Voice and Speech in Parkinson’s Disease: Motor Control, Physiology, and Acoustics

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Acknowledgements
Stepp Lab, Boston University:

Agenda
 What is PD?
 Acoustic and physiological sequelae of PD across speech subsystems
 Voice and speech motor control in PD
 Assessment and treatment of voice and speech symptoms in PD
Parkinson’s disease (PD)

- Disorder of the brain that leads to shaking (tremors) and difficulty with walking, movement, and coordination
- Most often develops after age 50: one of the most common nervous system disorders of the elderly
- Nerve cells in the brain that make dopamine are slowly destroyed
- The disease is degenerative: the damage gets worse with time
- Cause: unknown
- Cure: unknown

Primary Motor Symptoms

- Tremor
- Rigidity
- Postural Sway / Coordination

“gold-standard” evaluation: subjective multi-question EAI scale: Unified Parkinson’s disease Rating Scale

Is PD a “disease of the basal ganglia”?

Braak et al., 2004
Treatment of Motor Symptoms
- Dopaminergic medications
- Deep brain stimulation
- Evidence for these in speech improvement is generally weak

Parkinson’s disease (PD)
- Known for motor symptoms
- Reduced speech intelligibility and speech naturalness → decreased quality of life
  - Reduced loudness: hypoprosody
  - Impaired prosody: monopitch, monoloudness
  - Impaired resonance: velopharyngeal incompetence
  - Imprecise articulation: hypokinetic dysarthria

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- What is PD?
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Respiration in PD

- Decreased vital capacity\(^1\)
- Impaired tidal breathing characteristics: more time in inspiration\(^2\) and faster rate\(^3\)
- Impaired speech breathing:
  - Greater use of abdominal vs. rib cage breathing\(^3\)
  - Fewer words per breath group and longer pauses\(^3,4\)

\(^1\) De Letter et al. 2007; \(^2\) Vercueil et al. 1999; \(^3\) Solomon & Hixon 1993; \(^4\) Huber & Darling 2001

Responds to medication\(^1,2,3\)

Does not respond to medication\(^3\)
Voice in PD

- Hypofunction
- VF Bowing

Voice in PD: loudness

- Predominant perceptual speech feature: Reduced loudness, hypophonia
- Acoustic correlate → Speech intensity or vocal amplitude
- Average intensity of PD speech is approximately 4 decibels (dB) lower than that of healthy adults

Voice in PD: motor correlates

Intrinsic laryngeal activations in 26 patients with PD and voice complaints and 26 age/sex-matched controls:

- Rigidity: yes!
  - 73% of patients with PD presented abnormal muscle firing during voice rest: hypertonicity
  - Normal EMG in all but six (23%) of the control patients, in whom hypertonicity was observed at rest
- Tremor: maybe, but … from where?
  - A tremor was observed in 11% of participants with PD during clinical, vocal, and videolaryngoscopic examinations
  - No tremor from EMG of the intrinsic laryngeal muscles in any of the 26 patients or 26 controls

Zarzur et al., 2009
Voice in PD: perception

Overall dysphonia
- Grade
- Roughness
- Breathiness
- Asthenia

Midi et al. 2007

Voice in PD: aerodynamics

15 individuals with PD OFF and ON medication
- OFF meds: mean glottal airflow 185.2 mL/sec (SD 103)
- ON meds: mean glottal airflow 250.9 mL/sec (SD 111.1)

Jiang et al., 1999

Voice in PD: acoustics

- 32 participants (23 male, 9 female) and age- and sex-matched controls were recorded during reading
- PD tested both OFF and ON medication
- Fundamental frequency variability
  - Standard deviation of F0 (F0SD)
  - F0SD in semitones (STSD)

Bowen, Hands, Pradhan, Stepp 2013
Voice in PD: acoustics

Highest STSD in Controls = 4.2 ST
Voice in PD: acoustics
Lowest STSD in PD OFF = 1.12 ST

Power-Source-Filter Model: Subsystems

Resonance in PD
- Velopharyngeal incompetence is a hallmark of hypokinetic dysarthria
- Suggested to be due to weakness of the levator palatine muscle
- Thought to lead to reduced velar seal

1) Folkins, 1988
**Resonance in PD: listener perception**

- 37 PD and 37 control speakers
- Monologue rated by 10 listeners
- Percentage occurrence of hypernasality across participants according to the four grades perceptual scores

Novotny et al. 2016

**Resonance in PD: nasal airflow**

- 20 with PD (10 mild, 10 moderate)
- 20 controls

Hoodin & Gilbert, 1989

**Power-Source-Filter Model: Subsystems**

- Speech Components
- Lungs (Power)
- Vibrating Vocal Folds (Source)
- Vocal Tract (Filter)
- Subsystems
- Respiration
- Voice
- Resonance
- Articulation
Articulation in PD

- Smaller movements – visible in movements and formant traces
- Vowel Space Area
- Diphthong transitions

Articulation in PD

- Issues with VSA: just a few values don’t represent real running speech
- New suggested solution: Articulatory-acoustic vowel space

Whitfield and Goberman, 2014

Articulation in PD

The formant trajectory trace (FTT) for a male from the PD group showing habitual (left pane) and clear (right pane) speaking conditions.

Whitfield and Goberman, 2014
Articulation in PD

Estimated Means and standard error for the articulatory–acoustic vowel space (AAVS) for participants in the older adult (OA) control group and Parkinson disease (PD) group.

Whitfield and Goberman, 2014

Summary: Speech symptoms in PD

Speech Components Subsystems Impact of Parkinson’s disease
Lungs (Power) Respiration Decreased vital capacity
Vibrating Vocal Folds (Source) Voice Impaired tidal breathing characteristics: more time in inspiration and faster rate
Vocal Tract (Filter) Resonance Impaired prosody: monopitch, monoloudness
Articulation Articulation Laryngeal rigidity
Velopharyngeal incompetence: high voice disfluency and perceived hypernasality
Increased articulation Reduced range of movement: smaller vowel space areas

Impact of Parkinson’s disease
Reduced loudness: hypophonia
High subglottal pressures

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Basis of voice & speech impairment in PD

- Largely attributed to laryngeal and respiratory motor abnormalities co-morbid with PD
- A sensorimotor integration deficit?
  - Disordered somatosensation\(^1\)
  - Disordered audition\(^2\)

\(^1\) Hammer & Barlow, 2010; \(^2\) Troche et al., 2012

DIVA framework

- Perturbations to auditory feedback
  - Brief, unanticipated perturbations:
    - Near-immediate compensatory response
    - Engaging FEEDBACK mechanisms
  - Gradual, prolonged perturbations:
    - Gradual adaptation
    - Update of the FEEDFORWARD plan

"Reflexive Responses"
"Adaptive Responses"
Reflexive responses in PD
- Articulation: n/a
- Voice: brief perturbations of f0
  - Larger responses were reported in PD OFF medications compared to controls (Chen et al., 2013; Liu et al., 2012)
  - No difference in response magnitudes between PD ON medications compared to controls (Kiran & Larson, 2001)

Adaptive responses in PD
- Articulation:

- Voice:
Adaptive responses in PD

- Articulation: Gradual alterations in F1 caused reduced adaptive responses in PD (ON medication) relative to controls (Mollaei et al., 2013)
- Voice:
Adaptive responses in PD

- Articulation: Gradual alterations in F1 caused reduced adaptive responses in PD (ON medication) relative to controls (Mollaei et al., 2013)
  - Voice: ??

Mollaei et al., 2013
Study purpose:
To measure the adaptive responses to f0 perturbations and auditory acuity in individuals with and without PD.

Study design

<table>
<thead>
<tr>
<th>Baseline</th>
<th>20 trials</th>
<th>60 trials</th>
<th>40 trials</th>
<th>40 trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift f0 and play as feedback</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hold</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After-effect + 1 ST</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ 1 ST Ramp</td>
<td></td>
<td></td>
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</tbody>
</table>


Participants

<table>
<thead>
<tr>
<th>N=16 PD</th>
<th>N=19 Controls</th>
</tr>
</thead>
</table>
| Age (years) | M=64.8, SD=6.3  
Range: 52 – 73 |
|           | M=65.3, SD=4.6  
Range: 50 – 77 |
| Sex | 8 F, 8 M  
10 F, 9 M |
| Time since diagnosis (years) | M=6.97, SD=7.05  
Range: 1.5 – 30 |
|           | N/A  
N/A |
| Hoehn and Yahr | M=2.1, SD=0.6  
Range: 1 – 3 |
|           | N/A  
N/A |
| UPDRS Part III score (total motor score) | M=41.0, SD=13.6  
Range: 22 – 72 |
|           | N/A  
N/A |

Experimental Tasks

- **Auditory Acuity to f0**

**Sensorimotor Adaptation Conditions:**

- **Control:** no f0 changes
- **“Shift-up”:** feedback increases gradually 100 cents (1 ST) above speaker’s true f0
- **“Shift-down”:** feedback decreases gradually 100 cents (1 ST) below speaker’s true f0


**Auditory Acuity to f0**

- N=16 PD and N=19 Controls
- Two phases per trial with two pure tones judged as same or different
- Based on performance, difference between tones adaptively modified via a two-alternative forced-choice procedure


**Auditory Acuity to f0**

- Just-noticeable-difference (JND) calculated as average of the last six ‘reversals’
- Degree of f0 difference detected with 70.9% accuracy

Sensorimotor Adaptation Task

- 160 trials repeating the vowel /α/ per condition
- Headphone feedback via Audapter:
  - Amplitude: mic + 5dB
  - f0: +/- 1 ST
  - Inherent delay of 44 ms


Sensorimotor Adaptation Task

- N=15 PD and N=15 Controls
- Average f0 per trial of each condition normalized in ST to baseline
- “Shift up” and “Shift down” condition responses normalized to the Control condition


Sensorimotor Adaptation Task

- Group Analysis: Two two-way mixed-model ANOVAs on “shift-up” and “shift-down” adaptive responses
- Individual Analysis: Two-tailed t-tests on individual adaptive responses during the hold phase relative to zero (corrected)
  - ‘Compensatory’ response: shift-down greater than 0 or shift-up lower than 0
  - ‘Nonresponsive’ response: not different than 0
  - ‘Following’ response: shift-down lower than 0 or shift-up greater than 0

Results: Auditory Acuity to f0

No significant difference
(df = 32, T = -0.19, p = 0.85)


Mean adaptive responses


Individual adaptive responses: controls

Individual adaptive responses: PD

- N=7 compensatory
- N=3 nonresponsive
- N=5 following


Basis of variability in PD

<table>
<thead>
<tr>
<th></th>
<th>“Shift-up” compensation</th>
<th>“Shift-down” compensation</th>
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</thead>
<tbody>
<tr>
<td>age</td>
<td>0.31</td>
<td>-0.53</td>
</tr>
<tr>
<td>years post-diagnosis</td>
<td>0.27</td>
<td>-0.02</td>
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<tr>
<td>UPDRS total motor score</td>
<td>0.40</td>
<td>0.03</td>
</tr>
<tr>
<td>pitch JND</td>
<td>0.25</td>
<td>-0.34</td>
</tr>
<tr>
<td>intelligibility</td>
<td>0.45</td>
<td>0.05</td>
</tr>
</tbody>
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Study Limitations

- Relationship between ‘reflexive’ and adaptive responses in the same subjects
Study Limitations

- Relationship between ‘reflexive’ and adaptive responses in the same subjects
- Medication effects
- Attentional effects


Current work

- Comprehensive study of reflexive and adaptive responses to f0 and F1 perturbation, ON and OFF medication, with and without cognitive load
- DIVA model parameters to predict associated neural characteristics


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- What is PD?
- Acoustic and physiological sequelae of PD across speech subsystems
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### Functional Evaluation in PD
- PD can impact all speech subsystems
- Progression across subsystems may not be linear
- Functional Evaluation
  - Speech Naturalness
  - Speech intelligibility
  - Communication Efficiency

### Intelligibility and PD
- "The degree to which the speaker’s intended message is recovered by the listener"\(^1\)
- Intelligibility is often used as a benchmark for therapy or treatment\(^2\)

\(^1\) Kent et al., 1989; \(^2\) Miller, N. (2013).

### Measuring Intelligibility
- “Gold standard” is orthographic transcription\(^1\)
  - Transcription of known text
  - Intelligibility = percentage of words correct
  - Number of listeners, cost, and time make inaccessible to clinicians\(^2\)
- Visual-analog scale (VAS) rating shows promise\(^3\)
  - Intelligibility = subjective rating
  - Less objective, lower inter- and intra-rater reliability
  - Cheaper, easier, faster

\(^1\) Miller, N. (2013); \(^2\) Gurevich & Scamihorn, 2017; \(^3\) Stipancic et al., 2016.
Methods

- Speakers: 12 M and 8 F with PD, 3 M and 2 F without
- 11 SIT sentences from each speaker mixed with multi-speaker babble and intensity normalized
- Listener tasks:
  - Transcription: 17 F and 16 M transcribed 28 SIT sentences (1 from each speaker, and 3 repeated for reliability)
  - VAS: 7 F and 7 M rated 308 SIT sentences (all 275 sentences, and 33 repeated for reliability)

How many listeners are needed?

How does the VAS vs. transcription relationship change with number of listeners

- Simulate all possible combinations of 1 to 14 possible listeners
- Again calculate speaker averages, re-calculate $R^2$, and determine mean and SD of that $R^2$

Results

SLPs can substantially improve the quality of their intelligibility estimates by enlisting the ear of just one additional listener
Treatment based on cueing

- People with PD may not be aware that their speech is getting softer and less intelligible
- Patients describe feeling like they are shouting, even though listeners hear them speaking normally
- They can respond to an external cue, but their ability to cue themselves internally to use a louder voice is impaired

LSVT: Think Loud!

- LSVT® LOUD focuses on a single goal - "speak LOUD!" – to stimulate the respiratory, laryngeal and articulatory function to maximize speech intelligibility
- Although treatment focuses only on SPL, due to the intrinsically tied nature of prosodic cues, patients may see improvements in respiration and articulation as well

LSVT: evaluation

- Significant treatment effect on trained speech (~15 dB)
- Maintenance (~9 dB) on trained speech
LSVT: evaluation

- The treatment effect is ~ 4dB for real speech
- The treatment effect is ~ 2-3 dB by 2 years post-treatment

Ramig et al., 2001

LSVT: evaluation

RCT: matched dosage and high-effort speech therapy in PD, differing by subsystem target:

- Voice (respiratory-laryngeal) – LSVT LOUD
- Articulation (orofacial-articulatory) – LSVT ARTIC

Ramig et al., 2018

LSVT: evaluation

Outcomes:
- dB SPL during running speech
- Modified Communication Effectiveness Index (CETI-M)

Evaluated before and after 1 month of:
- LSVT LOUD (n = 22)
- LSVT ARTIC (n = 20)
- No treatment (UNTXPD; n = 22)

Ramig et al., 2018
LSVT: evaluation

**Means and SDs for dB SPL at 30 cm.**

Ramig et al., 2018

**Means and Inter-quartile ranges for CETI-M scaled 0 – 100.**

Ramig et al., 2018

**LSVT: evaluation**

- Only evidenced-based behavioral treatment for speech in PD
- Evidence for voice relative to articulatory targets
- When generalized to running speech treatment effects are
  - 4-5 dB immediately / 1-month post-treatment
  - 2-3 dB 7-24 months post-treatment