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The Role of Executive Functions and Levodopa on Articulatory Timing

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Abstract

The study investigates the interplay between speech motor control and cognitive executive dysfunction by looking at inter-articulatory coordination patterns between consonants and vowels in the production of syllables with high (CCV) and low (CV) complexity. Kinematic speech data (EMA) of 25 people with Parkinson's disease (PwPD) and 25 healthy controls (HC) were recorded. Further, the influence of levodopa on syllable coordination as well as the relationship to cognitive executive dysfunctions were tested. Results showed preserved articulatory coordination on the level of intra-syllabic coordination. On the intra-gestural level, consonantal and vocalic movements were prolonged in the PD group and positively affected by the intake of levodopa. For the PD group, a correlation between the shift pattern of the second consonant and scores on the executive function test is found, indicating that executive dysfunctions possibly give rise to changes in articulatory timing patterns.

Keywords: *Parkinson's disease, speech motor control, articulatory coordination, executive functions*

1. Introduction

Speech production requires the control over motor processes and cognitive functions, both of which are affected in Parkinson's disease (PD). While gross motor symptoms like bradykinesia, rigidity, and resting tremor are prominent, the impact extends to speech impairment, characterized by hypokinetic dysarthria, and cognitive dysfunctions (Ziegler & Vogel 2010). PD-related speech impairment is linked to a hypo-functioning speech system and reduced fine motor control. The deficiencies in speech motor control not only hinder the preparation and maintenance of motor programs but also impede the ability to switch between them (Spencer & Rogers 2005). Articulatory movements are therefore affected in various ways: speech movements are smaller in amplitude, slower and consequently longer in duration, and articulatory coordination is compromised when comparing it to healthy control speakers (Yunusova et al. 2008, Ziegler & Vogel 2010). PD also affects cognitive processes, including working memory, attention, executive control, and visuospatial domains (Aarsland et al. 2021). Executive functions, one of the most frequently impaired functions in PD (Kalbe et al. 2016), play a crucial role in orchestrating cognitive processes. They are thought to be an umbrella term comprising, amongst others, set-shifting abilities (Kudlicka et al. 2011) - the ability to switch between different tasks or mental sets. Executive functions/set-shifting skills can be assessed with the Trail Making Test (TMT). There is only a very limited number of studies on the kinematics of speech in PwPD in general and while a first step has been made to relate acoustic speech parameters to cognitive dysfunction (Thies et al. 2020), its relationship to articulation is yet to be explored.

In the present study, we therefore investigate the interplay between speech motor control and cognitive dysfunction by examining kinematics of syllable coordination patterns in syllables with branching onsets (/pl/) in the production of PwPD and HC. We also explore the role of dopaminergic substitution in form of levodopa, the most common and effective form of treatment for PD, on these timing patterns by additionally comparing medication OFF (med-OFF) and ON (med-ON) status within the PD group. We then correlate the articulatory findings with cognitive scores of the TMT. We tested the following assumptions for the PD group when being compared to the HC group: (i) We expect the PD group to produce deviant articulatory timing patterns in syllables with high complexity. (ii) We expect a positive effect of levodopa on the inter-gestural coordination. (iii) We expect that articulatory changes in the timing of syllables with high complexity correlate with lower performance scores on the executive functions test.

2. Methods

The analysed data were collected as part of a larger study by Thies (2023) conducted at the Department of Neurology of the University Hospital in Cologne. We here investigate a subset of the data that has not been looked at so far.

2.1. Participants

25 PwPD (5 female, 20 male) aged between 40 and 77 (mean age = 60 years) and 25 age- and sex-matched HC participated in the study. Four HC had to be excluded from the analysis due to issues with the sensor tracking leading to inaccurate data trajectories or due to incorrect articulation of the target words. Of the HC included in the analysis, 3 were female and 19 male (mean age = 61 years). All participants were native speakers of German and underwent a screening process to rule out the presence of dementia or depression. Motor functions for both groups were assessed using part III of the Unified Parkinson's Disease Rating Scale (UPDRS-III). The PwPD were diagnosed between 1 to 20 years (mean = 8 years) prior to study inclusion and were recorded in both med-OFF and med-ON conditions. Med-OFF involved withdrawing PD medication for at least 12 hours, while med-ON entailed the intake of a predetermined standardized levodopa dosage of 200 mg.

2.2. Neuropsychological assessment

All participants underwent a neuropsychological assessment. The TMT was administered to assess executive functions. It consists of two parts: In part A, participants are asked to connect a sequence of consecutive numbers from 1 to 25; In part B, participants have to connect a sequence of numbers (1 to 13) and letters (A to L), alternating between the two (i.e., 1-A-2-B etc.). The time needed to complete TMT-A serves as an indicator for processing speed, and the time score of TMT-B allows for drawing conclusions on mental flexibility which is related to set-shifting. Additionally, the TMT difference score (B-A) and ratio score (B/A) were calculated as they are said to control for influences of motor control and other non-set-shifting elements, thereby emphasizing executive functions (Muir et al. 2015). One person in the HC group did not complete the TMT. The neuropsychological assessment for the PwPD was only carried out in med-ON condition.

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2.3. Speech recording and speech material

Speech data were recorded acoustically and kinematically using 3D electromagnetic articulography (EMA, AG501). The speech material consisted of words with simple and complex onsets with initial syllables of the target words following either CV (C_1V /pina/ or C_2V /lina/) or CCV structure (C_1C_2V /plina/). Participants were instructed to embed the target words in a predefined sentence ("Er hat wieder … gesagt" | "He said … again") and to produce it twice. To analyze articulatory timing patterns of the initial consonant clusters, EMA sensors were placed on the lower lip, tongue tip, and tongue body.

2.4. Speech data annotation and measurements

Speech data were processed in the EMU-webAPP of the EMU-SDMS environment (Winkelmann et al. 2017). On the acoustic level, we calculated segment durations of the first stressed syllables. We used the C-center coordination paradigm for the kinematic analysis: When a C is added to a CV syllable to form a complex CCV onset, the coordination of Cs and Vs is reorganized. This can be measured in terms of articulatory overlap patterns (Pouplier 2012). Therefore, target positions of the articulators for consonants (C_1, C_2) and vowels (V) in the first stressed syllables were identified in the vertical plane using zero-crossings in the respective velocity trace. To measure the overlap, latencies between the maximum target positions of C_1, C_2, and the C-centre (midpoint between two Cs) to the V were computed. Consonantal shifts were calculated by comparing the latencies in CV and CCV syllables: The leftward shift is captured by comparing the latency from C_1 to V in the syllable C_1V (/pi/) with C_1C_2V (/pli/) (latency should increase from CV to CCV); The rightward shift is usually present from C_2V (/li/) with C_1C_2V (/pli/) (latency should decrease from CV to CCV).

2.5. Statistical analysis

The data was analysed using the statistical computing software R (version 4.3.3; R Core Team, 2024). To test differences in acoustic segment durations and articulatory timing patterns between syllable structures (CV vs. CCV) and between groups/conditions (HC vs. med-OFF, HC vs. med-ON, med-OFF vs. med-ON), linear mixed effect models were conducted. Syllable structure and group/medication condition were set as predictor variables, and random intercepts for intra-speaker variability were included. For the correlation analysis, the difference in shift of C_1 and C_2 between CV and CCV syllables was correlated with the different TMT scores (A, B, B-A, B/A) of the HC group and the PwPD (med-ON). The data were tested for normal distribution in which case the Pearson method was used for the correlation analysis. Otherwise, the Spearman method was applied. Based on the first round of results, some additional correlation analyses were performed: latencies/syllable durations ~ TMT scores, UPDRS ~ syllable durations/C_2 shift/TMT scores. Interaction effects between TMT and UPDRS scores on C_2 shifts were also tested with linear models.

3. Results

3.1. Acoustic data

The mean acoustic segment durations for C_1 /p/, C_2 /l/, V /i/ and for the entire syllable are reported in Table 1. Results show that durations of C_1 /p/ do neither differ between syllable structures nor between groups/conditions ($p > .05$ across all comparisons). Durations of C_2 /l/ are shorter in CCV compared to CV syllables ($p < .001$ across all comparisons, mean difference = -56.2 ms). The comparison between groups/conditions shows longer C_2 durations for med-OFF compared to the HC ($p = .012$, mean difference = 21.3 ms). The durations decrease from med-OFF to med-ON, eliminating group differences between med-ON and HC ($p > .05$). The durations of the vowel /i/ do not differ between syllable structures across all groups/conditions ($p > .05$). However, med-OFF presents with longer V durations both compared to HC ($p = .010$, mean difference = 28.5 ms) and to med-ON ($p < .001$, mean difference = 16.1 ms). The durations decrease from med-OFF to med-ON, eliminating group differences between med-ON and HC ($p > .05$). Thus, durations of CCV syllables are longer compared to CV syllables and longer durations of C_2 and V in med-OFF lead to longer syllable durations in this condition (Table 1).

Table 1: *Means and sd of acoustic durations in ms specified by group/condition and by syllable structure.*

		/p/	/l/	/i/	syllable
HC	C_1V	197 (64)	—	121 (37)	318 (90)
	C_2V	—	96 (34)	133 (37)	230 (64)
	C_1C_2V	205 (78)	57 (24)	117 (36)	379 (110)
med-ON	C_1V	188 (45)	—	123 (31)	324 (67)
	C_2V	—	121 (68)	144 (43)	265 (94)
	C_1C_2V	186 (62)	55 (20)	136 (40)	364 (86)
med-OFF	C_1V	200 (44)	—	150 (47)	350 (77)
	C_2V	—	130 (57)	166 (48)	296 (89)
	C_1C_2V	197 (68)	67 (23)	142 (54)	406 (106)

3.2. Articulatory data

The mean articulatory latencies between C_1 /p/, C_2 /l/, and C-centre and the vocalic anchor respectively are reported in Table 2. The latencies of /p/ to /i/ increase from CV to CCV across all groups/conditions ($p < .001$, mean difference = 68.6 ms). When comparing groups/conditions, latencies of C_1 to V only differ between med-OFF and med-ON, i.e., they are longer in med-OFF ($p < .001$, mean difference = 20 ms). The latencies of C_2 /l/ to V differ slightly between CV and CCV syllables in the two PD conditions only, i.e., they are longer in CV compared to CCV ($p = .026$, mean difference = 9.73 ms). When comparing groups/conditions, the C_2 latencies are longer in med-OFF both compared to HC ($p = .016$, mean difference = 30.8 ms) and compared to med-ON ($p < .001$, mean difference = 15.8 ms). The latencies decrease from med-OFF to med-ON eliminating group differences between med-ON and HC ($p > .05$). The med-OFF/med-ON effect is further reflected in the shortening of the latency between the C-centre and the vocalic anchor ($p = .001$, mean difference = -22.2 ms).

Table 2: *Means and sd of articulatory latencies in ms specified by group/condition and by syllable structure.*

		C_1 to V /p/ → /i/	C_2 to V /l/ → /i/	C-centre → /i/
HC	C_1V	177 (63)	—	—
	C_2V	—	119 (51)	—
	C_1C_2V	254 (75)	119 (47)	186 (52)

med-ON	C_1V	188 (52)	—	—
	C_2V	—	141 (42)	—
	C_1C_2V	243 (53)	130 (38)	187 (43)
med-OFF	C_1V	201 (50)	—	—
	C_2V	—	158 (55)	—
	C_1C_2V	274 (68)	147 (52)	211 (56)

The shift pattern for the complex onset /pl/ is visualised in Figure 1. It shows the leftward (negative values) and rightward (positive values) shifts of C_1 and C_2 respectively. For all groups/conditions we find a clear leftward shift of C_1. Looking at the C_2 shift, a small rightward shift for med-ON and med-OFF, and a small leftward shift for HC become apparent.

Figure 1: *Shift patterns of C_1 (in red) and C_2 (in blue) from CV to CCV. Shift direction: < 0 to the left, > 0 to the right.*

3.3. Executive functions and correlations

The mean TMT performance scores of the two groups are shown in Table 3. TMTA differed between the two groups with the PD group taking longer to complete the test ($p = .042$, mean difference = 8.28 ms). The same group difference can be observed for TMTB and the derived scores (Table 3).

Table 3: *Means and sd of TMT scores in s.*

	TMTA	TMTB	TMTB-A	TMTB/A
HC	30.3 (10.2)	78.1 (31.3)	47.8 (28.4)	2.67 (0.9)
med-ON	38.8 (14.9)	94.1 (61.6)	55.3 (54.4)	2.42 (1.03)

Correlations between shift patterns of C_1 and C_2 and the different TMT scores were first assessed across the two groups and then for each group individually. For the across groups analysis, there was a single correlation between C_1 shift and TMTA ($p = .005$, $r_S = .411$). When looking at the two groups individually, visual inspection revealed two outlier points (> 2 sd) in the PD group. To make sure the correlations are not driven by these outliers, analyses were performed excluding the two speakers. The results are shown in Table 4, revealing that C_2 shift corelates with all executive function scores. This correlation, exemplified by C_2 shift ~ TMTB-A, is shown in Figure 2: More extreme rightward shifts of C_2 are associated with higher TMTB-A scores. No such correlations were found for the HC group.

Table 4: *P-values and correlation coefficients between C_2 shift and TMT scores.*

	C_2 shift ~		
	TMTB	TMTB-A	TMTB/A
med-ON	$p = .044$ $r_P = .423$	$p = .008$ $r_P = .540$	$p = .010$ $r_S = .526$

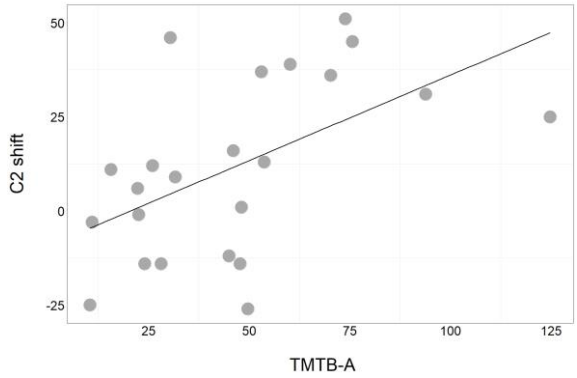

Figure 2: *Correlation of C_2 shift with TMT difference score (TMTB-A). Shift direction: < 0 to the left, > 0 to the right.*

The acoustic and articulatory analyses showed a trend pattern between groups with durations of C_2 and V as well as all latency measures being longest in med-OFF > med-ON > HC (with the exception of C_1 latency in CCV for med-ON). At the same time, the intra-syllable coordination patterns were stable across groups/conditions. Therefore, we tested the relationship between changes on the temporal level and TMT performance. In a first step, we correlated the latencies of C_1 and C_2 in CCV to syllable duration. Results show that both latencies correlate with syllable durations (latency C_1 ~ syllable duration: $p < .001$, $r_S = .872$; latency C_2 ~ syllable duration: $p < .001$, $r_S = .555$). We then tested the correlation between syllable duration and the different TMT scores across groups as well as for HC and PD separately. No correlations were found for any of the measures.

Finally, we tested whether the disease severity might have affected our measures. To validate our results, we tested for correlations with the UPDRS scores. Syllable durations did not correlate with the UPDRS scores for all groups/conditions. No correlation between UPDRS scores and C_2 shift could be found across groups/conditions and for individual groups/conditions. Looking at PD in med-ON only, UPDRS scores did correlate with the TMT pure scores (TMTA: $p = .011$, $r_S = .497$; TMTB: $p = .032$, $r_S = .430$). However, no correlation between UPDRS scores and TMT derived scores (difference/ratio) could be found. A slight interaction effect between TMTB and UPDRS scores was found for the C_2 shift in med-ON condition ($p = .042$). Visual analysis of this interaction showed that with increasing UPDRS scores, the correlation between TMTB and C_2 shift also increases.

4. Discussion and conclusion

In line with prior research, the articulatory results reveal a non-symmetrical timing pattern for the complex onset coordination /pl/ for neurotypical speakers of German. While C_1 /p/ presents with a leftward shift, C_2 /l/ does not shift considerably towards the following V from CV to CCV. Instead, the acoustic C_2 segment was shortened in CCV due to coarticulatory effects of the jaw, lips, and tongue in terms of compensatory shortening

(e.g. Pouplier 2012, Mücke et al. 2020). The same non-symmetrical timing pattern was observed in PwPD for complex syllable organization, even in a poor motor status, i.e., without medication. It is noteworthy, that while there is a small leftwards shift of C_2 present in the HC group, both PD conditions show a slight C_2 shift to the right. Both phenomena are not surprising and have been reported for /pl/ in German in previous research (Mücke et al. 2020). Our results on inter-gestural timing patterns extend the findings of studies reporting stable and preserved timing patterns in PwPD for vowel productions (e.g. Yunusova et al. 2008). However, we found an effect of levodopa on durations of C_2 and V: In the med-OFF condition, PwPD produced longer consonantal and vocalic movements, and these durational changes on the intra-gestural level led to longer latencies between Cs and Vs on the inter-gestural level. A general trend of med-OFF > med-ON > HC emerged, where group differences between med-ON and HC are often eliminated. This underlines a beneficial effect of levodopa on speech planning abilities, which has been shown before (e.g. Thies et al. 2021).

Turning towards the neuropsychological test scores, group differences were observed for all TMT scores with PwPD presenting with lower performance scores than the HC. However, we want to point towards a limitation of this study as TMT scores for the PD group were only obtained in the med-ON condition. Some studies show that set-shifting skills are likely to improve under levodopa which might lead to even more significant differences between HC and PwPD (Gul & Yousaf 2022). Nonetheless, we did find a correlation between the C_2 shift and all TMT scores involving part B of the test within the PD med-ON group. This relationship between timing patterns and executive functions, particularly set-shifting, lets us assume that some PwPD change their articulatory timing patterns as C_2 tends to shift more to the right when there is a decline in set-shifting abilities, indicating the possibility of a less efficient/deviant timing. The general tendency of stable coordination patterns that are scaled in time that we observed for the PwPD did not correlate with the executive function scores which suggests that impaired executive function skills might be the cause of articulatory timing changes. A further, in detail analysis of PwPD who present with larger rightward shifts of C_2 and lower scores in TMT performance and their clinical characteristics might paint a clearer picture of the processes at play.

The correlation of the motor scores with TMTA within the PD med-ON group are an indicator that processing speed declines as a function of disease severity. It explains the group differences found between HC and PD med-ON regarding their performance on the TMTA. As UPDRS scores correlated with TMTB, their interaction effect on C_2 shift was investigated. It was found that increased disease severity, measured by UPDRS scores, likely reinforces the negative effect executive dysfunction has on the shift pattern of C_2. However, future research might want to investigate whether this interpretation holds when further disease severity and cognitive measures are considered, or whether what we observed is rather a parallel decline of speech motor control and executive functioning.

All things considered, this study contributes to the understanding of the interplay between speech motor control and cognitive executive functioning. Its findings indicate that speech therapy concepts might need to be adapted to include cognitive training, which in turn will have a positive effect on speech symptoms of PD. In the future, it might be worthwhile to replicate the present study including assessment of the TMT for the med-OFF condition to be able to assess the influence of levodopa on executive functioning and correlate timing patterns with executive function skills both on and off medication. We would expect an even stronger correlation for the PD med-OFF group. Also, including consonant cluster types other than /pl/ in the analysis would deepen our understanding of how articulatory shift patterns and executive function skills correlate in neurotypical and impaired speech. There are compensatory shortening mechanisms in German /pl/, that might have increased the variability in our data.

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6. References

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