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More than words: Recognizing speech of people with Parkinson's disease

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CHAPTER 8
ACOUSTIC CHANGE OVER TIME IN SPEECH OF ONE INDIVIDUAL WITH PARKINSON'S DISEASE

ABSTRACT

This chapter builds on the acoustic findings reported in the previous chapter and provides an exploration of longitudinal speech changes in one bilingual speaker with PD. The chapter reports on a single case study that aims to explore the longitudinal speech changes in two working languages of one individual with PD in the time series of 36 recordings completed over the course of 3.6 years. Moreover, it explores whether speech therapy received in one language has an effect on the other language of the speaker. To those ends, the study investigates trends in ten conventional acoustic features related to the domains of prosody and voice quality as well as differences in these features in pre-, during and post-therapy periods.

8.1. INTRODUCTION

Hypokinetic dysarthria (HD) that often appears in the course of Parkisnon's disease (PD) is characterized by a number of speech and voice changes (see chapter 2). A variety of different parameterization techniques have been developed for acoustic analysis of speech changes appearing due to HD, including conventional and non-conventional speech features (for a detailed review see Brabenec et al. (2017)). The important difference between conventional and non-conventional speech features is that conventional features are clinically interpretable and can be correlated with auditory-perceptual assessments of dysarthria (Mekyska et al., 2016; Brabenec et al., 2017). Among the most studied and

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Verkhodanova V., Coler M., Jonkers R., de Bot K., Lowie W. (submitted). Acoustic change over time in speech of one individual with Parkinson's disease. Journal of *Clinical Linguistics & Phonetics* described conventional speech features of HD are f_0 deviations associated with monopitch (Skodda et al., 2013; Galaz et al., 2016), distorted rhythm of speech (Skodda and Schlegel, 2008; Klopfenstein, 2015), reduced intensity variability of voice associated with monoloudness (Skodda et al., 2013; Galaz et al., 2016), imprecise consonants (Fischer and Goberman, 2010; Tykalová et al., 2015) and a hoarse and breathy voice quality (Tsanas et al., 2010b). A number of studies have also demonstrated that prosody deficits together with harsh voice and reduced articulation are among the most prominent speech characteristics that are present in the acoustics of speech produced by people with PD (PwPD) (Rusz et al., 2011; Galaz et al., 2016; Brabenec et al., 2017; Verkhodanova et al., 2019), with some suggesting universality of prosodic deficits (Pinto et al., 2017).

Most studies concerned with speech production of PwPD and exploring acoustic changes in their speech have cross-sectional designs. In contrast, the present study focuses on acoustic changes appearing in a single speaker with PD over 3.6 years.

LONGITUDINAL STUDIES OF SPEECH OF PWPD

There are few studies that explore longitudinal changes in speech of PwPD. Extensive work on monitoring progress in PD was done by Skodda et al. (2009, 2011a, 2012, 2013), who studied acoustic manifestations of HD in German-speaking PwPD. In their first longitudinal study, Skodda et al. (2009) investigated prosodic changes in reading over time. The authors reported significant changes in speech rate in PD characterized by an articulatory acceleration in the earlier time point and slowing during disease progression especially in male PwPD. The authors demonstrated that in female PwPD the f_0 variability decreased over time suggesting gender particularities reflected by this feature (Skodda et al., 2009). In 2011, Skodda et al. explored the instability of syllable repetition in two diadochokinetic tasks (pa–pa–pa and ba–ba–ba) using conventional measures of stability of pace. The authors demonstrated that two measures have a significant elevation with time for PwPD: the perceptual coefficient of variance of interval length and percentual pace acceleration. However, the control group in this study was not retested in the second examination, which did not allow the authors to exclude potential effects of ageing entirely (Skodda et al., 2011a). Another study by Skodda et al. (2012) focuses on an analysis of two vowel articulation features over time: triangular vowel space area (VSA) and vowel articulation index (VAI). Their findings demonstrate the VAI decline over the course of the disease. VAI was also found to be correlated with overall speech impairment based on perceptual impressions. Additionally, VSA showed reduction over time. Both findings have only been described for female PwPD. The authors showed that both VSA and VAI correlate with gait dysfunction, suggesting that vowel articulation might serve as a potential marker of axial disease progression (Skodda et al., 2012). In 2013, Skodda et al. published another study demonstrating that progression of voice and speech impairment can be captured by auditory-perceptual assessments and also by acoustic measurements with a significant increase in shimmer, noise-to-harmonics ratio as measures of voice quality, and a reduction of speech rate, intraword pauses, and VAI. Summarizing the assortments four studies, the observed changes appear to be independent of global motor function as measured with the Unified Parkinson's Disease Rating Scale (UPDRS). But in Skodda et al. (2013), the authors reported that the percentage of pauses within polysyllabic words and the percentage of pause rate found in the reading task significantly correlated with baseline measures of the Hoehn–Yahr stages. These findings suggest that speech and voice changes in PwPD could be the result of an escalation of axial dysfunction too subtle to be mirrored by global UPDRS motor score, but rather captured by the Hoehn-Yahr score (Skodda et al., 2013).

Studies exploring the longitudinal effect of treatment and medication on speech production constitute another group of research. Harel et al. (2004) describe a retrospective analysis of videotape footage of a single individual and a matched control subject over an 11-year period (7 years prior to diagnosis of PD, and 3 years post-diagnosis). Results demonstrate that f_0 variability decline could be detected as early as 5 years prior to the diagnosis, and that symptomatic pharmacological treatment served to ameliorate this speech change with a normalization of f_0 variability to a level comparable to that observed prior to a potential five year prodromal period (Harel et al., 2004). Tykalová et al. (2015) investigated the long-term effect of dopaminergic medication on speech fluency in PwPD. The authors calculated the percentage of dysfluent words in monologues and reading at three time points: before the initiation of dopaminergic treatment and twice in the following six years. Their findings demonstrate the development of stuttering-like disfluencies in PD indicating an adverse effect of prolonged dopaminergic therapy (Tykalová et al., 2015).

Another study by Rusz et al. (2016) examines the effects of dopaminergic medication on acoustic changes in the speech of PwPD. Similar to the previous study by Tykalová et al. (2015), speakers were tested three times: before the initiation of dopaminergic treatment and twice in the following six years. Speech tests included prolonged phonation, diadochokinetic tasks, and a short monologue. The authors reported that at the baseline, the PD group showed significantly altered speech including imprecise consonants, monopitch, inappropriate silences, decreased quality of voice, slow alternating motion rates, undershot vowels and monoloudness. The follow-up assessments demonstrated preservation or slight improvement of speech performance in two-thirds of the PD group. The extent of speech improvement correlated with the Levodopa equivalent dose as well as with the reduction in principal motor manifestations based on the UPDRS (Rusz et al., 2016).

Another group of studies apply a longitudinal approach to investigate speech of PwPD are concerned with the development of computer-aided tools to monitor PD progression. These studies use a time series design for monitoring acoustic change rather than the pretest – posttest design employed by many longitudinal studies on speech of PwPD. For example, a study by Arias-Vergara et al. (2018) proposes a method of training individual models for each speaker with PD based on two approaches: Gaussian Mixture Models - Universal Background Models (GMM-UBM) and i-vectors. The aim was to assess the dysarthria level and neurological state of PwPD over time. Arias-Vergara et al. (2018) explored different communication channels for data collection including landlines, mobile phones and Voice over IP technologies such as Skype. They tested their approach on two longitudinal corpora: a) on recordings of 7 PwPD made in controlled acoustic conditions during several sessions from 2012 to 2016, and b) on recordings made during 16 sessions in 4 months performed at home for several PwPD (every two hours over an eight hour period, one day per month). The feature set included non-conventional speech features related to phonation, articulation and prosody. Their results indicated that the i–vector approach was suitable when the acoustic conditions among recording sessions differ, while the GMM-UBM approach seems to be more suitable when the acoustic conditions do not change a lot among recording sessions (Arias-Vergara et al., 2018)[1].

While there are studies of longitudinal speech changes in PwPD, there is hardly any research done on bilingual speakers with PD, not to mention longitudinal effects of PD on bilingual speech. This constitutes a big gap in the existing literature, given that most people in the world are not monolingual. To our knowledge, only two studies focused on speech and language issues of bilingual PwPD (Zanini et al., 2004, 2010) and no publications reported the effects of speech therapy in bilingual PwPD. In these two existing studies, Zanini et al. (2004, 2010) demonstrated that people with PD evidence more phonological, morphological, and syntactic errors in their first language, Friulian, rather than in their second language, Italian. The only study investigating effects of speech therapy in dysarthric bilingual speakers examines two cases of flaccid dysarthria due to a stroke in Mandarin-English speakers (Lee and McCann, 2009). Lee and McCann (2009) demonstrated that the therapy was more effective for intelligibility of only the first language – Mandarin.

FOCUS OF THE CURRENT STUDY

This single case study is dedicated to the exploration of the changes in two languages, Dutch and English, in the time series of 36 recordings performed over 3.6 year period. We also wanted to determine if such changes over time are comparable in the different spoken languages of the participant. Another focus of this study is the comparison of speech production of a speaker with PD before, during and after speech therapy. Therefore, this study addresses two gaps in the existing literature. First, we explore whether the acoustic changes are similar in two working languages of a person with PD, Dutch and English. Secondly, we investigate whether there is any effect of speech therapy on acoustic parameters in either language, given that speech therapy was provided in Dutch. We expected to see typically occurring PD effects (such as rise in mean f_0, change in speech and articulation rate, decline in f_0 variability, etc. – see Ramig et al. (2004)) to become stronger in both working languages. Furthermore, we hypothesized that a global effect of therapy would be significant on the voice quality and f_0 measurements in both languages. Regarding other prosodic measurements, we expected that if the therapy effects were present, they would be significant in the language in which the therapy was provided – Dutch.

8.2. METHODS AND MATERIALS

The present study uses a time series design following one individual's speech with dense observations over time. This approach to data collection is closer to the studies on automatic PD speech monitoring (e.g., Arias-Vergara et al. (2018)) rather than to the classic pretest-posttest design of longitudinal studies concerned with PD speech (e.g., Skodda et al. (2009)).

[1]A comparable approach to longitudinal speech tracking was described in Orozco-Arroyave et al. (2016), Klumpp et al. (2017), and other studies.

PARTICIPANT

One man diagnosed with PD participated in the longitudinal data collection during 185 weeks (approximately 3.6 years). The participant is a native speaker of Dutch but is also fluent in English, and reported to use both languages on a daily basis. He was diagnosed with PD six years prior to the beginning of the data collection, at the age of 60. He has not been diagnosed with hypokinetic dysarthria, but has a history of stuttering. After the first 12 sessions, he began with speech therapy largely based on Lee Silverman Voice Treatment (LSVT) (Ramig et al., 2004), mostly focusing on increasing vocal intensity and lowering pitch. During the next eight recording sessions, he continued his sessions with a speech and language therapist, which he stopped by recording session 22 (approximately 2 years after the beginning of the data collection). The participant reported having cognition and memory support therapy during the sessions 20-34 (in weeks 102.1 to 175 from the beginning of the recordings), while during the last two sessions (35-36, weeks 180.3-185.3) he started having pharmacological treatment to support executive functions in Parkinson's disease dementia.

RECORDING PROCEDURE

The recording protocol was the same as described in chapter 7. Every recorded session included five speech tasks: sustained phonation of the vowel /aː/, interview with an open question, description of one of the Heaton pictures (Heaton, 1972; Sánchez and Jarvis, 2008), a short video clip description taken from the freely available works of Charlie Chaplin, and a reading of the "North Wind and the Sun" passage. All tasks were performed first in English and subsequently in Dutch. The first two sessions lacked a video description task, and session 31 lacked a picture description task due to technical reasons.

The recordings were made roughly every month (mean interval is 5.3 weeks, SD = 2.6 weeks), one to three hours after medication intake. The first 28 recording sessions took place in quiet rooms with a Zoom H2 recorder placed at around a 40 cm distance from the speaker's mouth. Starting with session 29, the sessions took place mostly virtually via Zoom calls due to COVID-19 restrictions. During virtual sessions, the participant recorded his speech on his iPhone 10 with the preinstalled Dictaphone app.

The collection and analysis of the material was approved by the Ethical Committee of University Groningen, Campus Fryslân.

MEASUREMENTS

For the current study, we used recordings of three tasks out of five: prolonged phonation, monologues and reading. In this way, we were able to focus on conventional features characteristic of phonation and prosody aspects of speech affected by PD as captured by these tasks (Brabenec et al., 2017). The details of the speech features are described below. For the fundamental frequency (f_0) variability calculation we used the f_0 tracking performed by a Python script and the Speech Signal Toolkit (Imai et al., 2017) based on the robust algorithm for pitch tracking (RAPT) (Talkin, 1995). Two other prosodic features, speech rate and articulation rate, were calculated with a Praat script (De Jong and Wempe, 2009). Speech rate was measured as the number of syllables divided by the total time of the recording. Articulation rate was measured as the number of syllables divided by phonation time in that recording. Another feature belonging to the prosody domain, inappropriate silences, was calculated from the results of the same Praat script by De Jong and Wempe (2009) as the number of pauses relative to total speech time after removing periods of silence lasting less than 60 ms (Brabenec et al., 2017). Concerning phonation and voice quality, we measured means of the first and second formants (F1 and F2), maximum phonation time (MPT), jitter and harmonics-to-noise ratio (HNR) from the prolonged phonation (/aː/) recordings using a Praat script.

Because the recordings were done without strict supervision over the distance between the speaker and the microphone, the intensity measurements had to be excluded from the analysis. The list of all features, source tasks and explanations are presented in the Appendix F.1.

STATISTICAL ANALYSES

To analyze the presence of the trends we used a simple linear regression analysis and Monte Carlo simulation to determine whether the results of the linear regression were not random. In the simulation we modelled the probability of different slope outcomes. For each feature, we randomized the measurements 1000 times and calculated the slope for every randomized set of measurements. Linear regression analysis was performed after removing one session where the participant had residual effects of a recent cold (week 46).

To explore the possible effect of the therapy on each feature we conducted an analysis on the data after deducting general linear trends from each data point, since such trends could reflect both the progression of PD and/or the general effect of ageing (Pessin et al., 2017). After trend deduction, we conducted the Levene's test to check for significantly different variability of measurements for each feature. Depending on the results, we conducted either non-parametric Welch's F tests or one-way ANOVAs followed up with Tukey post hoc tests, to compare measurements in the periods before, during, and after therapy.

8.3. RESULTS

PROLONGED PHONATION

Analyses of HNR and jitter in the prolonged phonation of the vowel /aː/ showed no visible decline or rise. The plots of these measures are presented in Figure 8.1.

Linear regression results showed no significant trends for jitter or HNR. However, MPT demonstrated a significant decline (see Table 8.1). To test whether the results of the linear regression for the MPT feature were random, we applied a Monte Carlo analysis. The resulting distribution of slopes had a mean value of -2.3×10^{-4} and SD of 0.007 with a standard error of 2.2×10^{-4}.

Changes of mean f_0 and the first two formants are depicted in Figure 8.2. There is no visible trend for F1 or F2, while a clear rise is present for f_0. Linear regression showed that the trends for f_0 and F2 were significant (see Table 8.2). Monte Carlo simulated distribution for f_0 slopes had a mean value of 1.3×10^{-3} and SD of 0.029 with a standard error of 9.4×10^{-4}. For F2 simulated slope distribution had a mean of 0.02, SD of 0.61 and a standard error of 0.019.

After correcting for multiple comparisons with the Bonferroni method, the only significant p-values were for f_0 and F2 trends ($p < .001$ and $p = .039$ accordingly).

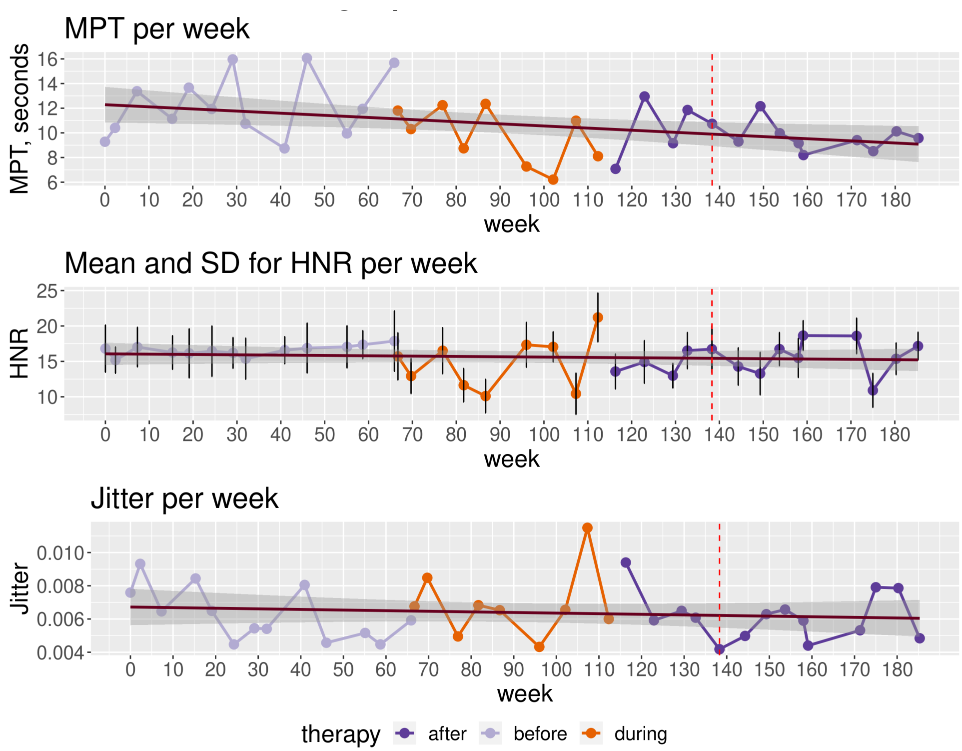

Figure 8.1 | Changes in MPT, HNR and jitter over time. Red vertical dotted line corresponds to the beginning of the COVID-19 related measures in the Netherlands.

Table 8.1 | Results of the linear regression analysis for MPT, jitter and HNR.

	Jitter			**HNR**			**MPT**		
Predictors	Est.	CI	p	Est.	CI	p	Est.	CI	p
(Intercept)	0.01	0.01:0.01	**<.001**	16.0	14.3:17.6	**<.001**	12.0	10.5:13.3	**<.001**
Week	-0.00	-0.00:0.00	0.375	-0.00	-0.02:-0.01	0.577	-0.02	-0.03:-0.00	**0.021**
Data points	35			35			35		
R^2 / adjusted R^2	0.024/-0.006			0.024/-0.006			0.010/-0.021		

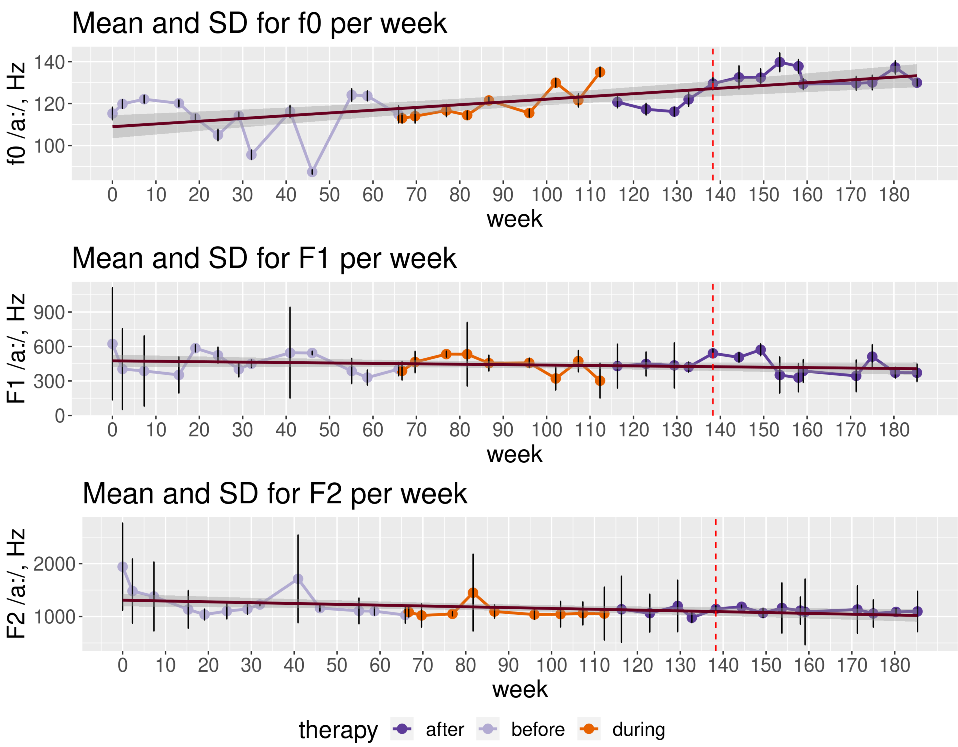

Figure 8.2 | Changes in f_0 and first two formants over time. Red vertical dotted line corresponds to the beginning of the COVID-19 related measures in the Netherlands.

Table 8.2 | Results of the linear regression analysis for f_0, F1 and F2.

	f_0			F1			F2		
Predictors	Est.	CI	p	Est.	CI	p	Est.	CI	p
(Intercept)	109	106:115	**<.001**	469	413:524	**<.001**	1314	1192:1435	**<.001**
Week	0.12	0.08:0.16	**<.001**	-0.33	-0.84:0.18	0.194	-1.59	-2.71: -0.48	**0.007**
Data points	35			35			35		
R^2 / adjusted R^2	0.498 / 0.483			0.498 / 0.483			0.051 / 0.022		

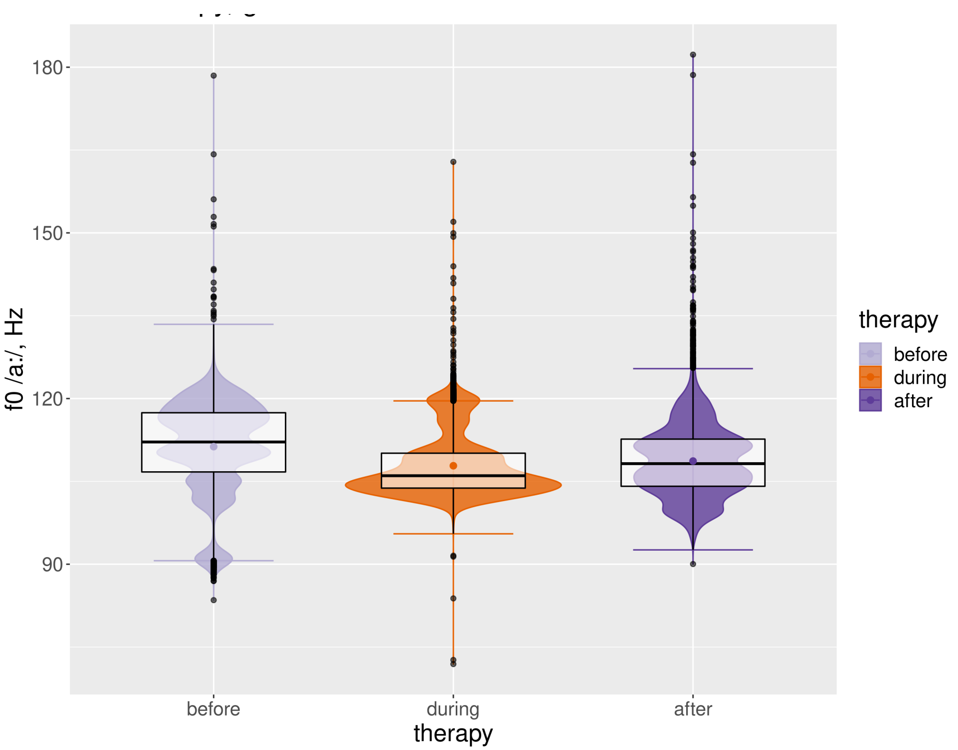

Figure 8.3 | Distributions of f_0 values at three therapy stages after the deduction of the general linear trend.

An analysis of the therapy effects after deduction of the general trend showed no significant results for any of the above features for the prolonged phonation. However, we also tested the absolute values of f_0 to avoid any information loss by aggregating features per session. Since the number of measurements was very high, we opted for the Kolmogorov-Smirnov test instead of ANOVAs to compare if the distributions of f_0 values differed at different stages of the therapy, after deduction of the general trend. Therefore, we compared stages "before" and "during" as well as "during" and "after" therapy by means of the Kolmogorov-Smirnov two-sample test on the main dependent variable of f_0. The percentage of f_0 for the comparison "before" – "during", $D = 0.383$, $p < .001$, and the percentage of f_0 for the comparison "during" – "after", $D = 0.164$, $p < .001$ indicated that both pairs of the distributions were significantly different (see Figure 8.3).

SPONTANEOUS SPEECH

Speech and articulation rates.

An analysis of speech and articulation rate in spontaneous monologues showed no significant trend over time (see Tables 8.3 and 8.4). An analysis of therapy effect after deduction of the general trend showed no significant results for any of the rate features in the monologue (see Appendix F.2).

Table 8.3 | Results of the linear regression analysis for speech and articulation rates in Dutch monologues.

	Articulation rate			**Speech rate**		
Predictors	Est.	CI	p	Est.	CI	p
(Intercept)	4.93	4.76:5.11	**<.001**	3.85	3.69:4.01	**<.001**
Week	-0.00	-0.00:0.00	0.761	-0.00	-0.00:0.00	0.719
Data points	35			35		
R^2 / adjusted R^2	0.003/-0.027			0.004/-0.026		

Table 8.4 | Results of the linear regression analysis for speech and articulation rates in English monologues.

	Articulation rate			**Speech rate**		
Predictors	Est.	CI	p	Est.	CI	p
(Intercept)	4.73	4.57:4.90	**<.001**	3.77	3.63:3.92	**<.001**
Week	-0.00	-0.00:0.00	0.607	-0.00	-0.00:0.00	0.191
Data points	35			35		
R^2 / adjusted R^2	0.008/-0.022			0.051/0.023		

f_0 variability and means

Changes over time in f_0 variability and means for both Dutch and English are plotted on Figures 8.4 and 8.5. The linear regression analysis resulted in significant trends for f_0 means over time in both languages, but not for f_0 variability (see Tables 8.5 and 8.6).

The Monte Carlo simulated distribution for mean f_0 slopes in Dutch monologues had a mean value of -8.4×10^{-5} and SD of 0.028 with a standard error of 8.9×10^{-4}. For English monologues, the mean value was -1.7×10^{-3}, SD was 0.027 with the same standard error of 8.9×10^{-4}. Bonferroni adjustment for f_0 measurements showed the preserved significance of all the previously significant trends: mean f_0 in Dutch ($p < .001$), mean f_0 in English ($p = .004$).

An analysis of the therapy effects after deduction of the general trend showed no significant results for f_0 variability or f_0 means in the monologue. Similar to the evaluation of the prolonged phonation, we tested the absolute values of f_0 obtained from the monologue recordings to avoid any information loss by aggregating features per session. The results of the Kolmogorov-Smirnov test for f_0 values at different stages of the therapy after deduction of the general trend in Dutch and in English are listed in Table 8.7.

Inappropriate silences.

The change in the number of inappropriate silences over time in both Dutch and English monologues are presented on Figure 8.6.

The linear regression analysis yielded no significant trends, as well as there was no significant results in comparison of distributions in therapy stages after the general trend deduction. For details see Appendix F.3.

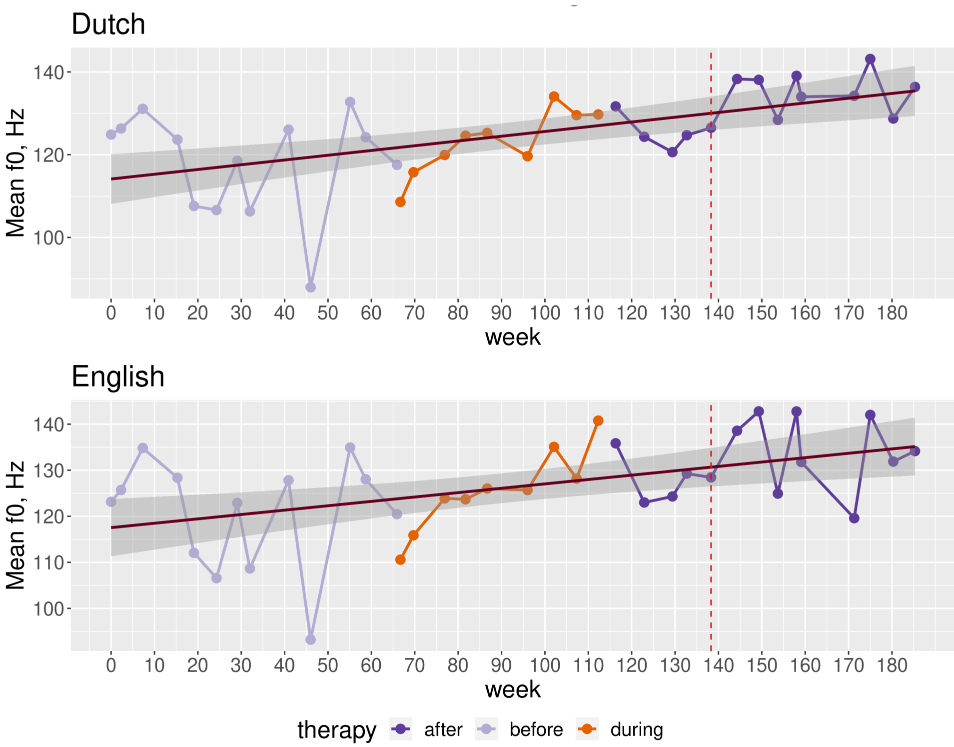

Figure 8.4 | Changes in mean f_0 in monologues in two languages over time. Red vertical dotted line corresponds to the beginning of the COVID-19 related measures in the Netherlands.

Table 8.5 | Results of the linear regression analysis for f_0 means over time in Dutch and English monologues.

	f_0 **means (Dutch)**			f_0 **means (English)**		
Predictors	Est.	CI	p	Est.	CI	p
(Intercept)	116.3	111.3:121.3	**<.001**	119.5	114.0:125.0	**<.001**
Week	0.10	0.06:0.15	**<.001**	0.08	0.03:0.13	**0.002**
Data points	35			35		
R^2 / adjusted R^2	0.381/0.362			0.253/0.230		

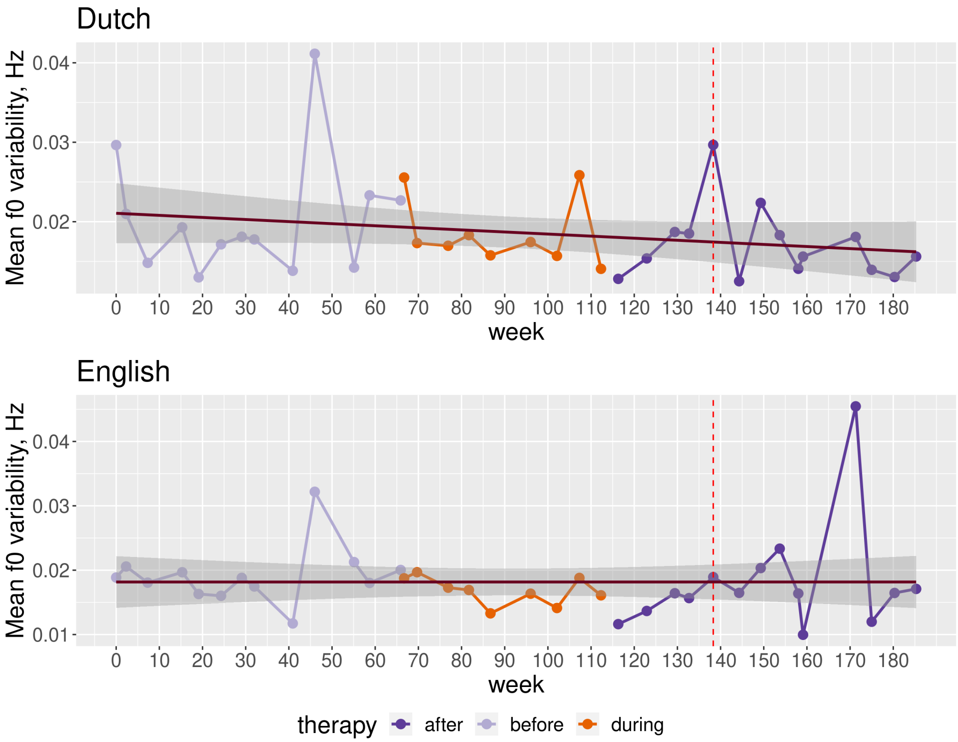

Figure 8.5 | Changes in f_0 variability in monologues in two languages over time. Red vertical dotted line corresponds to the beginning of the COVID-19 related measures in the Netherlands.

Table 8.6 | Results of the linear regression analysis for f_0 variability over time in Dutch and English monologues.

	f_0 variability (Dutch)			**f_0 variability (English)**		
Predictors	Est.	CI	p	Est.	CI	p
(Intercept)	0.02	0.02:0.02	**<.001**	0.02	0.01:0.02	**<.001**
Week	-0.00	-0.00:0.00	0.218	-0.00	-0.00:-0.00	0.728
Data points	35			35		
R^2 / adjusted R^2	0.046/0.017			0.004/-0.026		

Table 8.7 | Results of the Kolmogorov-Smirnov two-sample test on the main dependent variable of f_0 in Dutch and English monologues after deduction of the general trend.

Therapy stages comparison	**f_0 (Dutch)**		**f_0 (English)**	
	D	p	D	p
“before” – “during”	0.104	**<.001**	0.104	**<.001**
“during” – “after”	0.102	**<.001**	0.102	**<.001**

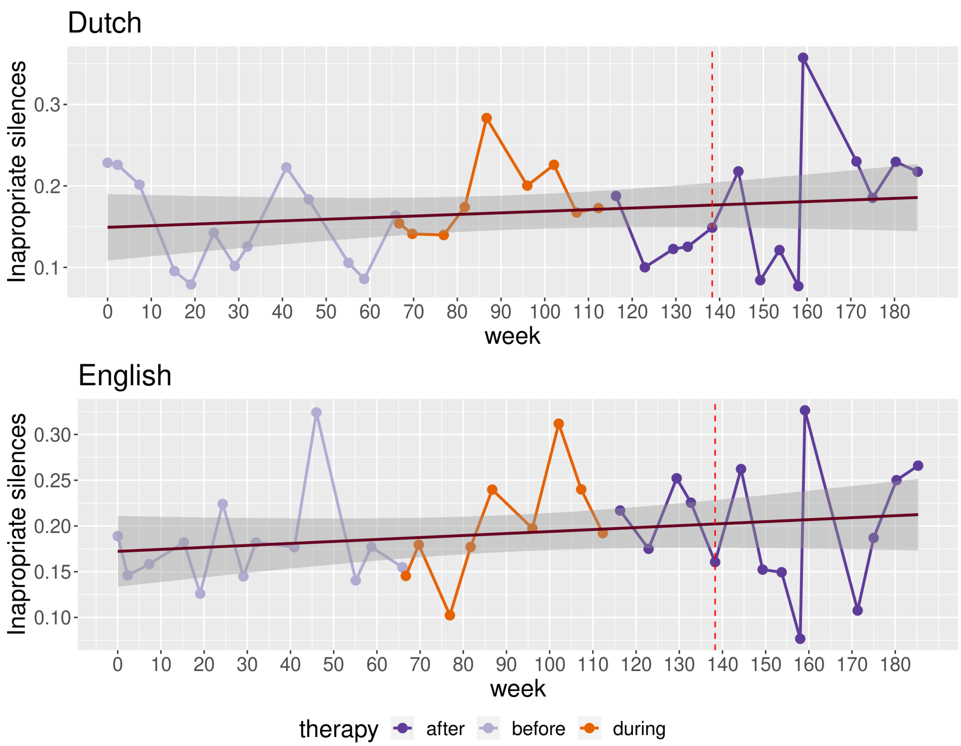

Figure 8.6 | Number of inappropriate silences in Dutch and English monologues over time. Red vertical dotted line corresponds to the beginning of the COVID-19 related measures in the Netherlands.

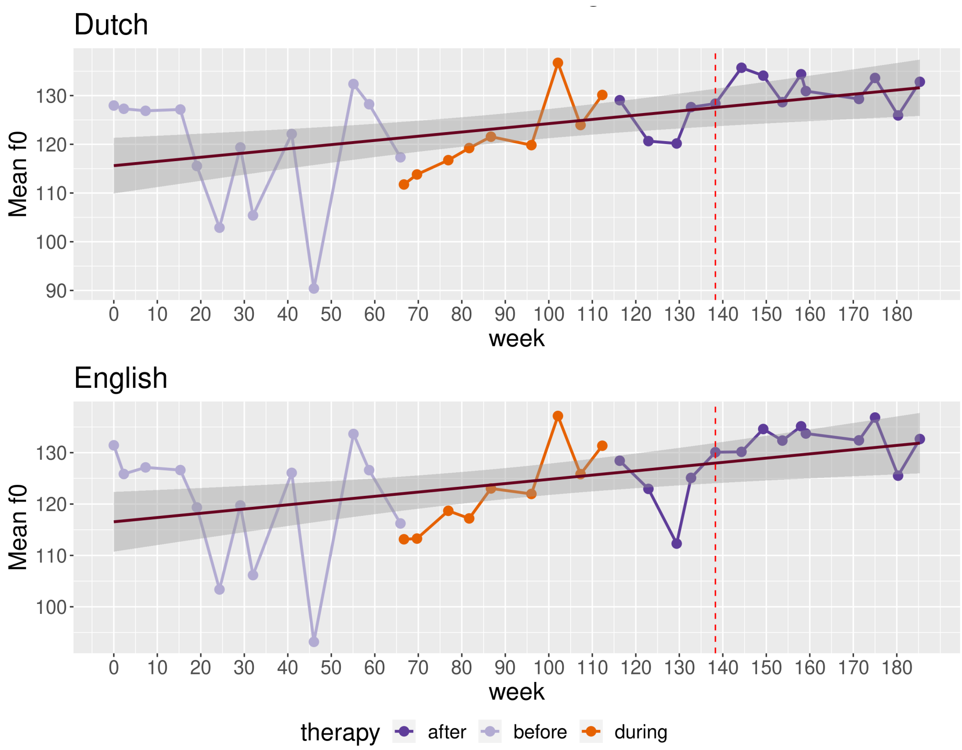

Figure 8.7 | Changes in mean f_0 in reading in two languages over time. Red vertical dotted line corresponds to the beginning of the COVID-19 related measures in the Netherlands.

READING

Speech and articulation rates

Features of speech and articulation rates showed no significant trend over time (for details, see Appendices F.4 and F.5). However, the analysis of the therapy influence on the rate measurements demonstrated one significant difference for speech rate in English reading. An ANOVA test showed that the differences between stages were significant, $F(2,32) = 4.372$, $p = .021$. A post hoc Tukey test showed the significant difference between "before" and "during" therapy stages ($p = .024$) and "during" and "after" therapy stages ($p = .04$).

f_0 variability and means

Changes in f_0 variability and f_0 means over time are plotted on Figures 8.7 and 8.8. A linear regression analysis showed significant trends for mean f_0 variability over time for English reading (see Table 8.8) and for mean f_0 in both Dutch and English reading (see Table 8.9). The Monte Carlo simulated distribution for f_0 variability slopes on English had a mean value of 2.08×10^{-7} and SD of 1×10^{-5} with a standard error of 3.2×10^{-7}. Regarding mean f_0 in Dutch reading, the mean value of the simulated slope distribution was 1.1×10^{-4}, with an SD 2.4×10^{-3} and a standard error of 7.6×10^{-4}. For English reading,

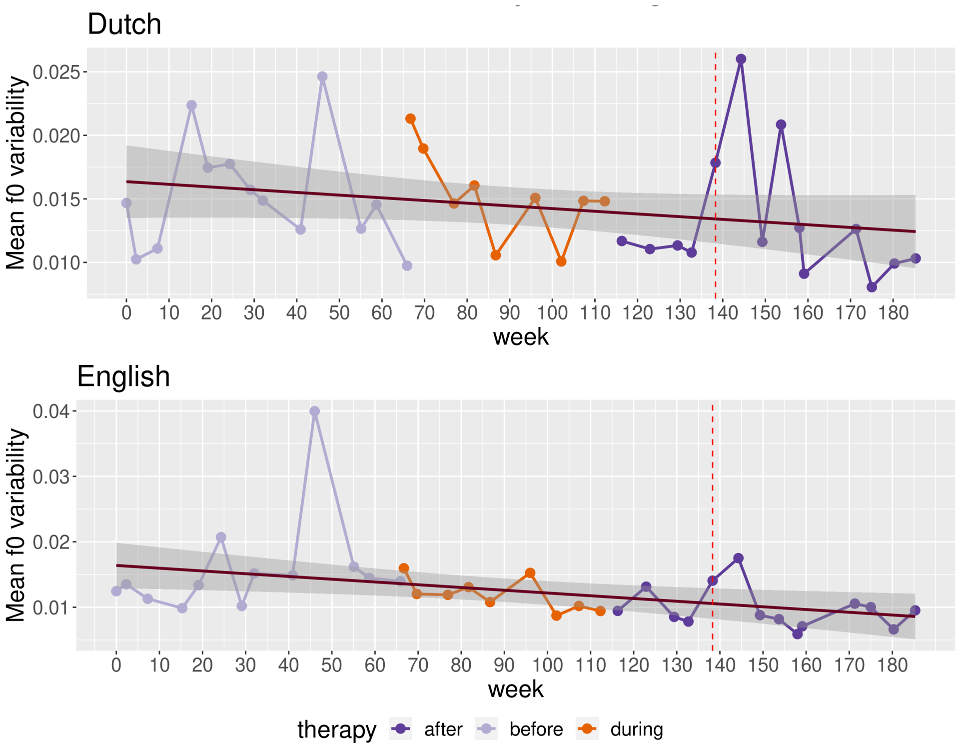

Figure 8.8 | Changes in mean f_0 variability in reading in two languages over time. Red vertical dotted line corresponds to the beginning of the COVID-19 related measures in the Netherlands.

Table 8.8 | Results of the linear regression analysis for f_0 variability over time in Dutch and English reading.

	Mean f_0 variability (Dutch)			**Mean f_0 variability (English)**		
Predictors	Est.	CI	p	Est.	CI	p
(Intercept)	0.02	0.01:0.02	**<.001**	0.01	0.01:0.02	**<.001**
Week	-0.00	-0.00:0.00	0.175	-0.00	-0.00:-0.00	**0.001**
Data points	35			35		
R^2 / adjusted R^2	0.055/0.026			0.280/0.259		

Table 8.9 | Results of the linear regression analysis for f_0 means over time in Dutch and English reading.

	Mean f_0 (Dutch)			**Mean f_0 (English)**		
Predictors	Est.	CI	p	Est.	CI	p
(Intercept)	117.6	112.8:122.4	**<.001**	118.4	113.3:123.5	**<.001**
Week	0.07	0.03:0.12	**0.002**	0.07	0.02:0.12	**0.004**
Data points	35			35		
R^2 / adjusted R^2	0.259/0.236			0.224/0.200		

the mean value was -1.1×10^{-3}, with SD 2.5×10^{-2} and standard error of 7.9×10^{-4}. Bonferroni adjustment for f_0 measurements showed the preserved significance of all the previously significant trends: mean f_0 in Dutch ($p = .002$), mean f_0 in English ($p = .008$), and f_0 variability in English ($p = .004$).

The comparison of the therapy stages after deduction of the general trend demonstrated significant differences for f_0 variability in English reading. A one-way ANOVA yielded F(2,32)= 6.177, $p = .005$. A post hoc Tukey test showed a significant difference between "before" and "after" therapy stages ($p = .004$). There were no significant differences for mean values of f_0 after trend deduction. We tested the absolute values of f_0 obtained from monologue recordings to avoid any information loss by aggregating features per session. The results of the Kolmogorov-Smirnov test for absolute f_0 values at different stages of the therapy after deduction of the general trend in Dutch and in English are listed in Table 8.10.

Inappropriate silences

The linear regression analysis yielded no significant trends for the number of inappropriate pauses in reading over time. Comparison of distributions in therapy stages after the general trend deduction also showed no significant difference between stages. For details see Appendix F.6.

Table 8.10 | Results of the Kolmogorov-Smirnov two-sample test on the main dependent variable of f_0 in Dutch and English reading after deduction of the general trend.

Therapy stages comparison	f_0 (Dutch)		f_0 (English)	
	D	p	D	p
"before" – "during"	0.109	**<.001**	0.109	**<.001**
"during" – "after"	0.125	**<.001**	0.125	**<.001**

8.4. DISCUSSION

The goal of this single case study was to explore changes in two languages, Dutch (native language) and English (second language), in the time series of 36 recordings completed over 3.6 years in a speaker with PD. We explored ten conventional speech features measured from three different tasks: prolonged phonation of the vowel /aː/, monologues and reading.

Among features related to voice quality and phonation, we found significant changes in maximum phonation time and F2 with only F2 changes remaining significant after Bonferroni adjustment. Nevertheless, the observed changes in MPT measure, characterizing the aerodynamic efficiency of the vocal tract, are in line with the descriptions of the clinical picture of HD (Ramig et al., 2004). However, at the same time, a potential effect of ageing can be reflected in the measures of MPT, as the findings of Pessin et al. (2017) and Maslan et al. (2011) show lower MPT values of the elderly participants. But since these authors found no statistical significance between age groups, it appears that the trend of shortening in MPT duration in this speaker wth PD is related to the reduction in the total amount of air expended during maximum phonation in PwPD (Ramig et al., 2004). The significant falling trend in F2 suggests presence of the centralization effects progression in vowels (Skodda et al., 2012), which might be more apparent with respect to the reduced tongue movements since there were no significant changes in F1 values. The significance of a rising trend for mean f_0 with time is also in line with the changes caused by PD (Ramig et al., 2004) and has also been noted by Pessin et al. (2017) in their elderly male group, once again with no significant difference between different age groups.

In the recordings of the two other tasks, monologues and reading, we explored five features: f_0 mean and variability, speech rate, articulation rates, and inappropriate silences in both Dutch and English languages. We found similar significant trends in f_0 means for both languages, which is consistent with the significant rising trend for f_0 means in prolonged phonation. There were no significant trends in speech or articulation rates or in inappropriate silences. This contradicts the findings of Skodda et al. (2009), who found speech rate declining in their male PD group. While a significant trend for f_0 variability is present in English reading, it is explained by a spike in one later recording, where the speaker seems to produce a larger range of f_0 values. This higher range of f_0 in one recording could indirectly be caused by an emotional topic the speaker spoke about that week (week 170). However, the lack of significance of f_0 variability in English monologues does not support this explanation. Without that peak, the lack of variability change is in line with Skodda et al. (2009), who found no significant change in f_0 variability of PD speakers with time, while there were significant differences in f_0 variability compared with the control group.

The lack of significant trends for speech and articulation rates, or for the number of inappropriate silences in both languages appears to be a positive result for the stability of these speech aspects with the disease progression. This, however, contrasts with the findings of Zanini et al. (2004) and Zanini et al. (2010), who demonstrated higher mistake rates for phonological, morphological and syntactic errors in the speakers' first language. The presence of mistakes on higher levels, such as syntax and morphology, could be related to the amount of pauses or changes in rate over time, however, this was not the case for either the first or the second language of this participant. On the other hand, the speech rate measure was shown to be sensitive for capturing changes related to PD dementia (Ash et al., 2017). Ash et al. (2017) demonstrated that speech rate measurement reflects a decline only in a group of demented people with Parkinson's disease spectrum disorder, while there was no decline in mildly demented people with the same disease. Therefore, with no significant trend for speech rate we can assume that no emerging cognitive difficulties have affected the speech of the participant.

Regarding the effect of speech therapy, with the removal of the general trend we found significant differences for f_0 in stages with and without therapy for all tasks in both languages of the participant. Interestingly, we also found significant differences between therapy stages for speech rate and for f_0 variability in reading, but only for English. These findings suggest that the effects of therapy in one language transfer to another language.These results on the effect of speech therapy on the second language of bilingual speakers are unique, though they are also exploratory. However, it is visible on the plotted f_0 means and variability for every task (Fig.8.2,8.4,8.5,8.7) how variable the values of f_0 measurements are in sessions before therapy while appearing more "stable" during and after therapy sessions. While we found effects in both languages, the only study on speech therapy effects in dysarthric bilinguals demonstrated better results for one language of the two (Lee and McCann, 2009). This warrants further research into longitudinal tracking of acoustic measurements in dysarthric speakers relating to effects of therapy in more than one language.

In interpreting our findings, there are several limitations that should be considered. First, this is a single case study which prevents us from making any generalizations. It was highlighted by many researchers that HD manifestations may often have an individual pattern, while little is known about development of different speech modalities in the course of the disease (Skodda et al., 2012, 2013; Arias-Vergara et al., 2018). Second, our study has an exploratory nature, as we analyzed the presence of general linear trends and compared distribution shapes of our data. Therefore, while we do not see any significant linear trends for some features, we cannot be sure there is no change present.

In conclusion, we found a differential pattern of longitudinal speech changes in both languages of our participant. The significant changes were present both in phonation and prosody as captured by MPT and f_0 means and variability. We also found an effect of speech therapy in one language present in both languages of the speaker, while in the case of speech rate such effects were significant only in the reading task and for the participant's second language (English). Further research should investigate the non-linearity of such time-series speech data and expand the list of features which may provide additional insights into the nature of acoustic change and therapy effects in both languages. Contrary to the common pretest-posttest designs, such longitudinal studies with dense measurements and time-series designs allow one to explore the progress and nature of HD development over time. The results of such studies could paint a more detailed picture of speech disorder progression and provide speech therapists with important insights into the "process" rather than the "product" of such change or therapy effects.

IV

Discussion and conclusions