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Neuroplastic Effects of Dance Training in Parkinson's Disease: Functional and Structural Modulation in Speech-Related Brain Regions

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Abstract

Objective: *This exploratory pilot study examined whether an 8-month dance training program in people with Parkinson's disease (PD; PwPD) was associated with functional and structural brain changes, using a multi-modal neuroimaging approach.*

Methods: *Ten PwPD participating in weekly community-based dance classes completed fMRI and T1-weighted MRI at four time points. A subset of four participants also completed diffusion-weighted imaging (DWI) at two time points. fMRI assessed BOLD signal changes in the inferior frontal gyrus and supplementary motor area (SMA) during a dance-imagery task. Cortical thickness in Broca's area and the left superior frontal language (SFL) area was analyzed, with reference data from the PPMI database. White matter integrity between Broca's and SFL areas was evaluated via fractional anisotropy (FA), axial (AD), radial (RD), and mean diffusivity (MD).*

Results: *Within-person comparisons revealed a significant decrease in BOLD signal in the inferior frontal gyrus and a significant increase in the SMA between September and January. Cortical thickness in the left SFL showed a biphasic pattern, with an initial increase followed by a decrease, while Broca's area remained stable. FA increased significantly from January to April. Descriptive analysis of F0SD in three participants suggested improvements over the five-year follow-up period.*

Conclusion: *This pilot study provides preliminary evidence that dance training in PwPD may be associated with functional and structural brain changes in regions relevant to speech-motor integration.*

Keywords: Parkinson's Disease, Dance, Structural Changes, Functional Magnetic Resonance Imaging, Diffusion-Weighted Imaging.

Introduction

Parkinson's Disease and Its Neural Implications

Parkinson's Disease (PD) is a progressive, age-related neurodegenerative disorder marked by both motor and non-motor symptoms [1]. It primarily arises from the degeneration of dopamine-producing neurons in the substantia nigra pars compacta [2]. The prevalence of PD increases with age, affecting around 1% of individuals aged 65–69, and rising to nearly 3% in those

aged 80 and older [3]. Due to its progressive nature, effective interventions must address both motor and non-motor symptoms to help maintain the quality of life (QoL) in people living with PD (PwPD).

In addition to motor impairments, PD is strongly associated with speech difficulties, affecting up to 90% of individuals [4]. This often present as hypokinetic dysarthria, characterized by reduced pitch variation, diminished vocal intensity, and monotonous speech. Speech impairments can appear in the early stages of the disease and tend to worsen over time, significantly hindering communication and social interaction, hence decreasing the QoL for both PwPD and their caregivers. Although pharmacological treatments like levodopa, dopamine agonists, and Monoamine Oxidase-B inhibitors can alleviate symptoms [5], they do not slow disease progression and may produce notable side effects [6, 7]. The side effects include, but are not limited to, fibrosis, sleep attacks, impulse control disorders, depression, hypotension, and liver toxicity [8]. Deep brain stimulation (DBS) has also emerged as a surgical intervention for managing motor symptoms in advanced PD.

While DBS can significantly improve motor function and reduce medication requirements, its long-term efficacy remains controversial. Some studies highlight sustained benefits over time, whereas others report a decline in therapeutic effects, along with potential complications such as worsening of speech, gait, cognition, and postural stability [9, 10]. Additionally, patient satisfaction with DBS outcomes appears to vary considerably, often influenced by disease progression and unmet expectations [11]. As a result, there is increasing interest in complementary therapies, such as physical exercise, music therapy, and dance, that aim to enhance neuroplasticity and support functional recovery [12-17]

Dance as a Neuroplasticity-Based Intervention in PD

Emerging research suggests that engaging in physical and cognitive activities, such as dance, may offer neuroprotective benefits for PwPD [18-22]. Dance-based interventions stimulate multiple brain networks involved in motor control, coordination, rhythm processing, and executive functioning, providing therapeutic effects that may extend beyond those of conventional rehabilitation approaches. Neuroimaging studies have demonstrated that dance may enhance neuroplasticity in key motor regions, including the supplementary motor area (SMA), putamen, and caudate nucleus within the basal ganglia [23]. These neural adaptations may support improvements in motor performance, balance, and gait and positively influence cognitive and emotional well-being in PwPD.

While prior studies have examined the motor and functional outcomes of dance interventions in PD, their influence on neuroplastic changes remains less well understood. In particular, it is still unclear how dance training may drive structural and functional changes within the brain's motor and language networks. Since speech impairments in PD are believed to result from dysfunction across both cortical and subcortical regions, investigating how dance affects brain areas associated with word production could yield valuable insights into its therapeutic potential for addressing speech and motor coordination deficits. Building upon this, our previous study demonstrated that weekly dance training in PwPD led to significant improvements in vocal performance, particularly in measures of fundamental frequency standard deviation (F0SD), a critical indicator of prosodic variability. While F0SD does decline as PD progresses, our findings suggested that dance-based interventions preserved speech prosody in 29 PwPD, reflecting possible engagement and plasticity within speech-motor integration pathways [24, 25].

Improvements in F0SD could be associated with more robust activation of cortico-subcortical circuits, including Broca's area, the SMA, and their connections with subcortical structures such as the basal ganglia and cerebellum, which are essential for precise vocal control. This highlights the importance of examining dance-induced changes in both functional activation and structural connectivity within speech-motor networks. By linking behavioral improvements in speech for PwPD (blue bars) who dance over 5-yrs with neuroimaging markers of brain plasticity, we can deepen our understanding of how dance interventions promote adaptive reorganization across multiple domains affected by PD.

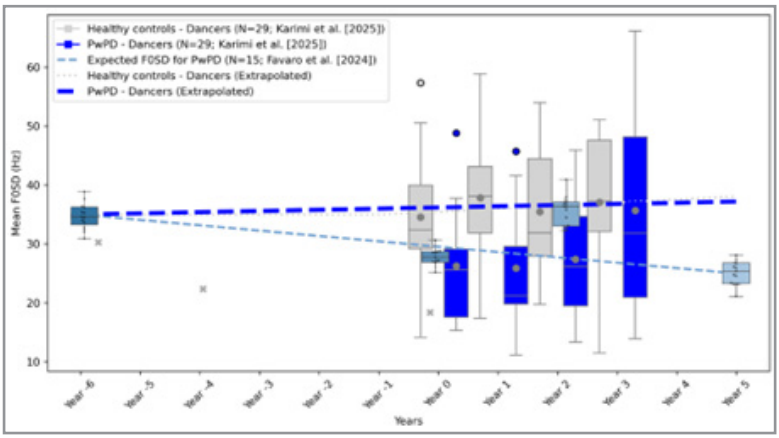


Figure 1: Illustrates F0SD trajectories for PwPD who dance (dark blue) and do not dance (light blue). PwPD dancers from our longitudinal behavioural speech study (2014 to 2019) in comparison to PwPD nondancers. These behavioral findings provide further rationale for examining dance-induced changes in speech-motor brain regions using multimodal imaging approaches.

Cortical Thickness and White Matter Connectivity as Biomarkers of Neuroplasticity

Neuroplasticity—also referred to as brain plasticity or neural plasticity—is the brain's capacity to undergo adaptive structural and functional changes [26]. Defined neuroplasticity as "the ability of the nervous system to change its activity in response to intrinsic or extrinsic stimuli by reorganizing its structure, functions, or connections." [27].

Cortical Thickness as an Indicator of Structural Adaptation

Cortical thickness, measured using T1-weighted structural MRI, reflects the morphological integrity of the cerebral cortex. Changes in cortical thickness have been linked to learning, motor training, and rehabilitation, making it a valuable biomarker for neuroplasticity [28]. Studies have shown that motor and cognitive training can lead to increases in cortical thickness, particularly in motor and prefrontal regions associated with skill acquisition and executive control [29, 30]. Conversely, cortical thinning in PD has been associated with disease progression, cognitive impairment, and motor decline [31]. Assessing cortical thickness in speech and motor-related regions, such as Broca's area and the left supplementary frontal language (SFL) area, may reveal structural adaptations associated with dance training in PD.

DTI/DWI and White Matter Plasticity

Among the imaging methods used to study structural neuroplasticity, diffusion MRI -particularly diffusion tensor imaging (DTI)- is considered a powerful tool for probing microstructural properties of brain tissue [32]. DTI offers various indices, such as fractional anisotropy (FA), which is commonly used to assess the integrity and organization of white matter fibers [33]. Other metrics, such as Mean Diffusivity (MD), Axial Diffusivity (AD), and Radial Diffusivity (RD), provide insights into different aspects of microstructural changes [34]. Several studies have reported significant training-induced alterations in DTI parameters within relevant white matter pathways, suggesting that DTI can potentially detect structural plasticity in both gray and white matter [35-37]. Nonetheless, these changes' precise biological and morphological interpretations are still not fully understood [38]. Motor learning, language acquisition, and rehabilitation studies have reported changes in white matter connectivity following training interventions [39, 40]. In PD, progressive white matter degeneration affects motor and speech networks, leading to communication deficits and impaired movement execution [41]. Examining structural connectivity changes between Broca's area and the left SFL area using DWI/DTI can provide insights into whether dance training enhances white matter integrity in language-motor pathways.

Motivation and Study Objectives

The motivation for this study stemmed from our findings in a recent investigation of voice features in 29 dancers with PD, which demonstrated that dance training significantly improved the standard deviation of fundamental frequency (F0SD) in PwPD. This study highlighted the potential of dance as a therapeutic intervention for addressing speech impairments in PD.

Building on these results, the current study aimed to explore the neural mechanisms underlying such improvements by examining the neuroplastic effects of dance using multi-modal neuroimaging techniques. Specifically, we examined:

- Functional activity in the motor cortex (inferior frontal gyrus) and the supplementary motor area (SMA) using functional MRI (fMRI).
- Cortical thickness in Broca's area and the left supplementary frontal language (SFL) area using structural MRI analysis.
- White matter integrity between Broca's and left SFL areas using DWI.

The multi-model MRI data (functional, structural, and diffusion) were collected between September 2013 and April 2014 as part of the initial phase of the study. Following this, from 2014 until the COVID-19 pandemic, a longitudinal follow-up study was conducted to examine motor and non-motor symptoms in PwPD who attended weekly dance classes. While F0SD measures were obtained during and after the MRI data acquisition, they offer a valuable opportunity to relate neuroimaging findings to later observed changes in voice features. For three PwPD who participated in both studies, we analyzed their F0SD trajectories over the follow-up period to examine potential associations between early neuroimaging markers and longitudinal changes in speech characteristics. The F0SD trajectories for these individuals, visualized in, illustrate both the within-subject variability and the overall pattern of change across pre- and post-dance session assessments. These retrospective observations provide an important extension of the original voice feature study, linking longitudinal behavioral improvements with neuroimaging data.

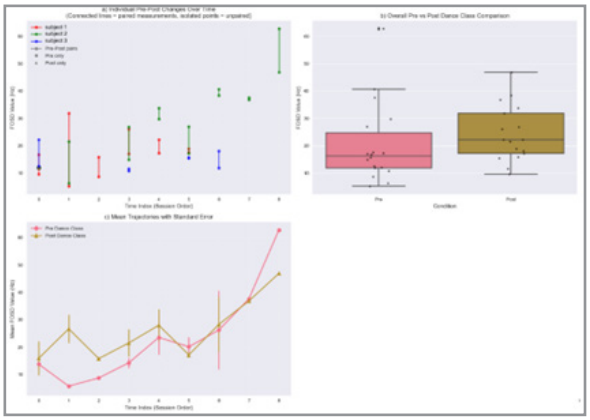


Figure 2: Fundamental frequency standard deviation (F0SD) in three people with Parkinson's disease (PwPD) following dance training. a) individual pre- and post-dance values for F0SD in Hertz (Hz), b) overall comparison of pre- versus post-dance, c) mean F0SD changes across time with standard error. The effect of time was significant for F0SD changes in mixed-effect ANOVA model ($p < 0.0001$).

We hypothesized that dance training would lead to functional adaptations in motor regions, structural changes in cortical thickness, and enhanced white matter connectivity between motor and language networks.

By integrating fMRI, cortical thickness analysis, and DWI, this study provides a comprehensive investigation of dance-induced neuroplasticity in PD, with potential implications for rehabilitation strategies and non-pharmacological interventions.

Methods

Overview and Participants

Participants were recruited from weekly, 75-minute, community-based Sharing Dance Parkinson's (SDPD) classes at Canada's National Ballet School (NBS).

Recruitment occurred at the start of a dance term, participation was voluntary, and interested individuals received written information before deciding to participate. Participants' characteristics are summarized in Table 1. Participants self-reported their health status.

All PwPD were on stable medication regimens throughout the study period and confirmed verbally that they were in the "ON" medication state (i.e., experiencing therapeutic benefit from their medications) prior to each scanning session.

Table 1: Characteristics of People with Parkinson's Disease (Dancer Group and PPMI Reference Group)

Subject ID	Age Range	Gender	Disease Duration (year)	Hoehn & Yahr (H & Y)	Matched PPMI Subject ID	Age
1	66-70	M	4	1	115448	66-70
2	56-60	M	9	2	101482	56-60
3	66-70	M	1	1	3102	61-65
4	61-65	F	11	1	100017	56-60
5	66-70	M	3	2		
6	71-75	F	14	-		
7	71-75	M	2	-		
8	61-65	M	4	-		
9 †	-	M	-	-		
10	71-75	F	3	0		

†: The age and disease duration for this subject were not retrievable.

SDPD classes are based on the Mark Morris Dance Group's Dance for PD® protocol and follow a structured format, progressing from seated exercises to paired and group movements, culminating in standing choreography and locomotion through space [42]. The study's choreography emphasized social interaction, with participants learning and practicing sequences weekly from September to June, leading to three public performances: Sharing Dance Day, Toronto City Hall (for Parkinson's Awareness Month), and the Parkinson's Central Annual Meeting. For dance protocol refer to study.

MRI Data Acquisition

MRI data were acquired using a 3T Siemens Tim Trio scanner with a 32-channel head coil at York University's Sherman Health Sciences Centre. Functional and structural data were collected across four time points (September 2013, December 2013, January 2014, April 2014) over an 8-month period from ten participants. A subset of four participants underwent DWI in January and April scans.

Diffusion-weighted imaging (DWI) was acquired in a subset of four participants during the January and April sessions only. During the September and December sessions, the time allocated to diffusion imaging was instead used for a toe-wiggling motor task designed to confirm functional activation in the supplementary motor area (SMA). Once SMA engagement was verified, the protocol was modified to acquire DWI data in subsequent sessions to maximize the scientific value of the limited scanning time available—an important consideration given the fatigue constraints typical in this patient population.

The imaging modalities included fMRI for functional activity, T1-weighted scans for cortical thickness analysis, and DWI for white matter connectivity assessment. This multi-modal imaging approach provided insights into functional activation, structural changes, and connectivity adaptations in response to dance training in PwPD.

FMRI Analysis

FMRI Task Paradigm

Participants performed an imagery-based dance task while in the scanner. They were instructed to mentally rehearse the choreography practiced during dance classes from a first-person/internal perspective, engaging both visual and kinesthetic modalities. The first minute of the associated music was played through headphones to facilitate accurately timed imagery. A block design was employed, alternating between task blocks (60 seconds of imagined dance movement accompanied by music) and rest blocks (30 seconds of resting fixation without music). Each participant completed five task/rest cycles, with a total scan duration of 8 minutes. The first 15 volumes were discarded from the analysis to allow for magnetic field stabilization.

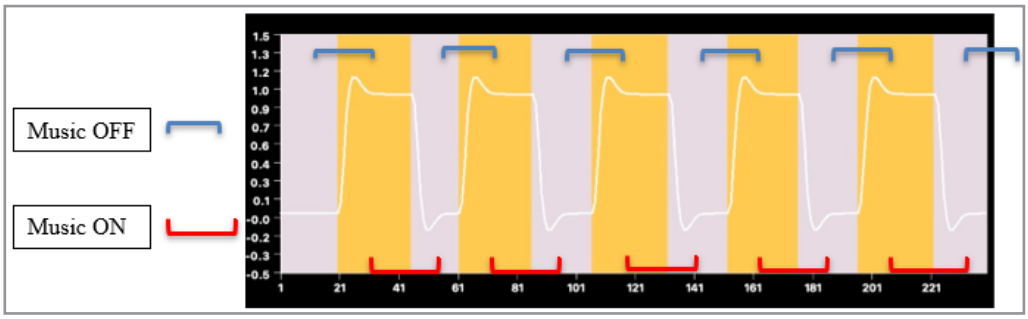


Figure S1: Block design of music ON (red) and music OFF (blue)

FMRI Preprocessing

Preprocessing was conducted using Brain Voyager QX version 22.0.3.4578, following standard pipelines. Functional data were co-registered to each participant's anatomical scan and transformed into Talairach space. The preprocessing steps included slice: (1) timing correction – temporal alignment of slices within each volume; (2) motion correction – realignment of functional images; maximum displacement did not exceed 1 mm (translation) or 3 mm (rotation) across time points; (3) temporal high-pass filtering – Fourier-based filtering to remove low-frequency drifts and physiological noise, using a General Linear Model (GLM) incorporating two sine and two cosine functions; (4) spatial normalization – transformation of functional data into Talairach space for group-level analysis, and (5) quality control – no scans were excluded, as all motion correction values were within acceptable limits.

Region of Interest (ROI) Selection

ROIs were selected a priori based on their established relevance to speech and motor functions:

Inferior Frontal Gyrus (IFG) ROI: Coordinates were derived from [43], who identified this region as showing significant activation during covert speech production in an fMRI paradigm. A spherical ROI was defined using Brain Voyager's built-in tools, centered at Talairach coordinates (x = −65, y = 6, z = 18) with a 4-mm radius (257 voxels). This region was selected to capture neural activity associated with speech motor planning.

Supplementary Motor Area (SMA) ROI: Coordinates were based on prior literature identifying SMA regions associated with vocalization [44]. Specifically, MNI coordinates reported at (x = −3.1, y = 9.4, z = 52) were transformed into Talairach space using established conversion methods, resulting in a final center at (x = −2, y = 11, z = 47). A spherical ROI with a radius of 10.1 mm (4,385 voxels) was defined around this center. The SMA was included due to its established involvement in motor planning, sequencing, and speech production [45].

Vocalization-Specific Analysis Window

A key component of the learned choreography involved participants simulating holding and rotating a lasso while vocalizing "yeeeee haw" aloud. This vocalization occurred between the 20th and 30th seconds of the dance routine and represented the only overt speech production within the choreography.

Based on the rationale that imagined actions engage overlapping neural substrates with executed actions, we hypothesized that mental rehearsal of this vocalization segment would engage speech-motor regions [46-48]. Therefore, BOLD signal changes within the SMA ROI were extracted specifically from this 10-second time window during the imagery task to assess neuroplastic adaptations related to integrated motor-speech processing. This analysis window was defined a priori based on the known structure of the choreography.

FMRI Analysis

A fixed-effects multi-subject analysis was conducted to compare brain activity during dance-imagery blocks and fixation blocks at each time point. Functionally defined regions were identified from the GLM contrast (dance-imagery vs. fixation) across all time points, with a statistical threshold of $p < 0.0001$ (Bonferroni-corrected) and a cluster threshold of $k > 22$. BOLD percent signal change was calculated relative to a baseline, which is defined as the average of the two volumes acquired before the music onset.

To examine longitudinal changes in task-related BOLD modulation, linear mixed-effects models were used, with time as a fixed factor (September as reference level). Random effects for individual samples to account for inter-subject variability. Autoregressive correlation structure of order 1 to model correlations between consecutive samples.

Cortical Thickness Analysis

Cortical Thickness Extraction

Cortical thickness was measured from T1-weighted anatomical scans using Free Surfer version 7.4.1 [49]. The "recon-all" processing pipeline was applied to each T1-weighted scan for each subject to extract cortical surface measurements automatically.

ROI Selection

ROIs were defined using the Human Connectome Map and selected based on their proximity to the fMRI ROI [50]:

- Broca's area – Speech production region.
- Left SFL – Associated with motor speech coordination.

Statistical Comparison

Cortical Thickness changes were assessed using a mixed-effect ANOVA comparison. To strengthen the analysis, a reference group was added, selected from the Michael J. Fox Foundation's Parkinson's Progression Markers Initiative (PPMI) dataset [51]. This group was matched for age, gender, and Hoehn and Yahr (H&Y) scores to the four participants in the dance intervention group, providing a baseline for comparison and enhancing the interpretation of observed changes . See Table 1 for the reference group demographics and their matched subjects.

DTI and DWI Analysis

DWI Acquisition & Preprocessing

Four participants underwent DWI scanning at two time points (January and April), yielding 8 scans total.

Data were processed using MRtrix3 (Tahedl, 2024), with the following pipeline: (1) denoising (dwidenoise); (2) motion and Eddy current correction (dwifslpreproc); (3) bias field correction (dwibiascorrect); (4) registration to standard space using the Human Connectome Map; (5) fiber orientation estimation using Constrained Spherical Deconvolution (CSD), and (6) whole-brain probabilistic tractography (iFOD2).

ROI-Based Connectivity Analysis

Tractography examined connectivity between Broca's and the left SFL areas. Ten million streamlines were initially generated, with ROI-based filtering used to isolate fibers connecting these regions.

Statistical Comparison

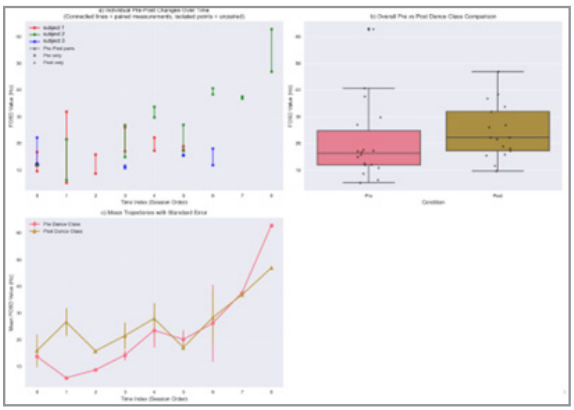
White matter microstructural integrity was assessed using four diffusion metrics: fractional anisotropy (FA), mean diffusivity (MD), axial diffusivity (AD), and radial diffusivity (RD). Within-subject changes from January to April were evaluated using paired t-tests.

Statistical Analysis

Statistical analyses were conducted using SciPy library (1.14.1), within JupyterLab environment (version 4.2.5), which was accessed through ANACONDA Navigator (version 2.6.5) on a MacOS Sequoia 15.5 system. Statistical significance was set at $p < 0.05$ for all comparisons. Given the exploratory nature of this pilot study, no correction for multiple comparisons was applied; findings should therefore be interpreted as preliminary and hypothesis-generating. Given the exploratory nature of this pilot study, no correction for multiple comparisons was applied; findings should therefore be interpreted as preliminary and hypothesis-generating [52].

Results

Figure 2 illustrates descriptive F0SD trajectories for three PwPD participants (Subject IDs 1, 2, and 3) who had longitudinal speech data available from 2014 to 2019. These case observations suggest within-person improvements in speech prosody over the follow-up period, though the small sample precludes statistical inference.



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FMRI Results

fMRI analyses examined BOLD signal changes in the IFG and the SMA across four time points (September, December, January, April) in all ten participants. Figure 3 shows a significant decrease from September to January ($p = 0.021$), and the difference between September and December signals was marginally significant ($p = 0.055$) for the motor cortex. No statistically significant differences were observed between subsequent time points. Complete statistical results are provided in Table S1 (Supplementary Material).

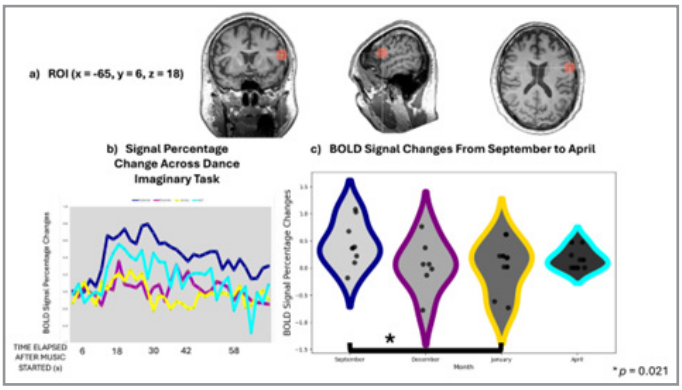

Figure 3: a) Inferior frontal gyrus Talairach coordinates. b) Signal percentage changes in inferior frontal gyrus during imaginary task in September, December, January, and April. c) BOLD signal percentage changes in the inferior frontal gyrus from September to Ap

Table S1: Mixed Linear Model Regression Results (Inferior Frontal Gyrus)

	Coef	Std Err	z	p >|z|	[0.025	0.975]
Time [T. December]	-0.314	0.164	-1.916	0.055	-0.635	0.007
Time [T. January]	-0.385	0.167	-2.302	0.021*	-0.713	-0.057
Time [T. April]	-0.226	0.187	-1.210	0.226	-0.592	0.140
Group Var	0.088	0.270				

statistically significant differences were observed between subsequent time points. Complete statistical results are provided in Table S2 (Supplementary Material).

Figure 4 shows a significant increase from September to January ($p = 0.010$) in the SMA. No

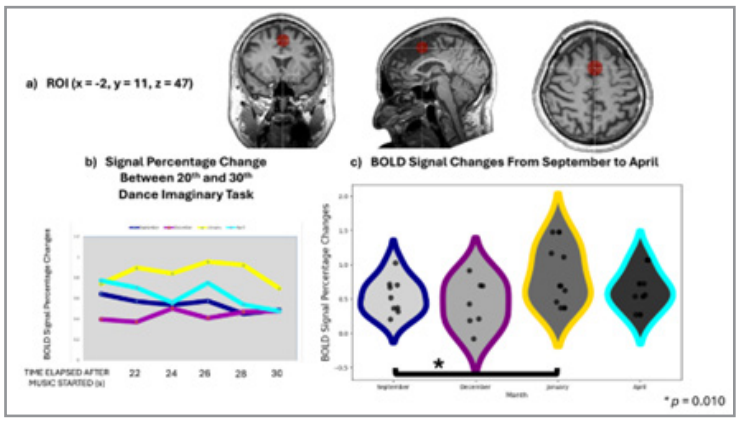

Figure 4: a) Supplementary motor area Talairach coordinates. b) Signal percentage changes in supplementary motor area during the vocal part of imaginary task in September, December, January, and April. c) BOLD signal percentage changes in the supplementary motor area from September to April.

Table S2: Mixed Linear Model Regression Results (SMA)

	Coef	Std Err	z	p >|z|	[0.025	0.975]
Time [T. December]	-0.101	0.129	-0.782	0.434	-0.354	0.152
Time [T. January]	0.343	0.133	2.547	0.010*	0.082	0.605
Time [T. April]	0.150	0.151	0.992	0.321	-0.146	0.446
Group Var	0.042	0.143				

Cortical Thickness Results

Cortical thickness changes were analyzed for Broca's area and the left SFL area across four time points in the dance group (n = 4 with matched PPMI comparisons; expanded analysis with all 10 participants available in Supplementary Material). Violin plots (Figure 5a & b) illustrate cortical thickness distributions for each time point. Broca's area showed no statistically significant changes in cortical thickness across time points ($p > 0.05$). In contrast, the left SFL area showed significant increase from September to December scan ($p = 0.049$), and a decrease from December to April ($p = 0.046$).

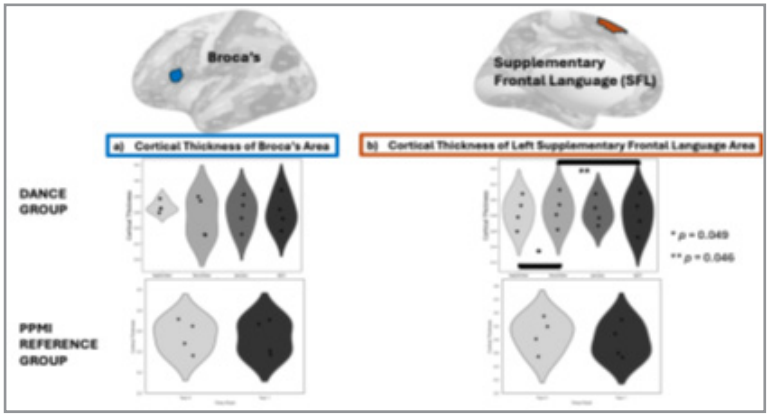

Figure 5: (a) Cortical thickness measurements of Broca's area across timepoints for the dance and PPMI reference groups. (b) Cortical thickness measurements of the left supplementary frontal language (SFL) area across the same time points for the dance and PPMI reference groups.

The cortical thickness analysis in the PPMI reference group across a comparable 1-year time window revealed no significant changes in cortical thickness for either Broca's area or the left SFL region during that period (Figure 5a & b). Descriptive statistics are provided in TABLE S3 (Supplementary Material).

Table S3: Cortical Thickness Means (± Standard Deviation)

Broca's Area				
	TIME 1	**TIME 2**	**TIME 3**	**TIME 4**
Dance group	2.66675 ± 0.076687	2.5435 ± 0.264167		2.60125 ± 0.217972
PPMI Reference Group	2.5535 ± 0.159884	-	-	2.54125 ± 0.17255
Left Supplementary Frontal Language				
Dance group	2.8475 ± 0.205487	2.875 ± 0.214864	2.855 ± 0.177106	2.815 ± 0.245561
PPMI Reference Group	2.87825 ± 0.258396	-	-	2.782 ± 0.262777

DTI and DWI Results

DWI was performed in January and April to assess the integrity of white matter between Broca's and the left SFL areas . The tracks connecting Broca's to the left SFL for each subject's scan in January and April are visualized in Figure 6. Descriptive statistics for streamline analysis are provided in Table S5 (Supplementary Material).

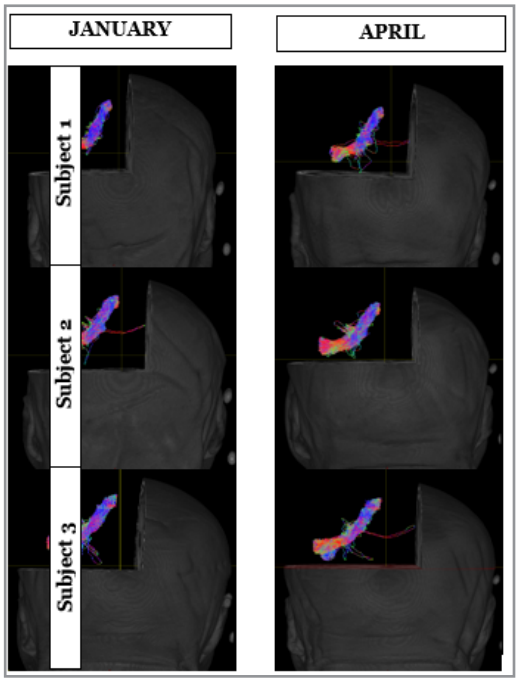

Figure 6: The tracks connecting Broca's to the left supplementary frontal language area for each subject in January and April

Table S5: Descriptive Statistics of the Streamlines Between Broca's and the Left Supplementary Frontal Language

Subject	Time Point	Mean	Median	STD. DEV.	MIN	MAX	COUNT
140	January	73.6174	71.4445	10.9546	57.7505	149.444	408
	April	73.2527	71.4309	11.7699	55.8497	196.196	533
142	January	78.0938	76.7318	9.83294	60.609	190.006	1224
	April	77.9044	76.0529	11.3409	60.0604	188.076	876
130	January	89.2351	87.0606	13.5828	65.2059	188.583	1003
	April	88.3505	86.6132	13.4954	64.5124	191.35	853

The result indicated that FA significantly increased from January to April ($p = 0.0247$) (FIGURE 7a). AD showed a marginal increase ($p = 0.056$) (FIGURE 7b). RD and MD did not express significant changes ($p > 0.05$). age (SFL) area across the same time points for the dance and PPMI reference groups.

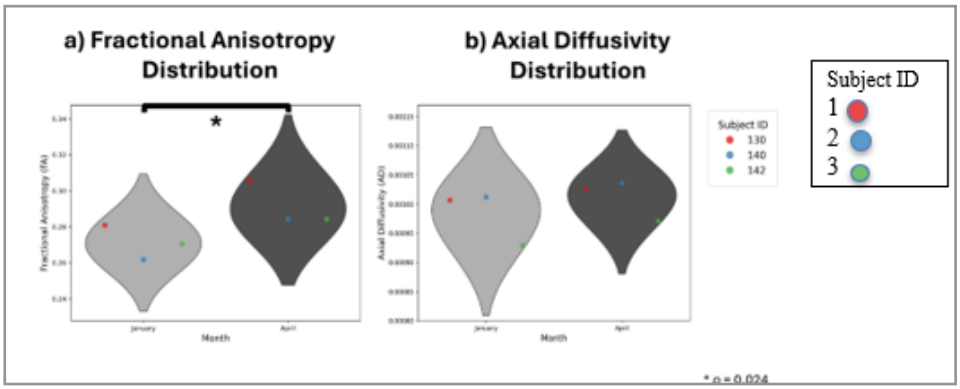

Figure 7: (a) Fractional anisotropy distribution and (b) Axial diffusivity distribution for tracks between the Broca area and the left supplementary frontal language (SFL) in January and April scans

Discussion

This exploratory pilot study examined whether dance training in PwPD was associated with functional brain activity changes, cortical structural modifications, and white matter connectivity adaptations across an 8-month period. Our findings suggest potential adaptations in speech-motor brain regions and white matter pathways, offering preliminary insights into possible neural correlates of dance-based interventions in PD. Given the small sample size and absence of a control group, these observations should be interpreted as hypothesis-generating rather than confirmatory.

Functional Changes in the Motor Cortex and the SMA

The fMRI analysis revealed two distinct patterns of functional change over the course of the dance program. In the inferior frontal gyrus (IFG), there was a significant decrease in BOLD signal activity from baseline (September) to January. This reduction may reflect increased neural efficiency associated with motor learning. Motor imagery tasks typically activate premotor and prefrontal regions involved in action planning, and the observed decrease in BOLD signal over repeated sessions is consistent with reduced neural demand as mental rehearsal of the choreography becomes more automatic. These findings align with previous studies demonstrating that the initial phases of skill acquisition elicit greater cortical activation, which subsequently declines as performance improves and motor processes become automated. Although no further significant changes were observed beyond January, the stabilization of BOLD signals suggests that functional adaptations may plateau with sustained training [53-55].

In contrast, the vocalization-associated region within the SMA exhibited a significant increase in BOLD signal activity from September to January. The SMA plays a critical role in the planning and initiation of internally generated movements, including the coordination of speech production with other motor actions [56]. The observed increase in SMA activation may reflect enhanced engagement of motor planning networks as participants became more proficient at integrating the cognitive, motor, and vocal imagery components of dance rehearsal. The SMA's role in temporal sequencing of complex motor acts makes it particularly relevant for the rhythmic and coordinated movements inherent in dance, as well as for the prosodic timing aspects of speech [57]. These patterns—decreased IFG activation alongside increased SMA engagement—may represent complementary aspects of motor learning: greater efficiency in lower-level motor representations coupled with enhanced recruitment of higher-order planning regions for complex, multi-modal task coordination. However, we acknowledge that an alternative interpretation exists: participants may have engaged verbal working memory processes during imagery to consolidate the choreography, which could partially account for the observed changes in speech-related regions. Future studies incorporating working memory assessments or verbal suppression tasks during imagery could help disentangle motor learning effects from cognitive strategy effects.

Overall, these preliminary findings suggest that dance training may be associated with region-specific functional plasticity in PwPD, though replication with appropriate control conditions is needed to confirm this interpretation.

White Matter Integrity Between Broca's Area and Left SFL

This finding is particularly relevant given the speech improvements documented in our F0SD analysis. The significant increase in FA between Broca's area and the left SFL area provides preliminary evidence for potential structural plasticity in pathways relevant to speech-motor coordination. This observation is noteworthy given the exploratory speech data suggesting improvements in prosody among participants with longitudinal follow-up.

Understanding these findings requires consideration of the functional anatomy underlying speech-motor integration. Broca's area (posterior inferior frontal gyrus, including pars opercularis and pars triangularis) is a core component of the speech production network, involved in phonological processing, articulatory planning, and the hierarchical organization of speech sequences [58, 59]. The left SFL area, located in the dorsomedial frontal cortex adjacent to the pre-SMA, contributes to the coordination of complex motor sequences and has been implicated in the temporal organization of speech movements [60, 61].

These regions do not function in isolation but are interconnected through white matter pathways that form part of a broader speech-motor network. The superior longitudinal fasciculus (SLF) and frontal aslant tract (FAT) provide structural connectivity between inferior frontal and medial frontal speech regions [62, 63]. The FAT, in particular, connects Broca's area with the SMA/pre-SMA complex and has been associated with speech initiation and fluency [64]. Strengthened connectivity along these pathways could theoretically facilitate more efficient com-

munication between regions responsible for speech planning (Broca's area) and motor sequencing/timing (SFL/SMA), which are essential for the rapid, precisely timed adjustments required for prosodic speech control.

The observed increase in FA, accompanied by a trend toward increased AD and stable RD and MD, suggests enhanced axonal coherence or organization rather than gross tissue changes. Several mechanisms may underlie training-induced white matter plasticity [65].

Myelin Remodeling: Repeated activation of neural circuits can promote oligodendrocyte activity and myelin plasticity, increasing conduction velocity and temporal precision of signal transmission [66, 67]. This would be particularly beneficial for speech-motor coordination, which requires rapid and precisely synchronized communication between planning and execution regions.

Axonal Reorganization: Training may promote increased axonal packing density or improved alignment of axonal fibers within a tract, both of which would manifest as increased FA.

Activity-Dependent Strengthening: The Hebbian principle suggests that repeatedly co-activated neural populations strengthen their connections. Dance training, which integrates rhythmic movement with vocalization and music processing, may promote synchronized activity across speech-motor networks, reinforcing the structural pathways connecting them [68].

These mechanisms are not mutually exclusive and may operate synergistically. The temporal synchronization demands of dance—coordinating movement with musical rhythm and, in this choreography, with vocalization—may be particularly effective at engaging and strengthening the neural circuits that support speech-motor integration. This is relevant to PD rehabilitation because dopaminergic dysfunction disrupts the basal ganglia-cortical loops that normally support motor timing and sequencing [69]. External rhythmic cues (such as music) are thought to engage compensatory pathways involving the SMA and premotor cortex, and our findings raise the possibility that sustained rhythmic training may promote structural adaptations in these compensatory networks [70].

However, given the small sample size (n = 4) and lack of a non-dancing control group, these interpretations remain speculative. The observed FA changes could also reflect non-specific effects of physical activity, social engagement, or other factors associated with participation in the dance program.

Cortical Thickness in Language-Related Regions

The biphasic pattern observed in left SFL cortical thickness—initial increase followed by decrease—may reflect an adaptive remodeling process characteristic of motor learning. Studies of skill acquisition have documented similar inverted-U patterns, where initial training demands lead to cortical expansion (potentially reflecting increased synaptic density, dendritic arborization, or glial changes), followed by pruning and optimization as skills become consolidated and more efficiently represented [71, 72]. The fact that this dynamic pattern occurred in the SFL area, a region involved in motor-speech coordination, while participants were engaging in dance training that included vocalization components, suggests the changes may be functionally relevant—though this interpretation requires caution given the small sample and absence of controls.

The stability of Broca's area thickness, in contrast to the SFL changes, may reflect the different functional roles of these regions. Broca's area is primarily involved in established phonological and articulatory representations, whereas the SFL contributes to higher-order coordination and sequencing of motor acts. The novel demands of learning complex choreography with integrated vocalizations may have preferentially engaged SFL-mediated coordination processes rather than Broca's area-mediated speech production mechanisms. This regional specificity, if replicated, could help explain why dance training appears to benefit prosodic aspects of speech (which depend on temporal coordination) rather than basic articulatory functions. The absence of significant cortical thickness changes in the PPMI reference group over a comparable time window provides some context for interpreting the dance group findings, though the reference comparison is limited by differences in study design and the lack of randomization [73-78].

Integration of Neuroimaging and Speech Observations

Three participants who completed both the neuroimaging study and subsequent longitudinal follow-up showed improvements in F0SD over a five-year period. While this sample is too small for statistical inference, these case observations provide preliminary, hypothesis-generating evidence that early neural adaptations may relate to longer-term behavioral outcomes. F0SD, a measure of prosodic variability, typically declines with PD progression the apparent preservation or improvement in these three individuals is therefore noteworthy and consistent with the possibility that dance training engages and strengthens speech-motor networks.

It is important to emphasize that these speech observations cannot be causally linked to the neuroimaging findings. The temporal gap between imaging (2013–2014) and the extended speech follow-up (through 2019), combined with the small and overlapping samples, precludes strong inferences about brain-behavior relationships. These observations are presented as descriptive case data that may inform future hypothesis-driven research with larger samples and appropriate control conditions. Despite this limitation, a separate analysis for the F0SD, revealed a preserved pattern for this measure in a larger dataset (29 PwPD and 29 healthy controls) across 2014 to 2019, which further confirms the potential effect of dance on preserving prosodic vocal features [79-84].

Limitations

This study has several important limitations that constrain interpretation of the findings:

1. **Sample Size and Statistical Power:** The small sample sizes—particularly for DWI (n = 4) and the longitudinal speech analysis (n = 3)—limit statistical power and generalizability. While significant effects were observed, these findings require replication in larger cohorts.
2. **Absence of a Control Group:** Without a non-dancing PwPD control group or waitlist comparison, it is not possible to attribute observed changes specifically to dance train-

ing. Alternative explanations include natural variation, placebo effects, general benefits of physical activity or social engagement, practice effects on the imagery task, or other lifestyle factors. The PPMI reference group provides some context for the cortical thickness analysis but does not constitute a true control condition.

3. **Participant Heterogeneity:** Participants varied in disease duration, severity (where H&Y data were available), and likely in their individual responses to dance training. This heterogeneity may have introduced variability in neuroplastic responses and limits the ability to identify factors that predict treatment response.
4. **Potential Confounds in the fMRI Paradigm:** The imagery task may have engaged verbal working memory processes in addition to motor imagery, which could contribute to the observed changes in speech-related regions. Additionally, while the vocalization analysis window was defined a priori based on the choreography structure, analyzing a specific 10-second segment introduces the possibility that results may not generalize to the full imagery task.
5. **Exploratory Design and Multiple Comparisons:** This was an exploratory pilot study, and multiple comparisons were performed without correction. The findings should therefore be considered preliminary and hypothesis-generating rather than confirmatory.
6. **Temporal Disconnect Between Imaging and Speech Data:** The neuroimaging data were collected in 2013–2014, while the extended speech follow-up continued through 2019. This temporal gap, combined with the small overlapping sample, limits the ability to draw conclusions about relationships between early neural changes and long-term behavioral outcomes.

Implications and Future Directions

Despite these limitations, the current findings provide preliminary evidence that warrants further investigation. Future studies should:

1. Include adequately powered sample sizes based on effect size estimates from this pilot data
2. Incorporate a randomized controlled design with a non-dancing PD control group or active comparison intervention
3. Collect comprehensive behavioral assessments (including speech, motor, and cognitive measures) concurrent with neuroimaging
4. Examine potential moderators of treatment response, including disease severity, cognitive status, and baseline connectivity patterns
5. Include assessments of working memory and other cognitive domains to help disentangle motor learning from cognitive strategy effects
6. Extend follow-up periods to assess durability of neural and behavioral changes

The multi-modal approach employed here—integrating functional, structural, and diffusion imaging—offers a framework for comprehensively characterizing neuroplastic responses to rehabilitation interventions and could be applied in future controlled trials.

Conclusion

This exploratory pilot study provides preliminary evidence that participation in an 8-month dance training program may be associated with functional and structural brain changes in speech-motor regions in PwPD. The observed patterns—decreased BOLD signal in the inferior frontal gyrus, increased BOLD signal in the SMA, a biphasic pattern of cortical thickness change in the left SFL, and increased fractional anisotropy in white matter connecting Broca's area and the SFL—are consistent with neuroplastic adaptations, though alternative explanations cannot be excluded given the study design [85-87].

Descriptive observations from three participants suggest that these early neural changes may coincide with longer-term improvements in speech prosody, though this finding requires replication with larger samples and appropriate controls. The convergence of multi-modal imaging findings with behavioral observations supports the potential value of dance as a rehabilitation approach for PD and provides a foundation for future hypothesis-driven research. Given the limitations of this pilot study, including small sample size and absence of a control group, these findings should be interpreted cautiously. Nevertheless, the results justify further investigation of dance-based interventions using rigorous controlled designs to determine whether the observed associations reflect true neuroplastic effects of dance training.

Data Availability Statement

The study data is available from the corresponding author on reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical Considerations

The original study was conducted with ethics approval from York University (certificate numbers: 2013-211 & 2017-296). All data were anonymized to protect participant privacy, and data integrity and security were maintained throughout the analysis. For the current study, a renewed ethics approved this secondary analysis (Certificate #: 2025-032).

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Supplementary Material Legend

Supplementary Material:

The supplementary file includes extended results and visualizations supporting the findings of the main manuscript. Specifically:

Figure S1: Block design illustrating Music ON (red) and Music OFF (blue) states used during the fMRI dance imagery task

Tables S1–S2: Mixed linear model regression results for the motor cortex (inferior frontal gyrus) and supplementary motor area (SMA), respectively.

Table S3: Cortical thickness means and standard deviations for Broca's area and the left supplementary frontal language (SFL) area across time.

Expanded Cortical Thickness Analysis: Detailed evaluation of cortical thickness changes including all 10 participants, not limited to the core imaging subset.

Figures S2–S3: Violin plots showing cortical thickness distribution in Broca's area and the SFL area across timepoints for all available data.

Table S4: Descriptive statistics of cortical thickness values (mean, median, SD, min, max) across all subjects and timepoints.

Table S5: Summary statistics for streamline analysis between Broca's and SFL areas (mean, SD, count, length) across timepoints and subjects.

Expanded Cortical Thickness Analysis

In addition to the main analysis presented in the manuscript, cortical thickness measurements were also performed for all ten participants in the dance intervention group across the available time points (September, December, January, and April). The main text focused on a subset of four participants who completed imaging at all four time points, ensuring consistency for longitudinal analysis. The remaining participants had missing scans at one or more time points, which precluded their inclusion in the primary longitudinal comparisons. However, to provide a more comprehensive view, we present here the results from all available data across the full cohort. Cortical thickness values for Broca's area and the left SFL area were extracted for each participant using Free Surfer's "recon-all" pipeline, following the same procedures described in the main text. Statistical comparisons were conducted using a linear mixed-effects model.

Broca's area

- When considering all ten participants, no significant longitudinal changes in cortical thickness were observed in Broca's area ($p > 0.05$).
- Individual variability was noted, with some participants exhibiting minor increases or decreases, but these did not reach statistical significance at the group level (Figure S2).

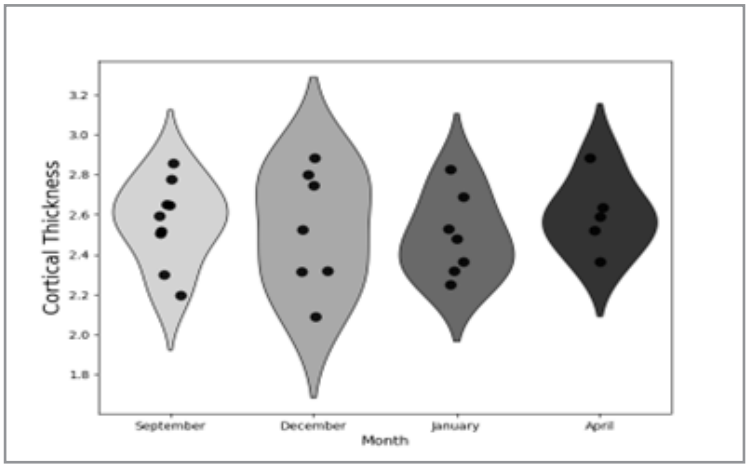

Figure S2: Violin plots showing the distribution of cortical thickness measurements across time points for Broca's area (all available data from 10 subjects). SFL area

- Similar to the subset analysis, the left SFL area showed a trend toward an initial increase in cortical thickness from September to December, followed by stabilization or slight decreases toward April (Figure S3).
- However, these changes did not reach statistical significance when considering all ten subjects with available data ($p > 0.05$).

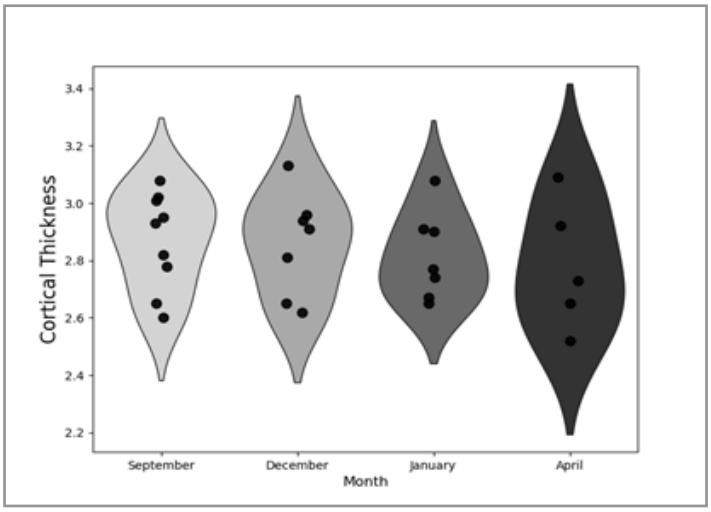

Figure S3: Violin plots showing the distribution of cortical thickness measurements across time points for the left supplementary frontal language (SFL) area (all available data from 10 subjects).

Table S4 represents the mean, median, standard deviation, minimum, and maximum values measured for the cortical thickness over Broca's area and the left SFL area across 4 time points from the 10 subjects.

Table S4: Descriptive Statistics of Cortical Thickness Values for Broca's Area and Left Supplementary Frontal Language Area Across Time Points for All Participants

Area	Time Point	Mean	Median	STD. DEV.	MIN	MAX
Broca	September	2.55988889	2.594	0.21087345	2.196	2.855
	December	2.52428571	2.523	0.29757112	2.088	2.885
	January	2.493	2.477	0.20734995	2.248	2.826
	April	2.5988	2.589	0.18884835	2.366	2.883
SFL	September	2.86966667	2.931	0.16900148	2.599	3.077
	December January April	2.85828571 2.81871429 2.7808	2.908 2.774 2.729	0.18010248 0.15455497 0.22436622	2.623 2.649 2.52	3.13 3.084 3.085

Streamlines Between Broca's and the Left SFL Areas

The mean, median, standard deviation, minimum and maximum length, and the number of tracks between Broca's area and the left SFL are presented in Table S5.

Table S5: Descriptive Statistics of the Streamlines Between Broca's and the Left Supplementary Frontal Language

Subject	Time Point	Mean	Median	STD DEV	MIN	MAX	Count
140	January	73.6174	71.4445	10.9546	57.7505	149.444	408
	April	73.2527	71.4309	11.7699	55.8497	196.196	533
142	January	78.0938	76.7318	9.83294	60.609	190.006	1224
	April	77.9044	76.0529	11.3409	60.0604	188.076	876
130	January	89.2351	87.0606	13.5828	65.2059	188.583	1003
	April	88.3505	86.6132	13.4954	64.5124	191.35	853

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