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Title: *Compensatory articulatory mechanisms preserve intelligibility in prodromal Parkinson's disease*

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Abstract

Introduction: Dysarthria is highly prevalent in patients with Parkinson's disease (PD) and speech changes have already been detected in patients with prodromal PD on the acoustic level. However, the present study directly tracks underlying articulatory movements with electromagnetic articulography to investigate early speech alterations on the kinematic level in isolated REM sleep behavior disorder (iRBD) and compares them to PD and control speakers.

Methods: Kinematic data of 23 control speakers, 22 speakers with iRBD, and 23 speakers with PD were collected. Amplitude, duration, and average speed of lower lip, tongue tip, and tongue body movements were analyzed. Naïve listeners rated the intelligibility of all speakers.

Results: Patients with iRBD produced tongue tip and tongue body movements that were larger in amplitude and longer in duration compared to control speakers, while remaining intelligible. Compared to patients with iRBD, patients with PD had smaller, longer and slower tongue tip and lower lip movements, accompanied by lower intelligibility. Thus, the data indicates that the lingual system is already affected in prodromal PD. Furthermore, lower lip and especially tongue tip movements slow down and speech intelligibility decreases if motor impairment is more pronounced.

Conclusion: Patients with iRBD adjust articulatory patterns to counteract incipient motor detriment on speech to maintain their intelligibility level.

Compensatory articulatory mechanisms preserve intelligibility in prodromal Parkinson's disease

Introduction

In addition to classic motor symptoms of limb bradykinesia and gait difficulties in Parkinson's disease (PD), patients with PD often suffer from hypokinetic dysarthria, a motor speech disorder that is associated with irregularities within the basal ganglia control circuit [1]. Hypokinetic dysarthria affects several speech-related systems, such as respiration, phonation, and articulation, and negatively impacts speech function [1]. Speech characteristics of patients with PD are related to imprecise articulation, monoloudness, monopitch and reduced intelligibility [1]. Patients with isolated rapid eye movement (REM) sleep behavior disorder (iRBD) do not exhibit relevant motor symptoms by definition but they are at high risk of developing Parkinson's disease (PD). Patients with iRBD already show beginning dopaminergic degeneration as well as minimal motor symptoms, which are typically not perceived by the patients' themselves or next of kin [2,3]. Furthermore, iRBD constitutes the prodromal marker with the highest likelihood of developing PD [4,5]. Therefore, deviations in speech performance might already evolve in patients with iRBD in the direction of a hypokinetic dysarthria.

Previous studies investigated speech in patients with iRBD on the acoustic level only, while underlying articulatory movements of the tongue and lips shaping speech production are scarcely studied. A reduced ability to modulate pitch was observed in speakers with iRBD [6–8]. Besides monopitch, articulatory deficits were reported most dominant [9], leading to a reduction of the acoustic vowel space [10] and a trend towards slowed articulation rates [7].

While acoustic speech parameters deviated between speakers with iRBD and a control group, no perceptual differences (= intelligibility) were identified by listeners [7].

The present study aimed to track articulatory movements of the lingual and labial systems with electromagnetic articulography to investigate early alterations of speech production in incipient PD. This enables us to go beyond the acoustic surface and analyze the underlying speech motoric disbalance. As the acoustic vowel space and articulation rate were previously shown to be reduced in iRBD [7,10], smaller movement amplitudes (reduction in range) and longer movement durations (more time needed to achieve articulatory target) were expected. Data of patients with iRBD were compared to speech patterns of age-matched healthy controls (CON) and patients with PD.

Methods

Participants and assessments

The study consisted of a production and a perception experiment. For the speech production part, 68 native speakers of German were included in the study (Table 1): 22 speakers with iRBD, 23 speakers with PD, and 23 CON speakers. While patients were recruited during clinical routine visits in the Department of Neurology of the University Hospital Cologne, healthy controls were either relatives of the patients with iRBD or subjects who had already participated in other studies of the investigators. None of the participants showed signs of dementia or depression according to screening tests (Parkinson Neuropsychometric Dementia Assessment [11], cut-off < 14 | Beck's Depression Inventory-II [12], cut-off > 20).

Table 1: Demographics, clinical characteristics, and intelligibility ratings per group. Means (sd) are presented. CON = healthy control, iRBD = isolated rapid eye movement sleep behavior disorder, PD = Parkinson's disease, UPDRS III = part III of Unified Parkinson's Disease Scale, PANDA = Parkinson Neuropsychometric Dementia Assessment, BDI-II = Beck's Depression Inventory-II.

	CON	iRBD	mild PD	advanced PD	p-values
sex	6 f, 17 m	4 f, 18 m	4 f, 10 m	1 f, 8 m	$X^2(3) = 1.3822$, $p = .71$
age (years)	61 (± 9)	64 (± 6)	60 (± 8)	60 (± 8)	$F(-3) = 1.0529$, $p = .38$
disease duration (years)	-	7 (± 6)	6 (± 5)	9 (± 3)	$F(-2) = 0.7209$, $p = .49$
UPDRS III	5 (± 4)	8 (± 4)	22 (± 6)	44 (± 5)	$F(-3) = 160.85$, $p < .001$ (only CON vs. iRBD is not significant, $p = .12$)
rated intelligibility (1 – 101 scale)	83 (± 20)	78 (± 21)	74 (± 24)	60 (± 28)	CON vs. iRBD: $p = .06$ CON vs. mild PD: $p = .008$ ($\beta = 0.86$) CON vs. advanced PD: $p < .001$ ($\beta = 1.85$) iRBD vs. mild PD: $p = .18$ iRBD vs. advanced PD: $p < .001$ ($\beta = -1.45$)
PANDA	24 (4)	25 (4)	23 (6)	24 (3)	$F(-3) = 0.4838$, $p = .70$
BDI-II	2 (2)	5 (6)	7 (4)	5 (5)	$F(-3) = 4.2719$, $p = .008$ (only CON vs. mild PD is significant, $p = .005$)

All participants' motor functions were assessed by using part III of the Unified Parkinson's Disease Rating Scale (UPDRS) [13]. Patients with PD were assessed in a pragmatically defined medication-OFF condition after withdrawing PD medication for at least 12 hours. The PD

group was divided into two groups: (i) patients with mild motor symptoms (UPDRS III $\leq$ 32) and (ii) patients with more severe motor symptoms (UPDRS III $\geq$ 33) [14].

Speech production data

Speech production data were elicited by using electromagnetic articulography (EMA; AG 501, Carstens). Small sensors were attached to the lower lip, the tongue tip, and the tongue body to capture the spatiotemporal characteristics of articulatory movements during speech (Figure S1). Two additional sensors were placed behind the ears on the cartilage that functioned as reference sensors for head correction. Transmitter coils positioned in a construction above the head generate a magnetic field that induces an alternating current to determine the position and movement of the sensors that were attached to the articulators and head in a three-dimensional space. The raw data were converted into positional data using CalcPos software first. Second, the data were head-corrected and rotated into a head-based coordinate system using a biteplane recording and the respective NormPos software. The used software was provided by Carstens. Afterwards, the kinematic data were converted into ssff-format to be displayed and further processed in the EMU-webAPP of the EMU-SDMS environment [15]. Further details of the experimental set-up, the speech material, and the data processing were described previously [16–18].

Speakers produced sentences, e.g., “Die Oma hat der Mila gewunken.” (“The grandma waved at Mila.”), with the girl’s name used in all sentences varying (e.g., Mila or Lina, C₁V₁C₂V₂ syllable structure). The sentences were constructed to control for articulatory and prosodic contexts. To identify underlying movement patterns, open and closed vowels were alternated around and within the target words. The analysis focused on the consonant-vowel sequence of the first syllable (C₁V₁) from each of the ten girl names (Table S1), which were produced in

three different focus conditions that reflect different degrees of prominence of the target word within the prosodic context of an utterance, ranging from low to high prominence of the name [19,20]. Tongue body movements refer to the production of the V_1 vowels (i, e, a, o, u), tongue tip movements to the production of the alveolar C_1 consonant /l/, and lower lip movements to the production of the labial C_1 consonant /m/. The articulatory movements producing these sounds in the vertical dimension within the oral vocal tract were the unit of interest. For each articulatory movement, the amplitude (mm) and the duration (ms) were calculated (Figure S2). While the duration indicates how much time a speech movement takes, the amplitude refers to the spatial distance the articulator travels during this time interval to reach the target position. Furthermore, the average movement speed was calculated as a ratio of amplitude over duration.

Intelligibility ratings

In a speech perception experiment, 280 naive listeners independently rated the intelligibility of a subset of sentences collected in the production experiment. Naive listeners instead of professional listeners were chosen to gain perceptual ratings that reflect daily communicative contexts. The speech recordings were divided into several unities of equal duration and were randomly presented to the listeners. Each audio was at least rated by 40 independent listeners. The sentences included were produced in the most natural prominence condition (broad focus) and contained only girl names with the V_1 vowels /i, e, u/ in their first syllable to reduce the experiment's time and counteract fatigue effects of the listeners. Ratings were elicited on a two-sided visual analog scale, ranging from 1 to 101, and conducted using SoSci Survey [21]. The higher the values, the more intelligible the speech output. Naive listeners were recruited via Prolific (www.prolific.co). The cohort was prescreened to include only listeners whose native language is German and who have no hearing difficulties.

Statistical analyses

To test differences in age, disease duration, motor functions and cognitive functions between the groups linear models were conducted by using the “lme4 package”[22]. The group effect was validated by comparing the test model (with critical predictor) to a reduced model (without the critical predictor) via likelihood-ratio tests. P-values are based on these comparisons. If the main effect of the critical predictors was found significant, pairwise post-hoc analyses were completed by using the tukey method within the “emmeans package”[23]. A two sample Chi-square test was used to test differences in the sex distribution between the groups. Results are reported in Table 1.

Linear mixed models were applied to test group effects on articulatory parameters using the ‘lme4’ package [22] in the software R [24]. While group and prominence conditions were predictor variables, random intercepts were included for speaker, vowel type, and consonant. The latter was added when investigating tongue body movement patterns only. If the main effect for the group was found significant at $p < .05$, pairwise post-hoc analyses were conducted by using the ‘emmeans’ package [25]. The tukey method was used for p-value adjustment. Please note that none of the interaction terms of group x prominence condition were found significant. All test results are reported in Table 2.

Continuous ordinal regression models were applied to test differences in intelligibility ratings across the groups [26]. Group, vowel, and consonant were predictor variables. Random intercepts were included for the speaker and rater. Significance was accepted at $p < .05$. Group effects on intelligibility ratings were tested pairwise in separate models (CON vs. iRBD, CON vs. mild PD, etc.). Results are reported in Table 1.

In addition, associations between motor impairment, articulatory speech parameters, and intelligibility ratings across speakers were explored. By using the Shapiro-Wilk test, the normal distribution of relevant parameters was tested. If both parameters were normally distributed, a Person correlation was calculated. In all other cases a Spearman correlation was calculated.

Results

Gross motor assessment

Patients with iRBD and PD as well as CON participants were comparable concerning age and sex distribution. While UPDRS III scores did not differ between CON participants and patients with iRBD, scores differed to patients with mild and advanced PD. Scores increased by 17 points from CON participants to patients with mild PD, and further to patients with more advanced PD by 22 points (Table 1).

Intelligibility

16111 ratings were considered for the continuous ordinal regression models to compare intelligibility across groups. Intelligibility ratings significantly decreased from CON speakers to mild PD (CON: $M = 83$, $SD = 20$ | PD_{mild}: $M = 74$, $SD = 24$ | $\beta = 0.86$, $p = .008$) and further to advanced PD (PD_{advanced}: $M = 60$, $SD = 28$ | $\beta = 1.85$, $p < .001$). Comparable to previous studies, patients with iRBD did not show lower intelligibility compared to CON speakers, but patients with advanced PD were less intelligible than speakers with iRBD (iRBD: $M = 78$, $SD = 21$ | $\beta = -1.45$, $p < .001$).

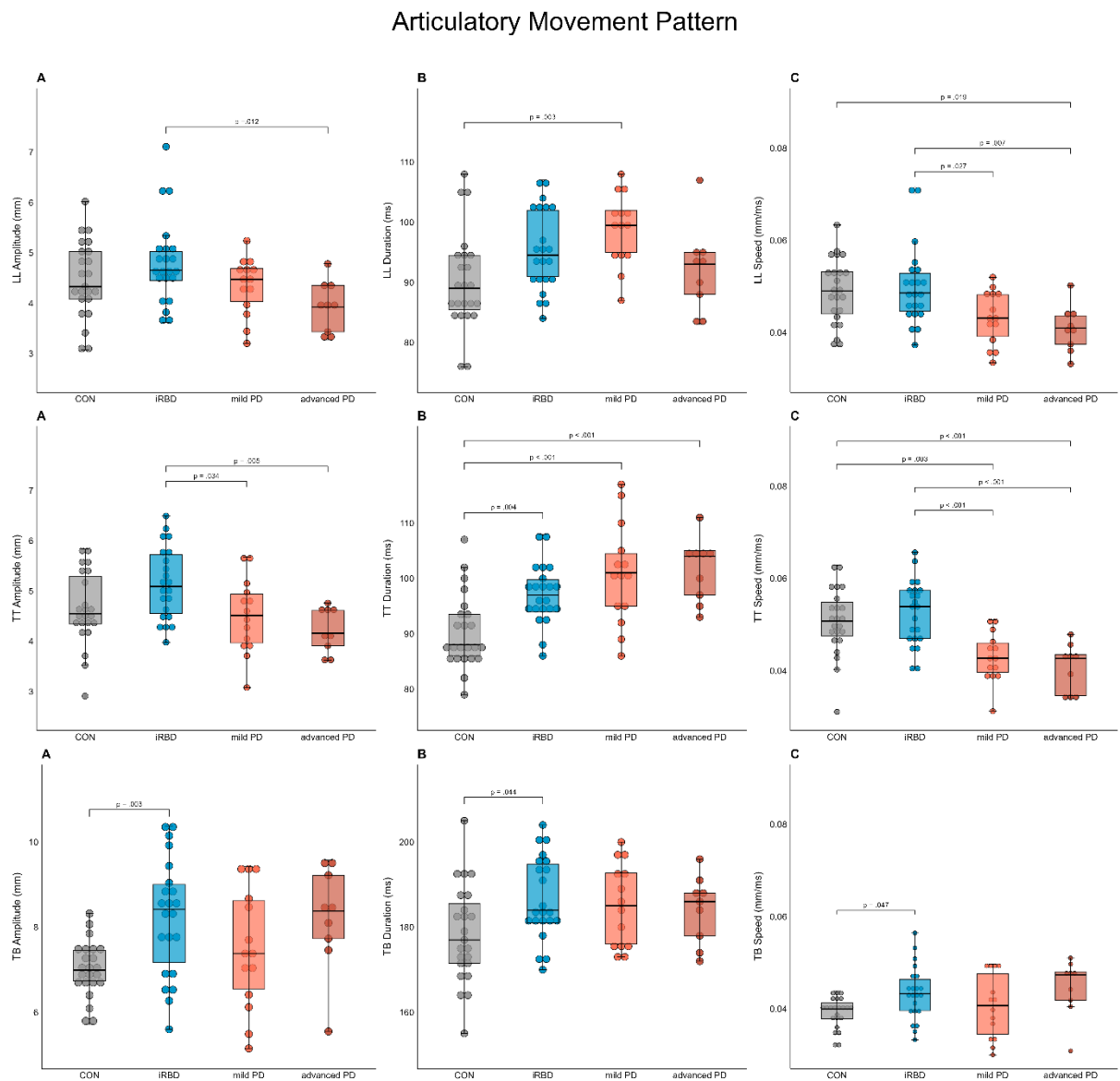


Figure 1: Articulatory results for lower lip (LL), tongue tip (TT), and tongue body (TB) movements per group and parameter as averages across prominence conditions. A: Movement amplitude, B: Movement duration, C: Average movement speed. Significant results of post-hoc analyses are indicated. CON = healthy control, IRBD = isolated rapid eye movement sleep behavior disorder, PD = Parkinson's disease.

Lower Lip Movement

1023 productions went into the analysis of lower lip movements. Statistical analyses revealed a significant effect of group for movement amplitudes ($X^2(3) = 10.153, p = .017$), movement

224 durations ($X^2(3) = 13.788$, $p = .003$), and movement speeds ($X^2(3) = 15.509$, $p = .001$). Results
225 of post-hoc analyses are presented in Figure 1 (top row).

226 Movement amplitudes were slightly but non-significantly enlarged between patients with
227 iRBD and CON speakers, and gradually decreased from iRBD to advanced PD, resulting in
228 nearly 1.0 mm reduction of movement amplitudes from iRBD to advanced PD (CON: $M = 4.5$,
229 $SD = 2.6$ | iRBD: $M = 4.8$ mm, $SD = 2.6$ | PD_{mild}: $M = 4.3$ mm, $SD = 2.4$ | PD_{advanced}: $M = 3.9$
230 mm, $SD = 2.5$; Figure 1).

231 Oppositely, the duration of lower lip movements gradually increased from CON speakers to
232 mild PD with patients with iRBD showing a duration in-between (CON: $M = 90$ ms, $SD = 25$
233 | iRBD: $M = 95$ ms, $SD = 25$ | PD_{mild}: $M = 99$ ms, $SD = 24$ | PD_{advanced}: $M = 92$ ms, $SD = 25$).

235 When analyzing the average speed as a result of duration and amplitude of the movement,
236 patients with iRBD exhibited identical speed of lower lip movements compared to CON
237 speakers; however, the average speed was slower in both PD groups as a result of smaller and
238 prolonged movements (CON: $M = 0.049$, $SD = 0.025$ | iRBD: $M = 0.050$, $SD = 0.025$ | PD_{mild}:
239 $M = 0.043$, $SD = 0.022$ | PD_{advanced}: $M = 0.041$, $SD = 0.021$; Figure 1, Table 2).

241 *Tongue Tip Movement*

242 1020 data points went into the analysis of the tongue tip movement. Statistical analyses
243 revealed a significant effect of group for movement amplitudes ($X^2(3) = 13.775$, $p = .003$),
244 movement durations ($X^2(3) = 26.577$, $p < .001$), and movement speeds ($X^2(3) = 28.936$, $p <$
245 $.001$). Results of post-hoc analyses are presented in Figure 1 (mid row).

246 Again, movement amplitudes were slightly but non-significantly larger in patients with iRBD
247 compared to CON speakers and gradually decreased from iRBD to both PD groups (Figure 1,

mid row, A). Similar to lower lip movement amplitudes, amplitudes of tongue tip movements decreased by 1.0 mm from iRBD to advanced PD (CON: $M = 4.7$ mm, $SD = 2.5$ | iRBD: $M = 5.2$ mm, $SD = 2.7$ | PD_{mild}: $M = 4.5$ mm, $SD = 2.6$ | PD_{advanced}: 4.2 mm, $SD = 2.7$).

Patients with iRBD had longer tongue tip movement durations than CON speakers: Movement duration increased from $90 \text{ ms} \pm 24$ in the CON group to $97 \text{ ms} \pm 23$ in the iRBD group. Movement durations of the tongue tip further increased in both PD groups (PD_{mild}: $M = 101$ ms, $SD = 27$ | PD_{advanced}: $M = 101$ ms, $SD = 27$). Thus, we could observe a stepwise increase from CON to iRBD to PD in tongue tip movement duration, comparable to our observations of lower lip movements. However, this increase is more pronounced in tongue tip movements.

Again, the average speed of movements of the tongue tip did not differ between CON speakers and patients with iRBD, but the speed of movements slowed down in both PD groups compared to the CON and iRBD groups, as a result of smaller and prolonged movements (CON: $M = 0.051$, $SD = 0.024$ | iRBD: $M = 0.053$, $SD = 0.025$ | PD_{mild}: $M = 0.043$, $SD = 0.021$ | PD_{advanced}: $M = 0.041$, $SD = 0.023$; Figure 1, Table 2).

Tongue Body Movement

2043 data points went into the analysis of the tongue body movements. Statistical analyses revealed a significant effect of group for movement amplitudes ($X^2(3) = 14.153$, $p = .043$), movement durations ($X^2(3) = 8.1259$, $p = .044$), and movement speeds ($X^2(3) = 10.038$, $p = .018$). Results of post-hoc analyses are presented in Figure 1 (bottom row).

We observed a different pattern compared to movements of the lower lip and the tongue tip: Patients with iRBD had again significantly larger and longer tongue body movements than

CON speakers, but parameters did not change from iRBD to PD groups (Figure 1, bottom row, A + B).

Amplitudes of tongue body movements were larger in the iRBD group, as they increased from 7.0 mm $\pm$ 4.2 in the CON group to 8.2 mm $\pm$ 5.0 in the iRBD group. Although speakers with PD did not differ significantly from CON speakers, there is a trend that tongue body movement amplitudes gradually increase from CON to mild PD to the advanced PD group (PD_{mild}: M = 7.5 mm, SD = 4.5 | PD_{advanced}: M = 8.2 mm, SD = 4.7). Movement amplitudes seem to be of the same height in the iRBD and advanced PD group.

Movement durations increased from 178 ms $\pm$ 41 in the CON group to 187 ms $\pm$ 38 in the iRBD group but did not change in the PD groups (PD_{mild}: M = 185 ms, SD = 41 | PD_{advanced}: M = 184 ms, SD = 44).

The differences in amplitude and duration of vocalic tongue body movements between CON speakers and speakers with iRBD was reflected in higher average speeds in the iRBD group (CON: M = 0.039, SD = 0.021 | iRBD: M = 0.043, SD = 0.023). The average speed of patients with PD did not distinguish itself from the other groups (PD_{mild}: M = 0.041, SD = 0.024 | PD_{advanced}: M = 0.045, SD = 0.024).

Table 2: Results of statistical analyses. Main effects were validated by model comparisons via likelihood-ratio tests. If the main effect for the group was significant at $p < .05$, pairwise post-hoc analyses were conducted, and test results are reported.

		Main effect: group	Post-hoc analyses for factor group	Estimated mean difference ($\pm$ SE)
Lower Lip	Duration	$X^2(3) = 13.788$, $p = .003$	CON vs. mild PD: $t(67.0) = -3.689$, $p = .003$	-8.67 (2.35)
	Amplitude	$X^2(3) = 10.153$, $p = .017$	iRBD vs. advanced PD: $t(68.5) = 3.169$, $p = .012$	0.89 (0.28)
	Speed	$X^2(3) = 15.509$, $p = .001$	CON vs. advanced PD: $t(68.5) = 3.007$, $p = .019$	0.008 (0.003)
			iRBD vs. mild PD: $t(67.4) = 2.870$, $p = .027$	0.007 (0.002)
			iRBD vs. advanced PD: $t(68.5) = 3.369$, $p = .007$	0.009 (0.003)
Tongue tip	Duration	$X^2(3) = 26.577$, $p < .001$	CON vs. iRBD: $t(67.6) = -3.549$, $p = .004$	-6.90 (1.94)
			CON vs. mild PD: $t(71.7) = -4.663$, $p < .001$	-10.61 (2.28)
			CON vs. advanced PD: $t(72.3) = -4.245$, $p < .001$	-11.23 (2.65)
	Amplitude	$X^2(3) = 13.775$, $p = .003$	iRBD vs. mild PD: $t(68.0) = 2.783$, $p = .034$	0.65 (0.23)
			iRBD vs. advanced PD: $t(68.6) = 3.443$, $p = .005$	0.93 (0.27)
	Speed	$X^2(3) = 28.936$, $p < .001$	CON. vs. mild PD: $t(67.9) = 3.593$, $p = .003$	0.008 (0.002)
			CON. vs. advanced PD: $t(68.6) = 4.042$, $p < .001$	0.010 (0.003)
			iRBD vs. mild PD: $t(68.1) = 4.405$, $p < .001$	0.010 (0.002)
			iRBD vs. advanced PD: $t(68.7) = 4.743$, $p < .001$	0.012 (0.003)
Tongue body	Duration	$X^2(3) = 8.1259$, $p = .044$	CON vs. iRBD: $t(68.2) = -2.8$, $p = .033$	-8.23 (2.94)
	Amplitude	$X^2(3) = 14.153$, $p = .003$	CON vs. iRBD: $t(67.7) = -3.629$, $p = .003$	-1.22 (0.34)
	Speed	$X^2(3) = 10.038$, $p = .018$	CON vs. iRBD: $t(67.6) = -2.661$, $p = .047$	-0.004 (0.002)

Associations between motor impairment and speech parameters across speakers

To test the dependency of motor impairment on the intelligibility level, a Spearman correlation was calculated. The relationship was explored across UPDRS III scores and averaged intelligibility ratings (averaged across all raters and productions) per speaker. Intelligibility was negatively correlated with UPDRS III scores ($r(62) = -.49$, $p < .001$). Thus, intelligibility decreases if motor impairment is more pronounced (Figure 2).

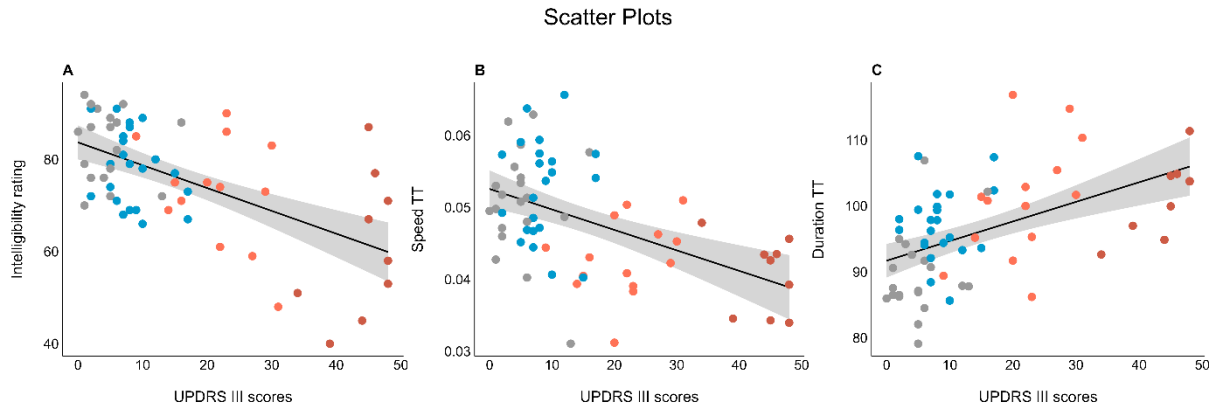


Figure 2: Tested relationships as average across all ratings/repetitions per speaker. A: Intelligibility as function of UPDRS III scores, B: Average tongue tip (TT) speed as function of UPDRS III scores, C: Tongue tip (TT) movement duration as function of UPDRS III scores. Regression lines were added for illustration purposes.

While none of the articulatory parameters were associated with the intelligibility ratings, consonantal movement patterns were correlated with motor impairment. Higher UPDRS III scores lead to lower average speeds of tongue tip movements ($r(63) = -.48, p < .001$) and are trending towards lower average speeds of lower lip movements ($r(63) = -.35, p < .01$), as Spearman correlations reveal. Additionally, the duration of tongue tip movements increases with higher UPDRS III scores (Spearman: $r(63) = .57, p < .001$). This relationship cannot be observed for lower lip movements (Spearman: $r(63) = .23, p < .001$). The data indicate that lower lip and especially tongue tip movements slow down if motor impairment deteriorates.

Discussion

Patients with iRBD neither showed significant motor impairment on UPDRS examination nor reduced intelligibility. However, patients with iRBD had longer and larger tongue movements than CON speakers despite preserved speed of movements. In contrast, the speed of movements slowed down in PD and movements became smaller and more prolonged. Hence, patients with iRBD already showed compensatory changes in the underlying articulatory movement patterns: Speech performance differed between the CON speakers and patients with iRBD as

well as between patients with iRBD and PD. Movement durations became more prolonged from the CON speakers to the patients with iRBD and further prolonged in PD accordingly to general motor impairment. In contrast, movement amplitudes were increased in patients with iRBD but decreased from overt PD onwards. While the average speed indicated an articulatory slowdown in consonantal movements in PD, the articulatory speed was preserved in patients with iRBD.

Articulatory movements of speakers with iRBD needed more time to achieve the articulatory target, but contrary to the expectations of reduced movement ranges, larger tongue movement amplitudes were determined. Longer and larger movements lead to a more distinct speech but also require an increased biomechanical effort of the articulators during speech (cf. hyper-articulation [27]). Generally, speakers aim to produce speech by following the principle of physical economy, i.e., they balance the degree of speech intelligibility and the articulatory costs. However, speakers also adapt their way of speaking dependent on internal or external factors. As can be seen in this data set, precisely the speech effort of vocalic and consonantal tongue movements increased in speakers with iRBD compared to CON speakers. Thus, speech changes in patients with iRBD are related to lingual overshoot, while the labial system showed less affection [28,29].

The observed speech pattern in patients with iRBD can be interpreted as a compensatory mechanism to counteract the effects of incipient motor detriment on speech to reach the articulatory goal. As smaller amplitudes usually lead to reduced intelligibility in dysarthric speech [30–32], this compensatory mechanism helped to maintain the intelligibility level, which was not necessary for CON speakers. Furthermore, larger articulatory movements have been observed in mild-dysarthric speakers with PD before [33]. Thus, the hyper-articulation

strategy may indicate that patients with iRBD are already developing dysarthria, which cannot be perceived auditorily yet – in the sense of a “prodromal” dysarthria in line with results of a previous study [7]. This means that although patients with iRBD do not show clinically manifested motor deficits that affect their activities of daily living, their speech pattern already differ from healthy controls. Thus, the compensatory mechanisms could be a predictive feature indicating the progression from iRBD to PD. However, this needs to be tested in a longitudinal study to observe how speech pattern in iRBD evolve over time. Only in this way, PD specific speech patterns occurring in the premotor and early stages can be sufficiently characterized. Another limitation of our study is that electromagnetic articulography is on the one hand a very powerful tool to uncover underlying speech movement deficits. On the other hand, it requires very controlled lab speech and the analysis procedure is rather time-consuming. A larger group of speakers with iRBD would be useful to extract effects that can serve as a speech biomarker for prodromal PD, either on the kinematic or acoustic level of speech production.

Patients with PD are less intelligible and show a slowdown of the tongue tip and the lower lip, indicating that dysarthric symptoms have already further developed from lingual to labial involvement [28]. Amplitudes of consonantal movements further decrease from mild PD to advanced PD. The reduction in amplitude is accompanied by a prolongation in the temporal domain and a decrease in the average speed. Knowing now that there may have been a phase of compensation (in terms of spatial enhancement) prior to the spatial reduction, patients with PD can no longer compensate for disease effects on their speech through spatial adjustments. The compensation mechanism may no longer be sufficient when motor symptoms get more pronounced. Thus, reduced movement amplitudes of the tongue tip and lower lip might be relevant indicators of incipient PD in iRBD.

Conclusively, this electromagnetic articulography study reveals compensatory mechanisms of speech in patients with iRBD to maintain the intelligibility level. One has to be aware that speech pattern changes in iRBD already at a level when no relevant motor symptoms are perceived by patients themselves and relatives. Moreover, the study shows that changes in tongue tip and tongue body movements might serve as a speech biomarker indicating the prodromal stage of PD. As especially vocalic tongue body movements differed between healthy controls and speakers with iRBD, vowel articulation should be focused to track speech changes as already proposed by Skrabal et al. [10] and to consider speech therapy early as possible in developing PD as especially vowel articulation has been shown to reduce intelligibility [34,35]. In addition, the knowledge about the compensation mechanisms could be interesting for the development of speech therapy approaches. Since compensation cannot be maintained in the advanced phase of PD, it could be considered whether this compensation mechanism could be re-learned in speech therapy intervention to improve intelligibility.

Data Availability

The data used to support this study's findings are available from the corresponding authors upon reasonable request.

Author contributions

TT conceptualized the study, collected and analyzed the data, and wrote the first draft of the manuscript. DM was responsible for the study design, the data analysis and a review of the manuscript. NG organized the participants' assignments and collected and annotated the data. AS also organized the assignments and provided clinical characteristics of the patients. GRF partly funded the study and critically reviewed the manuscript. MTB was involved in the study conceptualization and organization as well as in the data analysis. MS provided feedback on

the design, execution and analysis of the data. All authors read, reviewed and approved the final manuscript.

Declaration of interests

The authors declare no financial or non-financial competing interests relevant to this work.

Declaration of Generative AI and AI-assisted technologies in the writing process

No generative AI and AI-assisted technologies in the writing process were used.

Ethics

The study was approved by the ethics committee of the University of Cologne (18-425). All participants gave written consent prior to study inclusion. We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this work is consistent with those guidelines.

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