). Prior research has demonstrated that approximately 70%–90% of people with PD possess a distinctive alteration of speech termed hypokinetic dysarthria (Logemann *et al.*, 1978), which is a multidimensional impairment affecting various aspects of speech such as respiration, phonation, articulation, and prosody (Darley *et al.*, 1969). Imprecise vowel articulation is a common deficit associated with dysarthria and contributes to reduced speech intelligibility (Kim *et al.*, 2011a). Impairment of vowel articulation, occurring as a consequence of reduced articulatory range of motion ("undershooting" of articulatory gestures) (Forrest *et al.*, 1989; Robertson and Hammerstadt, 1996), has been widely documented in PD (Sapir *et al.*, 2007; Sapir *et al.*, 2010; Skodda *et al.*, 2011). Previous findings of acoustic and kinematic studies support a reduced amplitude and velocity of articulators (lips, tongue, jaw) in parkinsonian speakers (Forrest *et al.*, 1989; Robertson and Hammerstadt, 1996), suggesting that articulation deficits reflect hypokinesia and rigidity of the vocal tract (Forrest *et al.*, 1989; Hunker *et al.*, 1982).

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Although imprecise vowel articulation has been observed even in mild PD (Skodda *et al.*, 2011), previous studies have mainly focused on moderate or more advanced stages. As dysarthria can exert significant influence on speech performance in PD (Kim *et al.*, 2011b), one might expect that the extent of vowel articulation impairment is likely to reflect the severity of dysarthria. Moreover, the severity of dysarthria in PD is thought to be influenced by the severity of motor symptoms, disease duration, as well as specific effects of dopaminergic treatment (Goberman and Coelho, 2002; Schulz and Grant, 2000). Generally, findings related to vowel articulation in the course of PD are somewhat ambiguous. With respect to early stages, improvement of vowel articulation performance under dopaminergic therapy has been noted for several PD speakers (Skodda *et al.*, 2010; Rusz *et al.*, 2013). In contrast, recent research has revealed further decline of vowel articulation performance in PD throughout extended treatment periods (Skodda *et al.*, 2012). Considering that medical interventions as well as disease progression may affect speech performance in different ways, the examination of vowel articulation in early PD, before the onset of therapy, is essential to gain more insight into the development of parkinsonian speech disorders.

While deficits of vowel articulation are commonly present in PD speakers (Forrest *et al.*, 1989; Sapir *et al.*, 2007; Skodda *et al.*, 2011), little effort has been given to examine the severity of vowel articulation impairment under various speaking tasks. In treated patients with mild to moderate PD, imprecise vowel articulation has been found in the speaking task of sentence repetition (Sapir *et al.*, 2007; Sapir *et al.*, 2010) as well as reading passage (Skodda *et al.*, 2011). In addition, impaired vowel articulation has been observed in patients with severe PD while performing sustained prolongation of single vowels (Eliasova *et al.*, 2013). However, to the best of our knowledge, investigation of vowel articulation in PD has been primarily based on a single task and limited to simple utterances, and no evidence has been given regarding the sensitivity of vowel articulation under spontaneous speech. Additionally, there is a growing body of evidence that the signs of dysarthria vary across the specific type of speech task performed (Caligiuri, 1989; Rosen *et al.*, 2005). In particular, dysarthric speech performance has been found to be even more significantly altered acoustically during spontaneous speech production when compared to other non-spontaneous tasks (Kempler and Van Lacker, 2002). A study by Weismer (1984) has suggested that the degree of articulatory deviances seem to vary between simple versus complex utterances produced by speakers with parkinsonian dysarthria, which may be explained by the fact that simple speaking tasks do not require the subject's full attention and are likely to be more automatic than structured and complex tasks such as spontaneous speech. Based on these observations, in the present study we endeavored to determine if a certain type of speaking task is more sensitive to disturbed vowel articulation in PD.

The quality and intelligibility of each vowel can be determined primarily by the distinctive acoustic energy peak of the first (F1) and second (F2) formant frequencies. The F1 and F2 frequencies particularly reflect tongue position, with the acoustic-articulatory relationship defined such that the F1 frequency varies inversely with tongue height and the F2 frequency varies directly with tongue advancement (Kent *et al.*, 1999). Thus, limited articulatory range of motion due to PD may result in vowel formant centralization, i.e., formants with naturally higher frequencies tend toward lower frequencies, and formants with naturally lower frequencies tend toward higher frequencies (Kent and Kim, 2003; Sapir *et al.*, 2007). The overall reduction of working space for vowels in PD can be captured well by a reduced size of the vowel space area (VSA), which is constructed by the Euclidean distances between the F1 and F2 coordinates of the corner vowels /a/, /i/, and /u/ in the triangular F1-F2 vowel space (Kent and Kim, 2003), as compared to normal speech. Several studies have reported a relationship between the VSA and the perceptual impression of intelligibility in speakers with dysarthria (Liu *et al.*, 2005; Weismer *et al.*, 2001). Conversely, a study by Kim *et al.* (2011a) demonstrated that intelligibility in dysarthric speakers was better represented by the degree of overlap among vowels than by the vowel space. In fact, a report by Monses (1976) was the first to show correlation between speech intelligibility in speakers with severe hearing impairment and distance among the F2 frequencies of adjacent vowels in the vowel space. Similarly in PD, both the F2i/F2u ratio representing the distance between the vowels /i/ and /u/ and vowel articulation index (VAI) reflecting vowel centralization (considering all F1 and F2 frequencies across corner vowels) have been shown to be more sensitive in differentiating dysarthric speech from normal speech than the VSA (Roy *et al.*, 2009; Sapir *et al.*, 2007; Sapir *et al.*, 2010; Skodda *et al.*, 2011). Therefore, the current study further addresses the question of whether certain formant-based measurements are more sensitive than other measurements in capturing deficits of vowel articulation, and examined early-stage PD speakers as the main focus.

One potential application of the identification of changes in vowel articulation may be related to the early diagnosis of PD. Tetrud (1991) reported that family members and close friends of prospective patients with PD may note changes in speech several years before the diagnosis is established. More recently, Postuma *et al.* (2012) investigated prodromal Parkinsonism-related motor changes in idiopathic rapid eye movement (REM) sleep behavior disorder and revealed that voice and face akinesia were the earliest indicators of Parkinsonism with an estimated prodromal interval of 9.8 yr before diagnosis. However, speech disorders in the early stages of PD are often mild and have a limited effect on speech intelligibility, making them barely perceptible to others or even to the patients themselves (Stewart *et al.*, 1995). On the other hand, acoustic speech abnormalities have been reported even in PD patients with no perceptible dysarthria (Forrest and Weismer, 2009), and several investigators have found impaired speech parameters in early-stage PD using objective acoustic measures (Rusz *et al.*, 2011a; Stewart *et al.*, 1995). In clinical practice, movement disorder specialists (MDS) are responsible for making the early diagnosis of PD, with disability commonly evaluated using the Unified Parkinson's Disease Rating Scale (UPDRS) (Stebbing and Goetz, 1998). A global perceptual description of patient speech is part of the UPDRS III motor score (item 18) and its evaluation represents a part of daily practice for the MDS. As speech deterioration may be a prodromal feature of Parkinsonism and defects of vowel articulation are common findings in PD, the present study was designed to investigate whether changes in vowel articulation captured by objective acoustic analyses are superior to the perceptual impression of disturbed speech raised by the experienced MDS.

In summary, this study was designed to address following questions:

1. Can imprecise vowel articulation be considered as an early marker of PD? We hypothesized that early-stage, untreated PD patients can be differentiated from healthy speakers using objective measurements of vowel articulation.
2. Which speaking task, including sustained phonation, short sentence repetition, reading passage, and monologue is most sensitive to imprecise vowel articulation in PD? We hypothesized that (a) sustained phonation would not be sufficiently sensitive to differentiate healthy speakers from early-stage PD speakers, but (b) spontaneous speaking such as monologue would be more altered in PD speakers when compared to other speaking tasks.
3. Are some formant-based measurements, including F1 and F2 frequencies of each corner vowel (/a/, /i/, and /u/), VSA, F2i/F2u, and VAI more sensitive in capturing

deficits of vowel articulation in early-stage PD speakers in comparison to healthy speakers? We hypothesized that F2i/F2u and/or VAI would be superior to VSA in the description of mildly impaired parkinsonian speech.
4. Are objective measurements of vowel articulation superior to the clinical impression of disturbed speech as determined by the MDS? We hypothesized that changes of vowel articulation captured by objective acoustic analyses would uncover articulatory disorders in PD with greater precision than perceptual evaluation by the MDS.

II. METHODS

A. Participants

A total of 35 male, Czech native speakers were recruited for the study. Twenty subjects were diagnosed with *idiopathic PD*. They fulfilled the diagnostic criteria for PD (Hughes *et al.*, 1992) and were examined immediately after the diagnosis was established and before symptomatic treatment was started. Their age ranged from 34 to 83 yr (mean, 61.0; ± standard deviation (SD) 12.0), the Hoehn and Yahr (HY, Hoehn and Yahr, 1967, disability scale comprised of stages 1 through 5, where 5 is most severe) disease stage ranged from 1 to 3 (2.2 ± 0.5), the UPDRS III (Stebbing and Goetz, 1998, motor rating scaled from 0 to 108, where 108 represents severe motor impairment) ranged from 5 to 32 (17.9 ± 7.3), and the estimated duration of PD manifestations prior to examination ranged from 6 to 82 months (28.6 ± 19.9). None of the participants reported speech, language, or hearing disorders unrelated to their parkinsonian symptoms, nor had a history of speech-language treatment prior to participation in this study. All PD patients were free of depression and cognitive deficits that could interfere with measurements.

The *healthy control* (HC) group consisted of 15 persons of comparable age ranging from 36 to 80 yr (62.6 ± 13.4). None of these individuals reported a history of neurological disorders or other disorders that may affect speech, language, or hearing. Age distributions were not significantly different between the PD and HC groups. All participants provided their consent to the speaking tasks and recording procedure.

B. Recording

Recordings were made in a quiet room with a low ambient noise level using an external condenser microphone placed approximately 15 cm from the subject's mouth and coupled to a Panasonic NV-GS 180 video camera; the video material was not used in subsequent acoustic analysis. The external condenser microphone was manufactured as part of the original video camera set. The gain of the microphone was set to the same optimal level for all participants to ensure comparable recording conditions. The audio data were digitized from the video recording tape to a computer at a sampling rate of 48 kHz and 16-bit quantization using original Panasonic software. All participants were recorded in the same area of the neurological clinic. As the diagnosis of individual PD patients was made at the time, the specific date of recordings for each participant was different but the overall time schedule was the same. Each participant was recorded in a single session with the speech language pathologist. No time limits were imposed during the recording. All of the participants were familiarized with the speaking tasks and recording procedure. In each recording, the participants performed various speaking tasks as a part of the larger protocol. All participants could repeat their performance in case any errors occurred with respect to the speaking task. Neither participant fatigue nor any changes in the quality of voice from the beginning to the end of the session were observed.

C. Speech samples

Four different speaking tasks were evaluated in the present study including sustained phonation, sentence repetition, reading passage, and monologue. In all speaking tasks, the vowels /a/, /i/, and /u/ were of interest. In the first speaking task, subjects were instructed to make a sustained phonation at a comfortable pitch and loudness with one breath, each vowel separately. The second speaking task was multiple repetition of the Czech phrase "*Kolik mate ted u sebe asi penez*," (['kɔlɪk'maːtɛ 'ʊsɛbɛˀasɪ 'pɛɲɛs]; How much money do you have in your wallet?) which was read in one breath and repeated five times.[1] The acoustic analysis of the corner vowels was performed from the part "**u** sebe **a**s**i**". In the third speaking task, each participant read a standardized passage composed of 80 words (see Appendix A). As indicated by the underlined vowels in the text appearing in Appendix A, 30 vowels per passage were studied, including 10 occurrences of /a/, 10 occurrences of /i/, and 10 occurrences of /u/. The fourth speaking task consisted of monologue where the participants were instructed to speak about what they did during the current day or week, their family, their job, or their interests. For each participant, 10 occurrences of the three vowels /a/, /i/, and /u/ were extracted from the monologue. As there is no available methodology for vowel selection from spontaneous speech such as monologue, the inclusion criteria for the entire word and the vowel itself was established as follows:

(a) The word from which the vowel was selected, as a whole, had to be intelligible and perceptually normal.
(b) Only one same corner vowel (/a/, /i/ or /u/) could be extracted from one specific word.
(c) As there is no reduction in vowel duration due to occurrence in non-stressed syllables in the Czech language, the vowels were elicited from both stressed as well as non-stressed syllables equally.
(d) The selected vowel must not have been induced by confounding effects such as coarticulation with surrounding phonemes. To ensure this condition, the vowels were used only if they occurred separately or followed a voiceless consonant.
(e) The minimal length of the vowel had to be 40 ms, with at least a 30 ms segment that could be considered as a stable part of the vowel. The stable part of the vowel refers to the vowel segment where the first two formants were visible and their format contours did not exhibit marked slopes.

(f) The vowels were extracted from the entire duration of the monologue.[2]

D. Acoustic analyses

Acoustic measures were performed using the widely used, specialized speech-analysis software PRAAT (Boersma and Weenink, 2001, available at www.praat.org). Using PRAAT, both the combined wideband spectrographic display and the power spectral density were used to determine F1 and F2 frequencies in Hz. The formant frequencies of vowels /a/, /i/, and /u/ were extracted from the entire duration of sustained phonation, and from a 30-ms segment at the temporal midpoint of the stable part of each vowel (in order to avoid the influence of vowels preceding or following) in speaking tasks of sentence repetition, reading passage, and monologue.[3] The vowel data of F1 and F2 were separately averaged for all corner vowels of each participant and each individual speaking task. The measurements of VSA, F2i/F2u ratio, and VAI were calculated from these averages. The measurement of VSA is expressed in Hz^2, and can be easily calculated using the following formula (Liu *et al.*, 2005):

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

The measurement of VAI can be expressed using the following formula (Roy *et al.*, 2009):

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

E. Measurement reliability

Intra-judge reliability was assessed following the reanalysis of 25% of all vowel data by the investigator that performed the original set of measures. Pearson correlation analysis indicated significant, positive intra-judge correlation for F1 measures ($r = 0.91$; $p < 0.001$) and for F2 measurement ($r = 0.99$; $p < 0.001$). The mean intra-judge standard error of measurement (SEM) was 15 ± 11 Hz for F1 measures and 16 ± 12 Hz for F2 measures. *Inter-judge* reliability was calculated based on the reanalysis of 25% of all vowel data by a second investigator blinded to participant conditions that was well-trained in the analysis method using the same program. Pearson correlation indicated a significant, positive inter-judge correlation for F1 measures ($r = 0.93$; $p < 0.001$) and for F2 measurement ($r = 0.99$; $p < 0.001$). The mean inter-judge SEM was 15 ± 11 Hz for F1 measures and $17\,\text{Hz} \pm 12$ Hz for F2 measures. *Test-retest* reliability was performed following correlation between the second and third set of sentence repetitions. Pearson correlation indicated significant, positive test-retest reliability for F1 ($r = 0.93$; $p < 0.001$) and F2 ($r = 0.97$; $p < 0.001$) measures. Measurement reliability results in this study are in agreement with previous studies on vowel articulation in dysarthric speakers (Tjaden *et al.*, 2005; Sapir *et al.*, 2007; Sapir *et al.*, 2010).

F. Perceptual assessment of speech performance in PD

For further investigation, the PD subjects were separated into two groups according to independent perceptual assessment performed by three equally trained MDS experienced in the early diagnosis of PD. In accordance with clinical practice, the speech of PD patients was evaluated by item 18 of the UPDRS III (global perceptual description of patient speech, ranked from 0 to 4, where 4 represents complete unintelligibility of speech). As a result, the first group consisted of 10 PD subjects *with an absence of perceptible dysarthria* (hereafter, PD_{ND} ($PD_{no\ dysarthria}$), 0 points on item 18 representing "unaffected speech"), and the second group consisted of 10 PD subjects *with the presence of mild hypokinetic dysarthria* [hereafter, PD_{MD} ($PD_{mild\ dysarthria}$), 1 point on item 18 representing "slightly impaired speech"]. The patient was designated as PD_{MD} if at least one MDS raised suspicion about affected speech due to PD.

G. Statistical analysis and classification

As the Kolmogorov-Smirnov test for independent samples showed that acoustic variables were normally distributed, analysis of variance (ANOVA) with *post hoc* Bonferroni adjustment was used to assess group differences across the data. The adjusted level of significance was set at $p < 0.01$.

Although statistical significance provides useful information regarding the difference between group distributions, there are several classification methods that provide a complete picture of the sensitivity of a given measurement in determining subject-group status. To gain reliable classification results, we first removed the statistically insignificant measurements. As a result, only statistically significant measures (hereafter, main indices) were included in the subsequent classification.

The classification experiment was based on the *minimax theorem* (Schlesinger and Hlavac, 2002). The solution of the minimax theorem is established using a strategy which compares the likelihood ratio with the threshold value. Considering that X can be defined as a set of observations and K as a set of object states, the probability distribution $p_{X|K}(x|k)$ using the set X is then in correspondence with each state k. The strategy is based on the decomposition of $X(k)$, $k \in K$, which determines for each observation $x \in X$ that the object is in the state k on condition $x \in X(k)$. Each strategy is described by dividing set X into $|K|$ numbers,

$$\omega(k) = \sum_{x \notin X_k} p_{X|K}(x|k), \quad (3)$$

i.e., by the conditional probabilities of a wrong decision under the condition that the actual true hidden state of the object is k. The minimax task can then be formulated to find a strategy which minimizes $\max_{k \in K}\ \omega(k)$.

The Gaussian kernel density method with automatic data-driven bandwidth was applied to model the probability distribution of the main acoustic indices for the PD and HC groups, and the minimax task was further solved through a linear programming technique (Schlesinger and Hlavac, 2002). To validate the reproducibility of the minimax classifier, cross-validation with a leave-one-subject-out method was applied, i.e., data from one speaker was used for testing whereas data from the remaining speakers was used to train the classification model.

H. Overall evaluation

The individual steps related to overall evaluation, corresponding with the proposed aims of the study can be summarized as follows:

1. Analysis of variance (ANOVA) was used to find statistically significant differences between the PD and HC groups across all variables and speaking tasks. The significant differences between the PD and HC groups would indicate that imprecise vowel articulation can be considered a marker of early PD.
2. To investigate the suitability of each speaking task in differentiating between the PD and HC groups, we introduced the measure of *task index*, which is computed as the average classification performance (minimax task) across all main acoustic indices. A better task index classification score would indicate greater potential of the speaking task to reveal parkinsonian deficits in vowel articulation.
3. To examine the suitability of the main acoustic indices in differentiating between groups, we designed a measure termed the *acoustic index*, which is calculated as the average classification performance (minimax task) across all speaking tasks. A better acoustic index classification score would imply greater sensitivity of the acoustic variable to capture defects in vowel articulation of mildly impaired PD speech.
4. The minimax task was used to determine whether objective acoustic measures were more sensitive in revealing PD-induced articulation deficits than perceptual evaluation by an experienced MDS, and to predict whether the speakers with perceptible dysarthria (PD_{MD}) as well as speakers with no perceptible dysarthria (PD_{ND}) are correctly identified as PD. A high classification score for PD_{ND} would indicate that objective acoustic measures are able to capture even minor abnormalities in PD vowel articulation, which may be barely distinguishable from the speech of healthy individuals. A high classification performance for PD_{MD} would imply that the severity of vowel articulation deficits contributes to the overall perceptual impression of dysarthric speech.

III. RESULTS

A. Group differences (Objective 1)

Figure 1 shows the mean and SD (error bars), as well as statistically significant differences (stars) between the PD and HC groups, across all formant-based measurements and speaking tasks. The four main acoustic indices (F2u, VSA, F2i/F2u, VAI) were sufficiently sensitive to separate early-stage PD from HC. For single formant measurements, only F2u differed between PD and HC speakers. The significant differences between both groups for F2u were found for the speaking tasks of sentence repetition [$F(1,34) = 16.6$, $p < 0.001$], reading passage [$F(1,34) = 9.8$, $p < 0.01$], and monologue [$F(1,34) = 18.8$, $p < 0.0001$]. The direction of group differences in each case was consistent with the general hypothesis of increased F2u in PD. In addition, all three complex measurements (VSA, F2i/F2u, VAI) were sufficiently sensitive to capture deficits in vowel articulation, with a consistent direction of group differences indicating reduced vowel space as well as F2iF2u and VAI ratios due to PD. Considering reduced vowel space, significant differences between the PD and HC groups captured by VSA were revealed for the speaking tasks of sentence repetition [$F(1,34) = 11.2$, $p < 0.01$] and monologue [$F(1,34) = 8.4$, $p < 0.01$]. In the case of distinction between vowels, altered PD speech performance was found in the measurements of F2i/F2u for the speaking tasks of sentence repetition [$F(1,34) = 12.7$, $p < 0.001$], reading passage [$F(1,34) = 7.5$, $p < 0.01$], and monologue [$F(1,34) = 19.6$, $p < 0.0001$]. Regarding vowel centralization, significant differences between both groups were found in the measurement of VAI for the speaking tasks of sentence repetition [$F(1,34) = 8.2$, $p < 0.01$] and monologue [$F(1,34) = 13.3$, $p < 0.001$]. Therefore, in agreement with our hypothesis, imprecise vowel articulation can be considered an early marker of PD.

B. Differences across speaking tasks (Objective 2)

Figure 2 details classification results with estimated probability distributions for each speaking task across all main acoustic indices. In accordance with the results of statistical analyses, the task index showed that sustained phonation reached the lowest classification performance of 58.7%. All the remaining speaking tasks including sentence repetition, reading passage, and monologue can be considered suitable for the evaluation of vowel articulation in PD. Comparing the results of task index for non-spontaneous and spontaneous speech, sentence repetition and reading passage had an average performance of 69.5% (73.5% for sentence repetition and 65.5% for reading text) whereas monologue reached a score of 76.5%. These findings are consistent with our hypothesis that the performance of vowel articulation in PD speakers is altered to a greater extent in spontaneous rather than non-spontaneous utterances, whereas isolated sustained phonations cannot be considered a suitable task for the investigation of vowel articulation in early PD.

C. Differences across formant-based measurements (Objective 3)

Classification results based on the main acoustic indices (F2u, VSA, F2i/F2u, VAI) through individual speaking tasks are presented in Fig. 2. Considering differences between the PD and HC groups among individual measurements, VSA and F2i/F2u extracted from the monologue reached the best classification performances of 80.4% and 80.0%, respectively. The acoustic index showed very similar classification accuracy across all acoustic indices with a performance of 70.6% for F2u, 70.4% for VSA, 69.1% for F2i/F2u, and

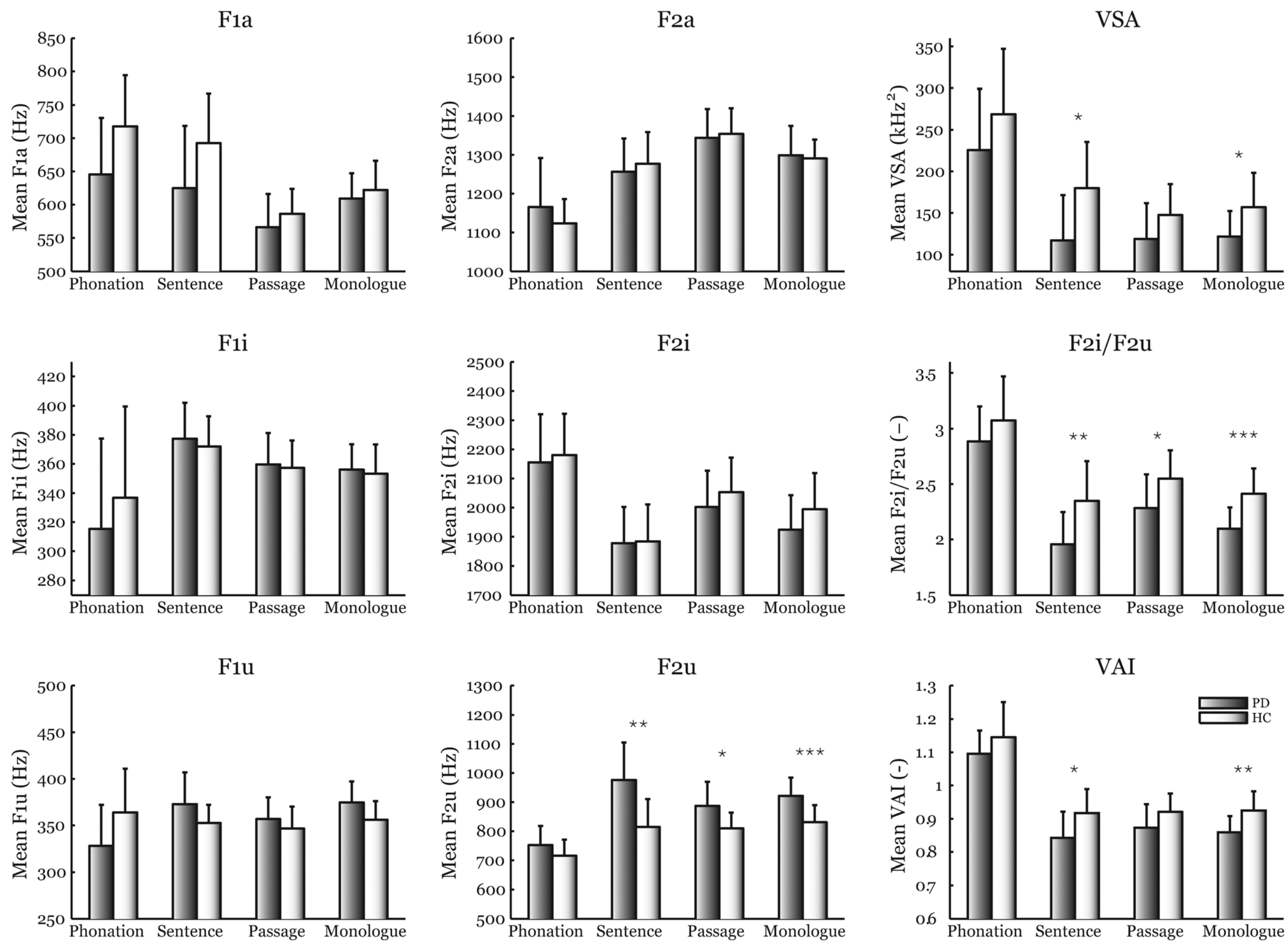

FIG. 1. First (F1) and second (F2) formant frequencies for each corner vowel (/a/, /i/, and /u/), vowel space area (VSA), F2i/F2u ratio, and vowel articulation index (VAI) in PD speakers (gray) and healthy controls (white). Measurements were performed using different types of speech material including sustained phonation, sentence repetition, reading passage, and monologue. The bars represent mean values and error bars standard deviations. Stars indicate significant differences between PD patients and controls: *$p < 0.01$; **$p < 0.001$; ***$p < 0.0001$.

64.1% for VAI. Contrary to our hypothesis, distinctions between vowels and vowel centralizations were not revealed to be superior to reduced vowel space in the detection of mildly impaired speech in early stage PD, while articulation of the vowel /u/ captured by F2u seems to be more affected when compared to changes in other vowel frequencies.

D. Comparison between objective measures and perceptual evaluation (Objective 4)

Table I details the results of classification for two groups of PD speakers, with perceptible dysarthria (PD_{MD}) and without perceptible dysarthria (PD_{ND}), across all main acoustic indices and speaking tasks. Altered vowel articulation in PD_{MD} patients was confirmed using all main acoustic indices (F2u, VSA, F2i/F2u, VAI) through all investigated speaking tasks except sustained phonation. This finding, related to imprecise vowel articulation in PD_{MD} subjects, was in agreement with the perceptual evaluation of the MDS. In other words, acoustic metrics generally achieved better results in predicting the group status of PD_{MD} patients than PD_{ND} patients. Interestingly, the measurement of F2 frequency based on the single vowel /u/ (F2u) was best able to capture mild dysarthria, with scores ranging from 81.9% to 88.7%. On the other hand, F2u alone was not sufficiently sensitive to reveal changes in vowel articulation of PD_{ND} patients. The contrary is true for measurements of VSA and F2i/F2u, especially when extracted from monologue, which were able to detect impaired vowel articulation in both PD groups. In fact, the VSA based on monologue was more successful in predicting PD_{ND} group status with a classification score of 80.3% in comparison to 76.3% achieved by F2i/F2u. In contrast, F2i/F2u extracted from monologue reached a higher score of 85.6% for the PD_{MD} group in comparison to 83.7% by VSA. The measurement of VAI was not found to be superior to complex measurements of F2i/F2u and VSA. In correspondence with our hypothesis, the performance of objective acoustic measures of vowel articulation was superior to the subjective clinical evaluation of disturbed speech.

IV. DISCUSSION

In the present study, we investigated various formant-based measures in a group of *de novo* male PD patients in comparison to healthy subjects. Vowel production was examined across different types of speech tasks including sustained phonation, sentence repetition, reading passage, and monologue. The acoustic parameters for subsequent analysis consisted of F1 and F2 for each corner vowel, the

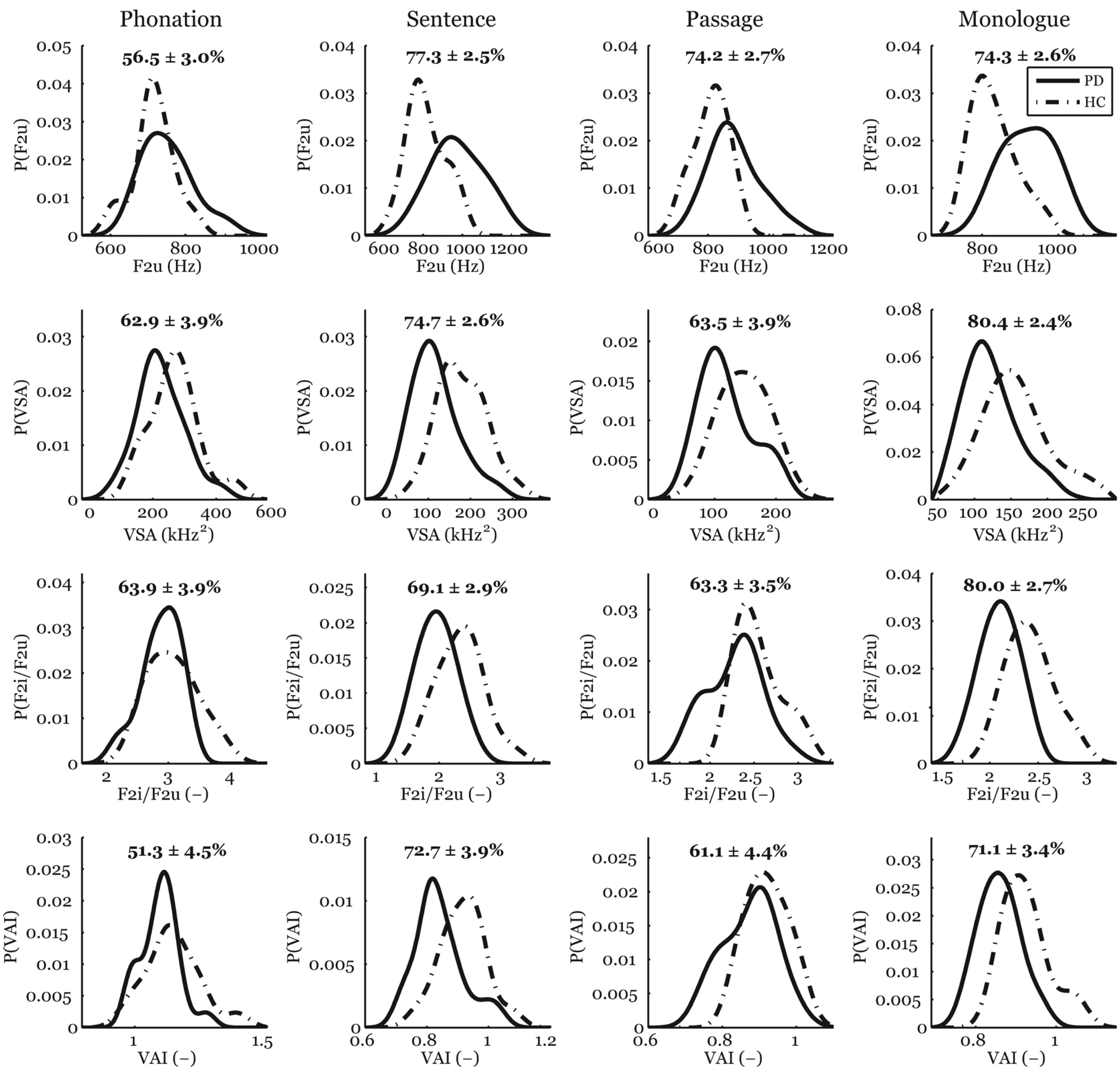

FIG. 2. Probability densities P('measure') with overall classification accuracy according to the minimax task across all main acoustic indices (F2u, VSA, F2i/F2u, VAI) and speaking tasks (sustained phonation, sentence repetition, reading passage, monologue). Solid lines are displayed for PD subjects, the dash-dot lines for HC speakers.

traditional measure of VSA, and the recently introduced measures of F2i/F2u and VAI. Much of what is known about vowel articulation in PD has generally been based on pharmacologically treated patients with various degrees of dysarthria, without comparison between different types of speaking tasks. Thus, the current investigation extends our knowledge related to the characteristics of vowel articulation in the early stages of PD prior to pharmacotherapy, and the usage of more complex speech material.

Our results show that early-stage PD speakers manifest increased F2u, lowered VSA, reduced distinction between vowels captured by F2i/F2u, and abnormalities in formant centralizations measured by VAI across sentence repetition, reading passage, and monologue. In fact, vowel articulation in PD was more acoustically altered during spontaneous speech such as monologue in comparison to the non-spontaneous tasks of sentence repetition and reading passage. Moreover, isolated vowel phonation was found to be an inappropriate task to reveal early changes in parkinsonian articulation. Considering comparisons between measurements, there were no essential differences between the results obtained using various complex formant-based metrics (VSA, F2i/F2u, VAI), although the production of the vowel /u/ (as captured by F2u) was found to be altered to a greater extent when compared to articulation of /a/ and /i/ vowels. Further results of our study indicate that objective acoustic measures are more sensitive in revealing PD-induced articulation deficits than perceptual evaluation by experienced clinicians, and therefore may be helpful in capturing even subclinical signs of speech impairment in PD. To summarize, these findings provide greater insight into impaired vowel articulation in the early stages of PD and may be helpful regarding the advent of neuroprotective treatment as well as speech rehabilitation in PD (Rusz *et al.*, 2011b; Sapir *et al.*, 2010).

TABLE I. List of classification results for PD speakers with mild dysarthria (PD_{MD}) and no perceptible dysarthria (PD_{ND}) across all main acoustic indices (F2u, VSA, F2i/F2u, VAI) and speaking tasks (sustained phonation, sentence repetition, reading passage, monologue).

	Classification score (%)	
Measurement	PD_{MD}	PD_{ND}
Sustained phonation		
F2u	53.5 ± 5.6	60.4 ± 4.8
VSA	67.0 ± 13.3	69.9 ± 12.9
F2i/F2u	72.8 ± 6.7	58.9 ± 4.8
VAI	64.3 ± 6.7	50.2 ± 7.7
Sentence repetition		
F2u	84.0 ± 3.0	72.9 ± 6.5
VSA	84.7 ± 3.5	69.7 ± 3.8
F2i/F2u	78.6 ± 3.2	64.3 ± 3.9
VAI	84.9 ± 3.0	67.2 ± 4.3
Reading passage		
F2u	81.9 ± 2.9	66.0 ± 3.6
VSA	62.2 ± 4.1	68.0 ± 4.1
F2i/F2u	72.3 ± 6.0	59.1 ± 5.9
VAI	69.0 ± 7.3	58.7 ± 7.7
Monologue		
F2u	88.7 ± 3.4	61.5 ± 3.8
VSA	83.7 ± 5.3	80.3 ± 5.5
F2i/F2u	85.6 ± 5.7	76.3 ± 5.2
VAI	71.0 ± 4.0	69.1 ± 3.9

A. Imprecise vowel articulation as an early marker of PD

Although imprecise articulation is considered as one of the most common deficits associated with hypokinetic dysarthria (Darley *et al.*, 1969), previous studies have reported that voice disorders in PD occur more frequently than articulation disorders (Logemann *et al.*, 1978). Moreover, prosodic patterns and features of dysphonia have been suggested to be the most salient early signs of vocal impairment in PD (Rusz *et al.*, 2011a; Stewart *et al.*, 1995). In contrast to previous reports, our results show that impaired vowel articulation was present in 80% of our patients and may be one of the first signs of speech impairment in PD. Individuals with early-stage PD demonstrated significant differences in measurements of F2u, VSA, F2i/F2u, and VAI relative to HC subjects. Our results are generally consistent with previous studies where reduced articulatory movements were investigated in treated PD patients with mild to moderate dysarthria (Sapir *et al.*, 2007; Sapir *et al.*, 2010; Skodda *et al.*, 2011), however, to the best of our knowledge, no previous studies have examined vowel articulation in *de novo* patients with hypokinetic dysarthria or dysarthria of another type.

B. Effect of speaking task

Our results indicate that both spontaneous and non-spontaneous speech is suitable for the assessment of early changes in vowel articulation associated with PD, while isolated vowel phonations were found to be inappropriate. In fact, vowel articulation performance in PD was found to be altered to a greater extent in spontaneous speech such as monologue when compared to the typical non-spontaneous speaking tasks of sentence repetition or reading passage. These findings are in agreement with the general assumption that the efficiency of speech production in PD varies with the task performed (Caligiuri, 1989; Rosen *et al.*, 2005; Weismer, 1984). Furthermore, in a previous study where both spontaneous and non-spontaneous speech were collected from a single patient with PD diagnosed 18 yr prior to investigation (Kempler and Van Lacker, 2002), the intelligibility of spontaneous speech was found to be severely affected when compared to non-spontaneous speech. As imprecise vowel articulation commonly contributes to reduced speech intelligibility in dysarthria (Kim *et al.*, 2011a; Liu *et al.*, 2005; Weismer *et al.*, 2001), the observation by Kempler and Van Lacker (2002) is in accordance with our results showing monologue as the most affected speaking task in parkinsonian patients, even in the early stages of the disease. Thus, it might be rewarding to take into account the type of speaking task during the evaluation of dysarthria.

With respect to differences in articulatory impairment between various types of speaking tasks, one possible explanation is the complexity of the speaking task. Contrary to more advanced stages of PD (Eliasova *et al.*, 2013) where sustained phonation may be a suitable task, in early-stage parkinsonian speakers it is too simple a task to capture subtle changes in vowel articulation. Indeed, the size and centralization of the VSA as well as the ratios of F2i/F2u and VAI obtained from phonation differ in comparison to the results elicited from other speaking tasks (see Fig. 1). Although sentence repetition maintains the advantage that each individual corner vowel is extracted from the same repeated phrase, usage of these extracted vowels does not appear to reflect the variety and flexibility of the entire utterance. Furthermore, the lexical factors of phonological neighborhood density and word frequency can significantly influence the performance of vowel articulation (Watson and Munson, 2008). In contrast to sentence repetition, the variety of utterances is captured well using reading passage where the vowel performances are extracted from a variety of words, and lexical factors are then partially controlled by average measurements. However, in non-spontaneous speech such as reading passage or sentence repetition, the speaker is simply pronouncing ready-made text and thus can provide special attention to articulatory planning (Levelt, 1989). In contrast to non-spontaneous tasks, spontaneous speech represented by monologue requires that the speaker carry out the complete planning process, and therefore the articulatory mechanisms receive relatively less attention. However, in spontaneous speech, there is a limited possibility of using the same words in the same phrases for each participant, and thereby the identification and extraction of vowels must be carefully conducted. In summary, we can assume that the final speech performances are related to the overall articulatory demands and complexity of the individual speaking tasks.

C. Acoustic changes in vowel articulation due to PD

In the present study, we did not detect any fundamental differences between various complex formant-based measurements. However, this is not unexpected as all of the complex formant-based measurements are based upon the same base measures of F1 and F2 frequencies. On the other hand, subtle differences in findings across formant-based measurements may provide certain clues about acoustic changes in vowels due to the development of PD. Considering the main acoustic indices, F2u is sensitive only to the vowel /u/, F2i/F2u to both /u/ and /i/ vowels, and VAI to all three corner vowels /u/, /i/, and /a/. F2u was the only measurement based on a single vowel that allowed the differentiation of PD and HC groups, and therefore the vowel /u/ can be considered the most affected in mild dysarthria of PD individuals. F2i/F2u was more sensitive in capturing deficits of PD vowel articulation than F2u alone, while VAI, which also takes formant frequencies of the vowel /a/ into account, achieved the worst classification performance in separating PD from HC speakers. The vowel /a/ also contributes to the VSA, but the formants based on the vowel /a/ do not need to negatively contribute to its overall performance (as given by the principle of VSA construction) such as in the case of formant centralization measured by VAI. In light of these observations, we may hypothesize that articulatory deficits are due mainly to alterations of the vowel /u/, followed by the vowel /i/, with the vowel /a/ remaining most resistant to change in the earlier stages of PD. This hypothesis is also in agreement with previous studies reporting the measurement of VAI superior to VSA in parkinsonian patients several years after the diagnosis was established (Sapir *et al.*, 2010; Skodda *et al.*, 2012).

This continuum of articulatory deficits developing through the vowels /u/, /i/, and /a/, respectively, can be also discussed in physiological terms. Considering tongue position and lip posture for the cardinal vowels /a/, /i/, and /u/, the tongue is positioned low for the vowel /a/, high and forward for the vowel /i/, and high and backward for the vowel /u/, whereas lip posture is spread for both the /a/ and /i/ vowels and rounded for the vowel /u/ (Hasegawa-Johnson *et al.*, 2003). Therefore, we may assume that production of the vowel /a/ is a less demanding task than production of the vowels /i/ and /u/. In comparison to the vowel /i/, the articulation of the vowel /u/ requires more demanding involvement of the orofacial muscles to create a tightly rounded lip posture. Admittedly, as the vowel /u/ is characterized by a posterior rise of the tongue root, we may consider that problems with tongue articulation develop in reverse, i.e., from the root to the tip of the tongue, and the resulting tongue restriction may also be related to swallowing abnormalities in PD (Sapir *et al.*, 2008; Tjaden, 2008). In general, concerning the pathophysiological mechanism responsible for the development of speech and other motor deficits in PD, speech impairment has generally been attributed to dopamine deficiency as well as hypokinesia and rigidity of the vocal tract (Schulz and Grant, 2000). On the basis of investigation in PD patients tested and re-tested within a few years, recent innovative studies have found that bradykinesia, rigidity, and axial parkinsonian symptoms are primarily responsible for restricted vowel articulation in PD (Rusz *et al.*, 2013; Skodda *et al.*, 2012).

D. Perceptual and acoustic findings in the speech of early-stage PD individuals

Previous studies have reported a relationship between measurements of vowel articulation and the perceptual impression of intelligibility in dysarthric speakers (Kim *et al.*, 2011a; Liu *et al.*, 2005; Weismer *et al.*, 2001). Although the perceptual classification of dysarthria is typically based on intelligibility rating measures using orthographic transcription (for example, see Kim *et al.*, 2011a; Liu *et al.*, 2005), such methods are not applicable to the evaluation of speech disorders in early-stage PD, where dysarthria is rather mild or even imperceptible, and has no or limited effect on speech intelligibility (Stewart *et al.*, 1995). In the present study, parkinsonian speakers were subjectively separated into two groups (no perceptible dysarthria and mild dysarthria) by experienced clinicians, and a very high classification performance was achieved (up to 90%) when comparing patients with mild dysarthria and controls. This finding suggests that measurements of vowel articulation may be considered suitable for the assessment of speech intelligibility. Subsequently, we observed that the objective acoustic measures of vowel articulation were able to predict articulatory impairment in PD patients with no perceptible dysarthria with relatively high accuracy (up to 80%). Accordingly, it has been proposed that objective acoustic measures may capture even minor abnormalities in PD speech (Forrest and Weismer, 2009; Rusz *et al.*, 2011a; Stewart *et al.*, 1995). Therefore, objective acoustic analyses may be helpful in revealing even subclinical signs of speech impairment in PD.

E. Limitations of the present study

In the course of this study, we investigated only 20 male parkinsonian patients due to limited opportunities in recruiting more early-stage PD individuals prior to dopaminergic treatment. Despite this limitation, we do not believe that there would be any fundamental changes in the overall progression of vowel articulation or that the current findings would differ with a substantial increase in the number of subjects. Previous research has suggested that gender may have an impact on the progression of dysarthria due to sexual dimorphism of laryngeal size (Hertrich and Ackermann, 1995). As our study consisted only of male participants, we cannot exclude that impairment of vowel articulation is influenced by gender-specific aspects of speech. One further limitation of the present study is that we did not investigate relationships between vowel durations and vowel articulation measurements (Tjaden *et al.*, 2005), and hence possible effects related to the speaking rate on vowel articulation in PD cannot be eliminated.

V. CONCLUSION

The present study provides evidence for restricted vowel articulation in early-stage PD speakers prior to dopaminergic treatment. Our results demonstrate that spontaneous speech is more likely to show true deficits in the speech performance of PD patients. Specific changes in speech due to neurological disorders such as PD may have the potential to contribute to existing assessment batteries. Acoustic measurements of vowel articulation may therefore be useful in the early detection of speech impairment in PD, for monitoring the severity of dysarthria and disease progression, and in the evaluation of treatment response.

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APPENDIX

Reading passage with labeled corner vowels /a/, /i/, and /u/ that was used in acoustical analyses.

Když člověk poprvé vsadí do země sazeničku, chodí se na ni dívat třikrát denně: tak co, povyrostla už nebo ne? I tají dech, naklání se nad ní, přitlačí trochu půdu u jejich kořínků, načechrává jí lístky a vůbec se obtěžuje různým konáním, které považuje za užitečnou péči. A když se sazenička přesto ujme a roste jako z vody, tu člověk žasne nad tímto divem přírody, má pocit čehosi jako zázraku a považuje to za jeden ze svých největších osobních úspěchů.

[1]The motivation behind the single exhalatory effort required for each sentence was to differentiate the task of sentence repetition from the connected reading of text, since it has been reported that the performance of PD speakers may differ at the beginning and end of an utterance (Skodda and Schlegel, 2008).

[2]As the previous observation has shown that the performance of PD speakers may differ through an utterance (Skodda and Schlegel, 2008), we suggest extracting vowels throughout the entire length of the monologue. However, in our early-stage PD patients there were no statistically significant differences between formants calculated using the first five occurrences and second five occurrences of corner vowels.

[3]In the sustained phonation speech task, only one repetition for each corner vowel was used to calculate formant frequencies as (a) articulation of isolated vowels is not influenced by the preceding or following phoneme and (b) certain fluctuations of formants are treated by the choice of multiple window length of the analyzed segment when compared to 30-ms segments used in sentence repetition, reading passage, and monologue tasks.

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