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Research Article

Variation in Speech Intelligibility Ratings as a Function of Speech Rate Modification in Parkinson's Disease

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Purpose: The aim of this study was to quantify changes in speech intelligibility in two cohorts of people with Parkinson's disease (PD; those with and without deep brain stimulation [DBS]) across a broad range of self-selected speech rate alterations in (a) read sentences and (b) extemporaneous speech (monologues).

Method: Four speaker groups participated in this study: younger and older controls, people with PD undergoing standard pharmaceutical treatment, and people with PD and DBS. Naïve listeners rated the intelligibility of read sentences and extemporaneous monologues, spoken by participants at seven self-selected speech rates from very slow to very fast. Intelligibility was modeled as a function of group, speech rate condition, and speech task.

Results: Overall, compared to habitual speech rate, slower speech rate conditions were not associated with changes in speech intelligibility, whereas faster-than-habitual conditions were associated in declines in intelligibility. Results were mediated by group and task effects, such that talkers with PD and DBS were more likely to see intelligibility benefits at slower self-selected speech rates and less likely to see detriments at faster rates, and these differences were amplified in monologues compared to sentences.

Conclusion: Findings suggest differences in the ways in which slower and faster speech rate adjustments impact speech intelligibility in people with PD with and without DBS, with the latter demonstrating greater magnitudes of change.

Improving speech intelligibility, that is, the degree to which a spoken utterance is understood by a typical listener (N. Miller, 2013; Weismer, 2008; Yorkston, Strand, & Kennedy, 1996), is one of the primary goals of behavioral speech intervention for individuals with Parkinson's disease (PD) and dysarthria (Duffy, 2019). The majority of people with PD will develop dysarthria at some point during the disease (Logemann et al., 1978; Mutch et al., 1986; Müller et al., 2001). For many individuals, global speech treatments, rather than system-specific treatments, are desirable to effect change at a broad level. Global speech targets, such as rate, loudness, prosody, or clarity, aim to affect multiple speech subsystems (Yorkston et al., 2007).

One such global treatment strategy is speech rate reduction. The goal of rate reduction is for the individual to learn to achieve a slower rate of speech more conducive to being understood when speaking (Duffy, 2013; Yorkston et al., 2007, 1990). Speech rate is an appealing treatment variable because it is highly modifiable (Blanchet & Snyder, 2009; Yorkston et al., 1992), and rate reduction has successfully been demonstrated to improve speech intelligibility across multiple motor speech disorders (Yorkston et al., 2007), including hypokinetic dysarthria in PD (Adams, 1994; Downie et al., 1981; Hammen et al., 1994; Hanson & Metter, 1983; LeDorze et al., 1992; Martens et al., 2015; Yorkston et al., 1990). However, the efficacy of rate reduction in improving intelligibility in talkers with PD is not straightforward. Despite promising findings in earlier case and small group studies, several recent studies have demonstrated that many talkers with dysarthria do not exhibit improved intelligibility when they reduce their speech rates, and some may even worsen (Fletcher et al., 2017; Hall, 2013; Kuo et al., 2014; McAuliffe et al., 2017; Van Nuffelen et al., 2010, 2009).

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It should be noted that the goal of rate reduction interventions is not necessarily a "normal rate" but rather "improved intelligibility." Some individuals with PD demonstrate faster rates of speech (Darley et al., 1969; Flint et al., 1992; McRae et al., 2002), and it may be the case that such individuals may approach a more "normal" rate as a consequence of rate reduction. Individuals with PD may also demonstrate greater speech rate acceleration (i.e., progressively speeding up) compared to controls (Skodda, 2011; Skodda & Schlegel, 2008). Other studies have reported slower rates of connected speech (Hsu et al., 2017; Martínez-Sánchez et al., 2016), and several studies have reported finding no group differences (or inconsistent differences) in speech rate of talkers with PD compared to healthy controls (Caligiuri, 1989; Connor et al., 1989; Kleinow et al., 2001; Ludlow et al., 1987; Metter & Hanson, 1986; Skodda & Schlegel, 2008; Tjaden & Wilding, 2004; Walsh & Smith, 2012; Weismer et al., 2001).

Yorkston et al. (1999) described the likelihood of a trade-off between speech accuracy and speech naturalness such that, for a given speaker with dysarthria, there may exist an intelligibility peak. Speaking too slowly in relation to this hypothetical peak would result in poorer understanding because of compromised speech naturalness, whereas speaking too quickly would lead to imprecise articulation. Yorkston et al. asserted that the goal of speech rate modification intervention is to identify a target rate that "will allow an optimal level of intelligibility without degrading naturalness unnecessarily" (p. 416).

The majority of studies that have explored intelligibility as a function of rate modification have done so by eliciting only one or two different rates (e.g., a "slow" and/or "fast" rate). The extent to which a speaker slows down (or speeds up) likely has a bearing on the extent to which intelligibility changes are noted. Two studies to date have demonstrated that slowing rates to 60% of speaker's habitual rate led to substantial improvements in sentence intelligibility in speakers with hypokinetic dysarthria compared to slowing rates only to 80% of their habitual rate (Hammen et al., 1994; Yorkston et al., 1990).

In their review of different rate control methods, Van Nuffelen et al. (2009) explored three rates of speech elicited via delayed auditory feedback. The authors found that slower rates of speech elicited tended to be associated with "lower" intelligibility ratings. Their follow-up study further found that maximal rate reduction across different rate control methods was not necessarily associated with maximal intelligibility gains (Van Nuffelen et al., 2010). Relatedly, while faster speech has received considerably less focus in the literature, at least one study has demonstrated that faster-than-normal speech is not necessarily associated with reduced intelligibility in talkers with PD (Kuo et al., 2014), and it may even be associated with increased naturalness or acceptability in some cases (Dagenais et al., 2006; Logan et al., 2002; Sussman & Tjaden, 2012). Perhaps given that faster speech is infrequently considered an appropriate clinical speech goal for talkers with dysarthria, there is a relatively wider body of literature on the mechanisms of fast speech in young, healthy talkers (e.g., Adams et al., 1993; Miller et al., 1986; Tjaden, 2000). The factors underlying changes in intelligibility as speech rate is adjusted by talkers with PD are still largely unknown.

Studies of speech rate modification in PD have exclusively elicited speech via read passages and have largely ignored spontaneous speech samples. Evidence suggests that structured speech tasks, such as reading, tend to be more intelligible than spontaneous speech in PD (Kempler & Van Lancker, 2002; Kent, 1996; Weismer, 1984; Yorkston & Beukelman, 1981; cf. Bunton, 2008; Tjaden & Wilding, 2011). Extemporaneous speech production is more ecologically valid but is difficult to administer in a controlled manner across speakers. Given that the goal of behavioral speech therapy, regardless of the method employed, is to improve communication in the context of daily life, there is a need to better understand the impact of rate modification on more extemporaneous speech in spite of the challenges.

Another notable omission in the literature on speech rate modifications in talkers with PD is the inclusion of individuals undergoing deep brain stimulation (DBS) therapy. Talkers with DBS are often excluded from clinical speech studies given the variability in their speech outcomes. Standard pharmaceutical interventions (i.e., Levodopa) tend to exhibit little to no effect on speech (Spencer et al., 2009; cf. Cushnie-Sparrow et al., 2018; Im et al., 2018), while DBS is associated with further speech impairment in many individuals (Aldridge et al., 2016). This is a crucial group to consider for the following reasons. Speech impairment following DBS is often marked by declines in speech intelligibility (Aldridge et al., 2016). The increasing popularity of DBS, especially since it was recently approved for use in earlier stages of PD with promising implications for gross motor symptoms (Hacker et al., 2020), suggests that this subgroup will continue to grow as a population served by speech-language pathologists. Therefore, a better understanding of not only the characteristics of speech production following DBS but also the characteristics in responses to behavioral speech adjustments is necessary to inform clinical decision making. How talkers with DBS respond to rate adjustments is not presently known.

Summary and Rationale for the Current Study

In summary, previous work has demonstrated that rate reduction may be an effective treatment for some talkers with PD and dysarthria, but not for others. Three main gaps in the literature have been identified that may aid in better understanding the benefits and limitations of using rate modification in speech treatment with this population. First, studies have typically explored a small number of rate adjustments, but little is known about how speech and speech intelligibility may vary across a wider range of modified rate targets (e.g., very slow to very fast). Second, no studies have as of yet quantified the impact of rate modifications on more naturalistic, ecologically valid speech tasks, that is, spontaneous speech. Eliciting such speech necessitates the use of voluntary (i.e., nonrigid) rate modification techniques, such as magnitude production (Yorkston et al., 1999). Lastly, talkers with PD and DBS have previously been excluded from studies of rate modification, despite the increasing prevalence of this form of intervention and its association with further speech decline. Studies of rate manipulation that encapsulate a wider range of speech rates, speech tasks, and speakers have the power to inform researchers on (a) the extent to which modifying rate impacts the intelligibility of an utterance, (b) the kinds of changes that occur when speech rate is increased or decreased, and (c) how variations in these changes affect distinct dysarthric speaker groups and across individual speakers. Given the variability and occasional improvements in speech outcomes associated with faster speech, this too merits further investigation for this population.

Determining the precise changes that occur for these speakers across a range of speech tasks and speech rates will permit researchers to better understand the specific differences that lead to optimal speech intelligibility and how these targets are achieved as well, aiding in the advancement of theoretical models of speech production in PD.

The purpose of the current study is to identify changes in speech intelligibility in two cohorts of talkers with PD (those with and without DBS) across a broad range of categorical speech rate alterations in (a) read sentences and (b) extemporaneous speech (monologues).

Primary Research Questions

Given the above, this article aims to address the three following research questions:

1. Compared to speech produced at habitual rates, how does speech intelligibility change across a range of categorically modified speech rates from very slow to very fast?
2. What differences emerge in talkers with PD and DBS compared to those with PD receiving standard pharmaceutical intervention across a range of speech rates, and how do these differences compare to younger and older healthy talkers?
3. How is intelligibility across such a range of modified speaking rates affected across read sentences and spontaneous monologues?

Method

The study was approved by the Health Sciences Research Ethics Board at Western University and the Lawson Health Research Institute. All participants provided informed written consent.

Speech Production Experiment

Speaker Participants

Four participant groups were included in the final study for a grand total of 69 speakers: (a) younger healthy controls (YC; $n = 17$, under 35 years of age, nine male and eight female), (b) older healthy controls (OC; $n = 17$, 56–82 years of age, 11 male and six female), (c) people with PD and dysarthria who were receiving standard pharmaceutical interventions (PD-Med; $n = 22$, 18 male and four female), and (d) people with PD who had undergone bilateral DBS of the subthalamic nucleus (STN-DBS) surgery (PD-DBS; $n = 13$, 11 male and two female). PD-DBS participants were also taking titrated doses of anti-parkinsonian medication.[1] Participant information for the PD groups is reported in Tables 1 and 2. All participants were native or near-native speakers of North American English and had self-reported adequate vision or corrected vision for reading print. All but the YC participants underwent a 40 dB SPL hearing screening at 0.5, 1, 2, and 4 kHz, unless they wore hearing aids. All YC participants self-reported normal hearing. All OC, PD-Med, and PD-DBS participants completed the Montréal Cognitive Assessment. Participants were not, however, excluded on the basis of hearing or cognitive status. Two OC, four PD-Med, and two PD-DBS participants reported wearing dentures.

Participants in the two PD cohorts were deemed eligible if they had (a) received a diagnosis of PD at least 1 year prior by an expert clinician in movement disorders (M. J.) using current diagnostic criteria (Postuma et al., 2015) and (b) were stabilized on anti-parkinsonian medication and/or via surgical STN-DBS settings. PD-Med participants were also recruited on the basis of evidence of at least mild dysarthria, as identified by a neurologist on the Unified Parkinson's Disease Rating Scale present in their patient chart history. PD-DBS participants were not recruited on the basis of speech symptoms and represented a convenience sample of STN-DBS patients. Deviant perceptual characteristics listed in Tables 1 and 2 were determined by consensus by the first two authors (T. K. and S. G. A.).

Audio Recording Procedure

Recordings were made in an audiometric booth (Industrial Acoustic Company) using a 2017 15-in. Dell laptop computer (Inspiron 15). Participants wore a headset microphone (AKG c520), positioned 6 cm from the mouth, and connected to the laptop via a preamplifier and digitizing unit (M-Audio MobilePre) attached via USB. The headset was positioned so as to allow hearing aids and glasses to remain in place. Experimental audio recordings were made via a customized MATLAB script (MATLAB Version 9.4.0 [R2018a], 2018), which digitized the audio signals at 44.1 kHz and 16 bits. Practice trials (described below) were recorded separately in Praat (Boersma & Weenink, 2011).

Speech tasks. The primary speech tasks of interest included (a) sentences read aloud and (b) extemporaneous monologue.[2] A unique randomized list of six sentences

[1]The term *PD-Med* is used for simplicity. Most PD-DBS participants were also continuing to receive medication.

[2]Two other tasks were included in the complete protocol as part of a larger project; these included (a) nonce words in a carrier phrase and (b) picture description. Tasks were designed to represent a continuum of linguistic complexity. Only sentences and monologue production are reported here.

Table 1. Demographic data for the PD-Med group.

ID	Sex	Age	MoCA	Years postdiagnosis	PD medications	LEDD (mg)	Deviant perceptual characteristics
01	m	60	29	12	Levodopa	400	Monopitch, mild hypophonia, short rushes
02	m	65	18	14	Levodopa	1200	Monopitch, moderate hypophonia, imprecise consonants
03	m	65	23	12	Levodopa	532	Repeated phonemes, imprecise consonants, short rushes
04	m	66	28	35	Levodopa	NA	Harsh voice, monopitch, short rushes, imprecise consonants
05	m	73	27	7	Levodopa	NA	Hypophonia, short phrases, short rushes
06	f	67	30	10	Levodopa, Mirapex	700	Short rushes, fast rate, breathy voice
07	m	72	29	9	Levodopa, Amantadine	NA	Imprecise consonants, breathy voice, increased pitch
08	m	85	24	4	Levodopa	400	Harsh voice, imprecise consonants, short rushes
09	m	56	28	25	Levodopa, Amantadine	NA	Strained–strangled voice, imprecise consonants, short rushes of speech, phoneme repetitions
10	m	71	25	5	Levodopa	800	Imprecise consonants, distorted vowels, high pitch, hyponasality
11	m	68	25	8.5	Pramipexole, Levodopa	300	Strained voice, hoarse voice, hypophonia
12	m	72	24	15	Levodopa, Pramipexole	1300	Hypernasality, monopitch, low pitch
13	m	62	26	3	Levodopa	800	Hoarse voice, imprecise consonants, short rushes
14	m	90	24	10	NA	NA	Hypernasality, high pitch, imprecise consonants, harsh voice
15	m	70	28	2	Levodopa	900	Moderate hypophonia, short rushes, imprecise consonants, high pitch
16	m	73	23	10	Levodopa	800	Moderate hypophonia, hoarse voice, imprecise consonants, monopitch
17	f	71	26	5	Levodopa	NA	Hoarse voice
18	m	64	28	6	Levodopa	600	Imprecise consonants, short rushes, monopitch, moderate hypophonia
19	f	68	28	18	Duodopa	NA	Mild hypophonia, breathy voice, imprecise consonants, short rushes
20	f	73	25	30	Levodopa, Mirapex, Amantadine, Apo-Gabapentine	1200	Imprecise consonants, short rushes, audible inhalations
21	m	64	28	8	Mirapex	450	Mild hypophonia, monopitch, imprecise consonants
22	m	71	25	10	Levodopa, Pramipexole	900	Imprecise consonants, harsh voice

Note. Levodopa refers to Levodopa/carbidopa. One PD-Med participant (PD14) was unsure of their current medication list, which is listed here as NA. Deviant perceptual characteristics for the PD-Med and PD-DBS groups correspond to features noted during the habitual monologue speech samples. PD-Med = people with Parkinson's disease without deep brain stimulation; MoCA = Montréal Cognitive Assessment; PD = Parkinson's disease; LEDD = Levodopa equivalent daily dose; m = male; f = female; PD-DBS = people with Parkinson's disease with deep brain stimulation; NA = not applicable.

was created for each participant and trial. Each list included words ranging from five to 10 words in length (one sentence at each length) from the Sentence Intelligibility Test item bank (Yorkston, Beukelman, & Tice, 1996). Sentences were split into two short lists (five, seven, and nine words and six, eight, and 10 words) during task administration. Participants also engaged in approximately 2 min of extemporaneous monologues in which they were prompted to talk about specific topics. Seven topics were presented in a random order for each participant and included the following: "Please tell me about…" (a) "one of your favorite vacations," (b) "your favorite food or foods," (c) "your family," (d) "a book or TV show that you like," (e) "where you grew up," (f) "what you do or used to do for work," and (g) "what you like to do in your free time."

Speech rate conditions. Seven categorical rate conditions were employed in order to elicit a wide range of actual speech rates: habitual rate, three slower rates, and three faster rates. Participants performed each speech task once for each of the conditions. The habitual rate was always elicited first. Faster and slower rates were elicited in blocks that increased or decreased respectively in the magnitude of the elicited modified rate. Rate blocks were counterbalanced across participants. Modified rates were elicited using magnitude production (i.e., rather than a more rigid method such as metronome pacing) in an effort to elicit more natural speech (Adams et al., 1993; Tjaden & Wilding, 2004; Turner et al., 1995). For each condition, the following instructions were given: "For this next part, please speak at a rate that feels [2×/3×/4×] [*slower/faster*] than your normal speaking rate." An outcome of this technique is that speech rates were self-selected and thus correspond to individual talkers' psychophysical self-scaling of their own speech rate, rather than objective, actual rates of speech (e.g., specific rate targets in words per minute [WPM]). Rate condition, thus, refers to each speaker's intended speech rate, rather than the actual, acoustically derived rate they produced. Additional instructions for the slower conditions included encouraging participants to stretch out their speech rather than pause more in between words (Tjaden et al., 2014). In addition to verbal instructions, participants had constant access to a visual prompt, as well.

Prior to beginning a new rate condition, participants were provided with an opportunity to practice the new rate with a probe sentence. This practice session was recorded and used to ensure they were indeed speaking more slowly

Table 2. Demographic data for the PD-DBS group.

ID	Sex	Age	MoCA	Years postdiagnosis	Years since DBS surgery	PD medications	LEDD (mg)	Deviant perceptual characteristics
01	m	60	24	12	2	Levodopa, Amantadine	300	Hoarse, breathy voice, monopitch, imprecise consonants, prolonged intervals
02	f	71	16	25	9	Levodopa	50	Hoarse, breathy voice, imprecise consonants, short rushes, fast rate
03	m	63	24	18	9	Amantadine, Levodopa	430	Mild hypophonia, imprecise consonants, short rushes, high pitch
04	m	73	20	12	4	Levodopa	NA	Strained–strangled voice, imprecise consonants, prolonged phonemes, slow rate
05	m	56	27	16	6	Levodopa	NA	Harsh voice, imprecise consonants
06	m	59	16	13	5	Levodopa, Amantadine, Sinemet	NA	Mild hypophonia, imprecise consonants, high pitch
07	f	69	25	16	3	Levodopa	550	Moderate hypophonia, strained–strangled voice, audible inspiration, voice breaks
08	m	66	28	14	6	Levodopa	NA	Mild hypophonia, strained–strangled voice, pitch breaks, imprecise consonants
09	m	55	28	8	1	Levodopa	500	Imprecise consonants, hoarse voice, short rushes, fast rate
10	m	66	23	4	3	Levodopa	150	High pitch, hypernasality, imprecise consonants, short rushes
11	m	60	25	12	4	Levodopa, Ropinirole	NA	Harsh, breathy voice, imprecise consonants, audible inspirations
12	m	66	28	14	7	Levodopa	500	Mild hypophonia, imprecise consonants, short rushes, fast rate
13	m	72	22	15	4	Levodopa	600	Imprecise consonants, breathy voice

Note. Deviant perceptual characteristics for the PD and DBS groups correspond to features noted during the habitual monologue speech samples. PD-DBS = people with Parkinson's disease with deep brain stimulation; MoCA = Montréal Cognitive Assessment; DBS = deep brain stimulation; PD = Parkinson's disease; LEDD = Levodopa equivalent daily dose; m = male; f = female; NA = not available.

or rapidly than the previous condition. They were encouraged to read the sentence aloud at least 2 or 3 times, but also as many times as they needed, to feel comfortable and accurate at the new rate. While the absolute rate was not important, they were encouraged to at least be sure they felt faster or slower than the previous rate (depending on the block). One of their practice sentences was then played back to them and then played again approximately every 10 trials in order to assist them in maintaining their target rate and verbal reminders to use their model rate were provided as needed.

Speech task randomization. Within each of the seven speech rate conditions, the four speech tasks were presented in a quasirandomized order. The monologue task was always presented last, while the order of all other speech tasks was randomized. This was done in order to ensure that participants were maximally adjusted to the given target speaking rate by the time they were asked to engage in spontaneous speech in order to minimize the cognitive load of this task. Breaks were offered as needed.

Intelligibility Experiment

Listener Participants

Listeners were six female graduate students recruited from Western University graduate speech-language pathology second-year class. All were under the age of 35 years. All received clinical speech hours for their participation in the study. Listeners passed a hearing screening at 20 dB SPL HL for octave frequencies from 250 to 8000 Hz. The listening task was performed in a sound-attenuated booth with audio stimuli presented via a pair of external speakers calibrated to 70 dB SPL (SPL-A; slow setting). All listeners completed the intelligibility tasks over the course of approximately 4 weeks, during which they came in for approximately four to five self-paced sessions, most lasting approximately 2 hr each (approximately 10 hr in total).

Intelligibility Procedures and Tasks

Stimuli preparation. Sentences and monologue passages were extracted and rescaled to 70 dB SPL. Six sentences and one monologue sample were presented per speaker per rate condition. Read sentences were extracted at the utterance boundaries. From the monologue recordings, 10–20 s of continuous, spontaneous speech samples from each participant in each condition were extracted. In some cases, for example, if 10–20 s of uninterrupted speech was not possible (e.g., because of long pauses or requests for more information), two to three subsets of continuous speech (selected at utterance boundaries) were identified and concatenated together until 10–20 s of speech was obtained. This occurred for 50 of the monologue speech samples (approximately 10.5%).

Listening task. Utterances were presented in five playlists: four playlists for the read sentences, composed of four to five speakers from each group, and one playlist containing the monologue samples from all speakers. Playlists were presented in a different random order for each listener, and utterances within each playlist were randomized each time.

Listeners rated the sentences and monologues along a computerized visual analog scale (VAS). All listeners heard all stimuli from all speakers (49 items in total per speaker participant: 7 items × 7 rates).[3] Ten percent of items were repeated for reliability purposes, amounting to 3,665 total utterances. The VAS tasks were administered via a customized Praat script written by the first author that featured a horizontal line with anchors *low intelligibility* and *high intelligibility*. Listeners were instructed to rate the intelligibility of each utterance by clicking the point along the scale corresponding to their rating. Listeners were not permitted repeat trials.

Inter- and intrarater reliability. Reliability of the speech intelligibility estimation task was calculated using the intraclass correlation coefficient (ICC; Koo & Li, 2016). Interrater reliability across the six listeners was examined using average consistency in a two-way random model (ICC 2, *k*) for each of the two tasks (sentences and monologue). Intrarater reliability for each listener and task was examined using average agreement in a two-way mixed model (ICC 3, *k*).

Outcome Measures and Statistical Analyses

Intelligibility ratings were treated as a proportion of the VAS (0–1, low to high), which was logit-transformed[4] (Baum, 2008) and modeled as a function of speaker group, speech rate, and speech task using mixed effects regression with the lmerTest package (Kuznetsova et al., 2017) in R (R Core Team, 2020). Random effects included by-participant random intercepts and random slopes for rate condition contrasts, as well as nested by-item random intercepts. Random slope terms were uncorrelated in order to facilitate convergence and avoid overparameterization of the models (Stuart-Smith et al., 2015; Tanner et al., 2017). The *p* values were calculated using the Satterthwaite approximation from the lmerTest package (Kuznetsova et al., 2017).

All categorical fixed-effects terms were contrast-coded in a manner that made theoretical sense for the levels being compared, as described below. *Speaker group* was coded as a four-way level variable and coded using reverse Helmert contrasts. Helmert contrasts allow the mean of each level to be compared to the overall mean of the subsequent levels. The contrast scheme for group may be interpreted in the following way: (a) young versus old (YC vs. OC, PD-Med, and PD-DBS groups combined), (b) healthy older versus clinical (OC vs. PD and DBS combined), and (c) PD with and without DBS (PD-Med vs. PD-DBS). *Speech rate condition*[5] was coded using treatment contrasts with the habitual rate condition (H1) set as the reference level. That is, each contrast level compares one of the six modified rate conditions to the habitual baseline. *Speech task* (sentence reading vs. monologue) was sum-coded. Comparisons between each modified rate condition were discerned with post hoc pairwise comparison testing. Speaker sex and listener were also included as fixed effects in the models to account for variability present.

To confirm whether the speech rate conditions were indeed associated with acoustically derived speech rate modifications in the expected directions, a secondary analysis was run. For this analysis, speech rate in WPM was calculated for each of the sentences in the sentence task. Utterance onsets and offsets were time-stamped, and sentence duration was divided by the number of words (i.e., five to 10 words, depending on the item). Pauses were not extracted, as rate of speech, rather than articulatory rate of speech, was the primary interest at this stage. This analysis was completed only for the sentence task.

For this analysis, speech rate (in WPM) was log-transformed (in order to meet model assumptions requiring normal distribution of residuals; Gelman & Hill, 2007) and modeled as a function of rate condition, group, and their interaction. Groups were coded using Helmert contrasts as above. Successive differences contrasts were applied to rate conditions using the MASS R package (Venables & Ripley, 2002) in order to test the difference in speech rate between each condition in a sequential, ordered fashion. With this coding scheme and the rate condition variable ordered from slow to fast, each contrast level may be interpreted as the difference between the means of subsequent levels, for example, the 3× slower and 4× slower rates, the 2× slower and 3× slower rates, the habitual and 2× slower rates, and so on.

Results

Acoustically Derived Speech Rate Modification

Habitual speech rates for the sentence task are presented in Table 3. Pairwise comparisons across groups during the habitual rate condition are presented in Table 4. Across all rate conditions, there was no main effect of group for any of the group contrasts, indicating that the groups demonstrated similar actual (acoustically derived) rates of speech during sentence reading ($p > .5$). There were no baseline group differences in WPM during the habitual rate condition, as indicated in Table 4.

Pairwise comparisons across sequential rate conditions for each group are reported in Appendix A. Full model results (i.e., pooled over groups) are reported in the text.

[3]Three participants with PD had incomplete data sets. One PD-Med participant (PD-Med 09) experienced dyskinesias that interfered with some of the audio recordings in the fast block, and two PD-DBS participants elected not to complete all rate conditions due to fatigue (PD-DBS 02 and 04). Specifically, PD-DBS 02 did not complete the fastest condition, and PD-DBS 04 did not complete the slowest condition and the two fastest conditions.

[4]It is recommended to perform logit transformations on proportional variables in regression models in order to account for the upper and lower limits of the response and avoid nonsensical model predictions (Baum, 2008).

[5]Speech rate condition, rather than acoustically derived speech rate, was used for the primary analyses for the following reasons: (a) in order to preserve a comparison to each talker's habitual rate, (b) in order to provide a similar comparison across speech tasks, and (c) given the supported nature of the speech task elicitation, in which maintenance of the target rate was facilitated with visual and audio prompts.

Table 3. Habitual speech rates for each group.

Group	*n*	WPM	*SD*	*SE*	CI
YC	17	216	25	6	13
OC	16	198	33	8	18
PD-Med	22	201	36	8	16
PD-DBS	12	191	28	8	18

Note. WPM = words per minute; *SD* = standard deviation; *SE* = standard error; CI = confidence interval; YC = younger healthy controls; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation.

Speech rate in WPM varied as expected across the rate conditions, with each rate contrast level associated with an increase in acoustically derived speech rate. This was significant for all contrast levels. As can be seen in Figure 1A, there was a greater degree of variability in the slower speech rate conditions, as evidenced by flatter density curves. This pattern is also visible in Figure 1B. Estimated differences across sequential rate conditions for each group, reported in Appendix A, demonstrated that this pattern of intended rate adjustments was generally consistent across all rates for all groups, despite not reaching significance at all rate condition comparisons. As can be seen in Appendix A, the magnitude of adjustments was not symmetrical in slow versus fast speech conditions. For example, the YC slowed their actual speech rate by an estimated 88 WPM from habitual to the 2× slower condition (S2–H1) but only quickened their rate by an estimated 50 WPM in the 2× faster condition (H1–F2). This pattern held for the older control group and both PD groups, as well. Changes in absolute WPM from habitual in the 2× slower and 2× faster rates, respectively, for each group were as follows: 59 WPM versus 25 WPM (OC), 53 WPM versus 37 WPM (PD-Med), and 42 WPM versus 20 WPM (PD-DBS).

Listener Reliability

Average interrater reliability values were .889 (95% confidence interval [.88, .897]) for the sentence task and .938 (95% confidence interval [.924, .949]) for the monologue task. This can be interpreted as *good* and *excellent* interrater reliability, respectively (Koo & Li, 2016).

Average intrarater reliability for the sentence task was *good* (M = .872, range: .824–1) and *excellent* for the monologue task (M = .934, range: .894–.983; Koo & Li, 2016). Intrarater reliability scores for each listener and task are presented in Tables 5 and 6.

Table 4. Pairwise comparisons of habitual speech rates between groups.

Contrast	Estimate	*SE*	*df*	*t* ratio	*p*
YC–OC	17.988	13.639	141.172	1.319	.552
YC–PD-Med	17.134	12.751	140.709	1.344	.537
YC–PD-DBS	24.894	14.378	140.393	1.731	.311
OC–PD-Med	−0.854	12.315	140.709	−0.069	1.000
OC–PD-DBS	6.906	13.993	140.393	0.494	.960
PD-Med–PD-DBS	7.760	13.129	140.393	0.591	.935

Note. Estimates reflect estimated differences in words per minute. *SE* = standard error; *df* = degrees of freedom; YC = younger healthy controls; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation.

Intelligibility

Main Effects

Main effects, that is, effects when other variables are held constant, are reported first. Interactions are reported in the following sections.

Speaker group. All three group contrasts were significant and may be interpreted in the following way: The YC group was rated as most intelligible (YC vs. OC, PD, DBS: $\beta = 1.901$, $p < .001$), followed by the OC group (OC vs. PD, DBS: $\beta = 2.022$, $p < .001$), with the DBS group being rated as least intelligible (PD-Med vs. PD-DBS: $\beta = 1.282$, $p < .001$).

Speech rate conditions. When averaged across all speaker groups, all three fast rate conditions were associated with increasing declines in speech intelligibility, as captured by significant effects of each rate condition compared to habitual speech and increasingly larger estimates (F2: $\beta = -0.448$, $p < .001$; F3: $\beta = -0.83$, $p < .001$; F3: $\beta = -1.268$, $p < .001$).[6] In contrast, none of the slowest rate conditions were associated with significant changes in intelligibility when averaged over speaker groups.

Task. The monologue task was associated with significantly lower speech intelligibility compared to the sentences (task: $\beta = 0.262$, $p < .001$).

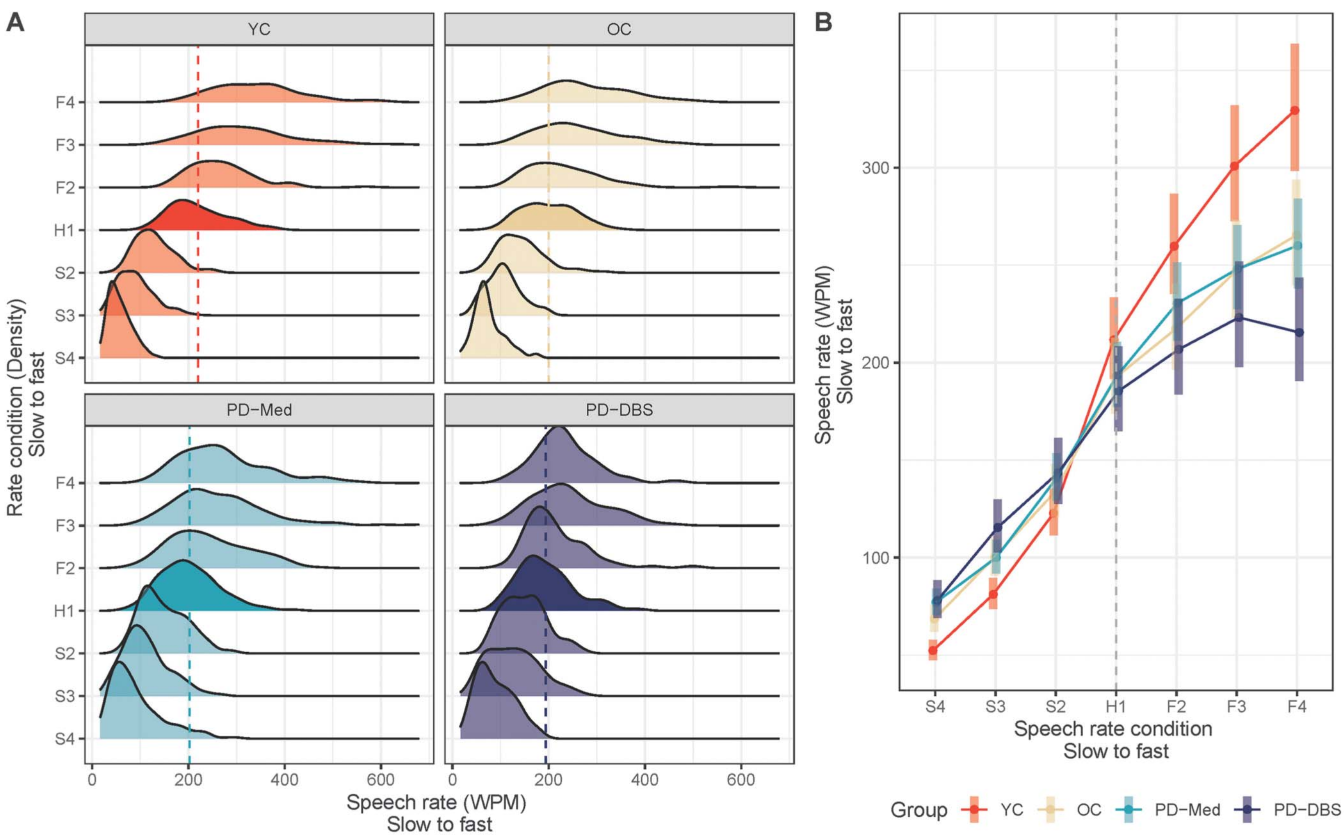
Group by Rate Interactions

Given the contrast coding, two-way interactions between speech rate condition and group reported in this section may be interpreted as follows. A significant interaction for a given rate condition (i.e., 2×/3×/4× slower or faster) and a given group contrast (i.e., YC vs. rest, OC vs. clinical, PD-Med vs. PD-DBS) indicates that, at that rate, the magnitude and/or direction of change in intelligibility compared to habitual speech differed for the groups at that contrast level. The model predictions in Figure 2A demonstrate the observed interaction patterns across both speech tasks. Empirical data are shown in Figure 2B.

Slow speech conditions. In this model, a significant positive estimate at a given rate level indicates that, compared to habitual, the intelligibility difference was "more positive" for the reference group in a given contrast, whereas a negative estimate indicates the difference was "smaller" or "more negative" for the reference group. As can be seen in Figure 2A, the YC, OC, and PD-Med groups do not

[6]Sentences from two participants (OC 08 and PD-DBS 12) were not included in the final playlist in error but were included in the monologue task.

Figure 1. Relationship between speech rate condition and actual speech rate in words per minute (WPM) for the sentence reading task. (A) Density plots of speech rate in words per minute for each group arranged by rate condition. Rate condition appears on the *y*-axis from slow to fast, bottom to top. Habitual rates are solid colored. Dashed lines represent average habitual speech rate for each group. (B) Predicted model responses and 95% confidence intervals for each rate condition. F4 = 4× faster; F3 = 3× faster; F2 = 2× faster; H1 = habitual rate; S2 = 2× slower; S3 = 3× slower; S4 = 4× slower; YC = younger healthy controls; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation.



demonstrate any changes in speech intelligibility in the slower rate conditions, whereas the PD-DBS group shows a sharp increase at the 2× slower rate condition before leveling off. In the model, this difference was reflected in the significant Group × Rate interaction for the PD-Med versus PD-DBS contrast in the 2× slower rate condition ($\beta = -0.44$, $p = .044$). There were no other significant interactions between group and rate for the 2× slower condition, indicating that intelligibility for all groups were rated similarly in this rate condition compared to their habitual speech ($p > .1$).

At the 3× slower rate condition, a significant negative interaction for the OC versus PD contrast suggested the OC groups showed less change (compared to habitual speech) than the PD groups combined (OC vs. PD, DBS: $\beta = -0.397$, $p = .044$). This finding was mainly driven by the finding that the PD-DBS group demonstrated steeper intelligibility gains in the 3× slower condition compared to

Table 5. Intrarater reliability for each listener: sentence rating task.

Listener	ICC	*F*	*p*	Lower bound	Upper bound
1	.831	5.929	< .001	.806	.854
2	.899	9.917	< .001	.884	.912
3	.933	14.955	< .001	.918	.945
4	.824	5.684	< .001	.785	.856
5	.884	8.652	< .001	.859	.905
6	.861	7.188	< .001	.830	.886

Note. ICC = intraclass correlation coefficient (ICC 3, *k*).

Table 6. Intrarater reliability for each listener: monologue rating task.

Listener	ICC	*F*	*p*	Lower bound	Upper bound
1	.983	57.921	< .001	.972	.989
2	.945	18.061	< .001	.910	.966
3	.895	9.546	< .001	.830	.935
4	.911	11.215	< .001	.855	.945
5	.894	9.410	< .001	.827	.935
6	.975	40.241	< .001	.960	.985

Note. ICC = intraclass correlation coefficient (ICC 3, *k*).

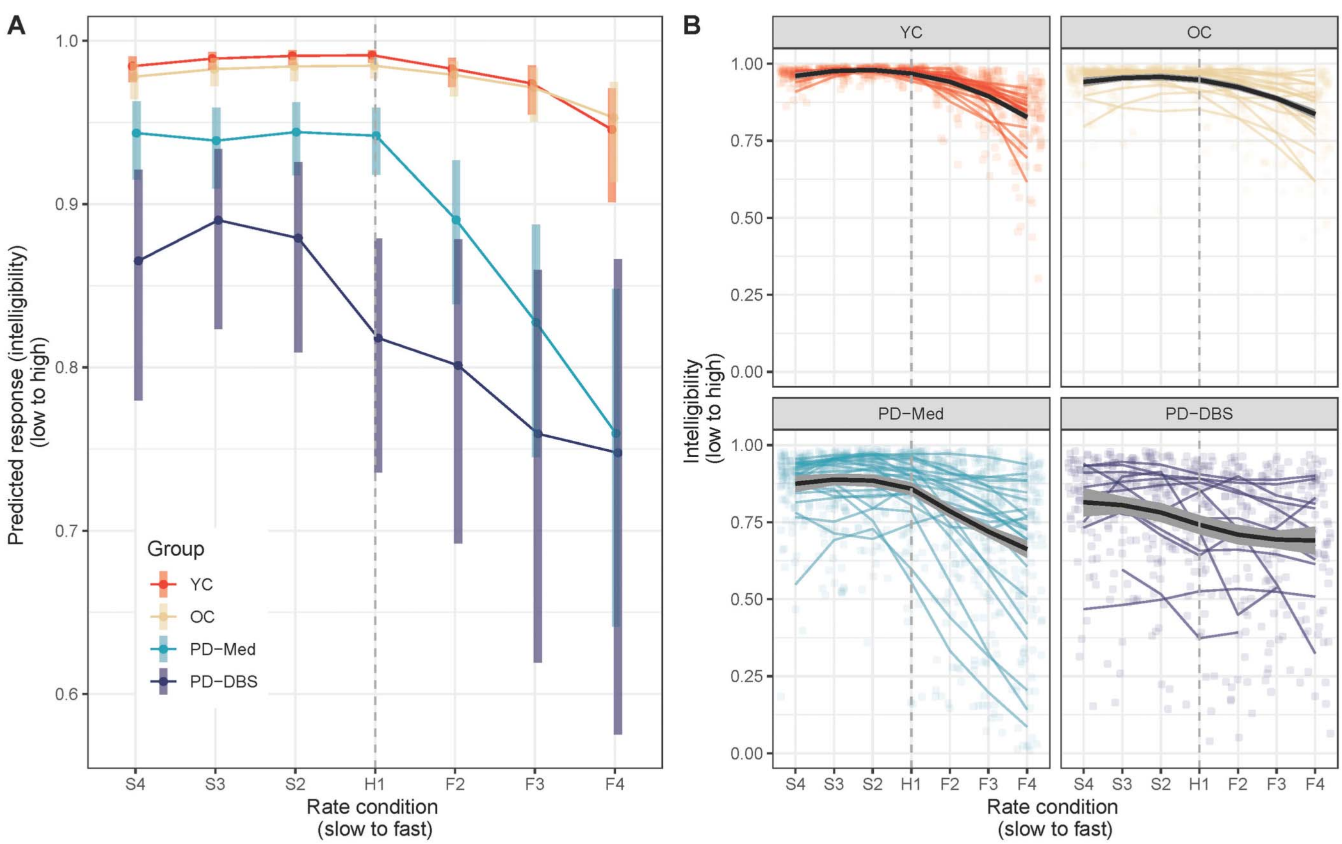


Figure 2. Intelligibility along the speech rate conditions for each group across both speech tasks. Plot A displays the predicted model responses and 95% confidence intervals for each rate condition. Plot B displays the empirical data averaged over listeners. Individual lines represent individual participants. Points represent individual utterances. Gray bands reflect 95% confidence interval around best-fit loess curves (black lines), averaged over participants. YC = younger healthy controls; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation; S4 = 4× slower; S3 = 3× slower; S2 = 2× slower; H1 = habitual rate; F2 = 2× faster; F3 = 3× faster; F4 = 4× faster.

habitual speech, as shown by the significant Group × Rate interaction for the PD-Med versus PD-DBS contrast (PD-Med vs. PD-DBS: $\beta = -0.643$, $p = .006$).

In the slowest rate condition (4× slower), interactions for the YC versus rest and OC versus clinical contrasts showed that the control groups showed relative decreases in intelligibility compared to baseline, while the PD groups combined showed relative increases (YC vs. rest: $\beta = -0.577$, $p = .005$; OC vs. PD, DBS: $\beta = -0.565$, $p = .011$). Once again, this was driven by the PD-DBS group. As can be seen in Figure 2A, in the 4× slower condition (S4), intelligibility for the PD-DBS group drops, bringing it closer to the lower intelligibility ratings observed in habitual speech. Meanwhile, intelligibility ratings for the PD-Med group remain essentially stable across all slow rates. It is this drop, then, for the PD-DBS group in the slowest rate condition that explains the lack of an interaction for the PD-Med versus PD-DBS groups for this comparison.

Fast speech conditions. As with slower speech, for the fast speech conditions, a negative estimate implies that the reference group (for that contrast) showed a "more negative" change in intelligibility compared to at habitual rates. Figure 2 shows that, in general, all groups showed relative declines in fast speech.

At all three faster rate conditions, significant negative 1interactions were found for the PD-Med versus PD-DBS contrast, indicating that the PD-Med group saw a greater decline in intelligibility at these rate conditions compared to the PD-DBS talkers (PD-Med vs. PD-DBS, 2× faster: $\beta = -0.582$, $p = .027$; 3× faster: $\beta = -0.862$, $p = .009$; $\beta = -1.218$, $p = .004$).

No significant interactions were found for the OC versus PD contrast at the faster speech rate conditions, indicating that the OC participants demonstrated an overall similar direction and magnitude of intelligibility declines in faster speech compared to the combined PD groups. A significant negative interaction for the YC versus rest comparison at the fastest rate (4× faster) suggests that the YC participants actually saw a greater *relative magnitude* of change in intelligibility at the fastest rate conditions compared to the OC group (YC vs. rest, 4× faster: $\beta = -0.792$, $p = .015$).

Interactions With Speech Task

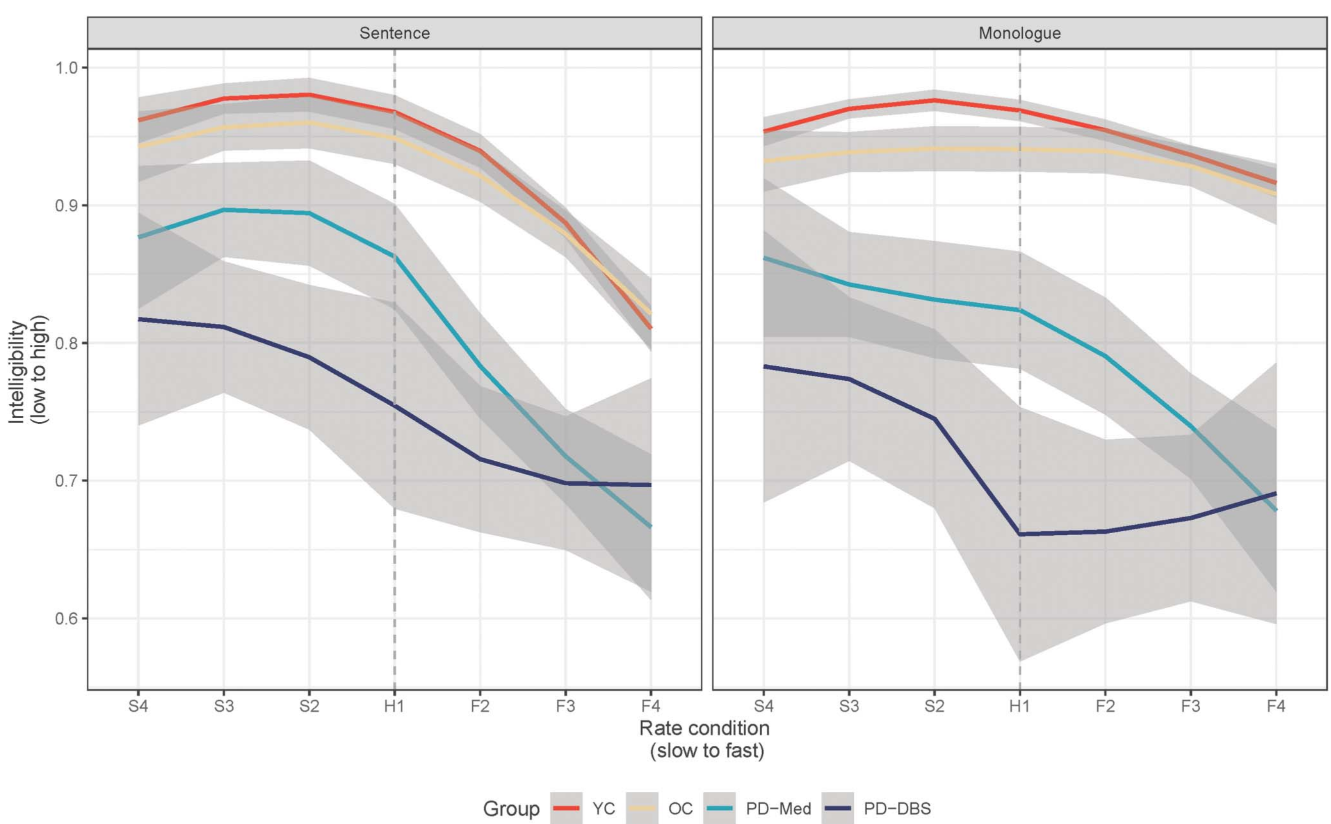
Group × Task interactions. Results are displayed in Figure 3. A significant interaction was found for the YC versus rest comparison, which indicated that, across all rates, task differences in intelligibility for the YC group were smaller than for the other three groups combined (YC vs. rest, task: $\beta = -0.243$, $p = .004$). Neither of the other group comparisons reached significance, though the PD-Med versus PD-DBS comparison demonstrated a nonsignificant trend, suggesting that while the PD-Med speakers were overall rated as more intelligible than the PD-DBS speakers, this difference widened in the monologue task ($\beta = -0.191$, $p = .068$).

Group × Rate Condition × Task interactions. For the most part, there were few significant three-way group, rate condition, and task interactions at both the slower and faster rates, suggesting that groups demonstrated similar patterns of intelligibility across the rate continuum in each of the tasks. At slower rate conditions, an exception to this was the three-way interaction for the PD-Med versus PD-DBS contrast at the 2× slower condition ($\beta = 0.487$, $p = .001$). This suggests that the PD-DBS group (compared to the PD-Med group) showed a larger intelligibility benefit at the 2× slower condition in the monologue task compared to the sentence reading task. This pattern is visible in the empirical plots displayed in Figure 3, in which the PD-DBS talkers show a steep spike in monologue speech intelligibility at S2 compared to H1 and compared to sentence intelligibility. The PD-Med talkers, on the other hand, show a much more modest increase in monologue speech intelligibility.

At faster rates, a nonsignificant negative interaction between the OC versus PD and DBS groups was observed for the 2× faster condition. This suggests that the difference in intelligibility between older healthy and disordered speaker groups widened in monologue speech, compared to sentence reading. Specifically, Figure 3 suggests a complex group pattern at this rate, whereby the OC group remained stable, the PD-Med group declined, and the PD-DBS group actually showed a modest increase in intelligibility.

The fastest rate condition (4× faster) was associated with a three-way interaction with group and task for both comparisons involving the control speakers ($\beta = -0.246$, $p = .04$; $\beta = -0.511$, $p < .001$). Similar to the pattern

Figure 3. Empirical data representing intelligibility ratings along the speech rate conditions for each group and task. Shaded band represents the 95% confidence interval around the best-fit loess curves for each group, averaged across participants. S4 = 4× slower; S3 = 3× slower; S2 = 2× slower; H1 = habitual rate; F2 = 2× faster; F3 = 3× faster; F4 = 4× faster; YC = younger healthy controls; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation.



observed in the two-way interaction, this suggests that the difference in intelligibility ratings between healthy and disordered speakers widened in monologue speech and, in this case, that the difference was observed to be even greater at the fastest self-selected speech rates. Figure 3 demonstrates that monologue speech intelligibility does not change for either control group to the extent that it did for the PD groups. There were no significant three-way interactions for the PD group comparison for any of the fast rate conditions.

Sequential Changes in Intelligibility Across Rate Conditions

A series of pairwise comparisons was run to test for differences within groups and tasks for each sequential rate condition (H1 vs. S2, S2 vs. S3, S4 vs. S4, etc.). These are reported in Appendixes B and C. Post hoc pairwise comparisons were computed using estimated marginal means (i.e., least-squares means) from the emmeans package, with *p* values adjusted using the Tukey method (Lenth, 2020). The estimates are equal to the estimated difference (on the response, not the logit scale) between pairs. Differences were computed as the contrast on the left minus the contrast on the right. In Appendixes B and C, the estimate reported for the contrast H1–S2 and then reflected the model's estimated intelligibility in the habitual condition minus intelligibility ratings in the 2× slower (S2) condition. A negative estimate, for example, between habitual speech and 2× slower (written as H1–S2), would indicate that the habitual rate (H1) had a lower intelligibility rating than the 2× slower rate (S2) for a given group. A positive difference, on the other hand, for example, between habitual speech and 4× faster (written as H1–F4), would indicate higher intelligibility for habitual speech compared to the 4× faster condition for a given group.

Only comparisons to habitual rate (e.g., S4 vs. H1) and sequential comparisons (e.g., S4 vs. S3, S3 vs. S2) are reported here. Comparisons spanning more than one rate adjustment were not of interest (e.g., S4 vs. S2 or S4 vs. F3). Comparisons were considered significant at $p < .05$.

Slower rate conditions, compared to habitual speech, did not yield any significant pairwise comparisons for any group in either task with two exceptions for the PD-DBS group. Compared to habitual speech, the S3 condition (3× slower) was associated with significantly higher sentence intelligibility (estimated difference = −0.061, $p = .016$), and the S2 condition (2× slower) demonstrated a nonsignificant trend toward higher monologue intelligibility (estimated difference = −0.11, $p = .054$).

Faster rate conditions, compared to habitual speech, were associated with significant declines in intelligibility for most comparisons in the sentence task. The 2× faster rate condition (F2) was associated with declines in sentence intelligibility for the PD-Med group (estimated difference = 0.067, $p = .001$). The faster rates, F3 and F4, were associated with declines in sentence intelligibility for both control groups and the PD-Med group (H1–F3: YC: estimated difference = 0.038, $p = .019$; OC: estimated difference = 0.037, $p = .039$; PD-Med: estimated difference = 0.158, $p < .001$; H1–F4: YC: estimated difference = 0.116, $p = .004$; OC: estimated difference = 0.086, $p = .018$; PD-Med: estimated difference = 0.216, $p < .001$).

These 3× and 4× faster conditions (but not the 2× faster condition) were also associated with declines in monologue speech intelligibility for the PD-Med group (H1–F3: estimated difference = $\beta = 0.109$, $p = .016$; H1–F4: estimated difference = $\beta = 0.182$, $p = .001$). Faster conditions were not associated with significant changes in monologue speech intelligibility for any of the other groups. Sequential differences across rate conditions (e.g., 2× vs. 3× and 3× vs. 4× slower or faster) were not associated with significant changes for any pairwise comparisons at $p < .05$.

Discussion

The current study aimed to quantify changes in speech intelligibility across a wide range of self-selected speech rates for individuals with and without PD. The three primary goals of this study included (a) characterizing intelligibility patterns at three slower and three faster rate conditions compared to habitual rates of speech, (b) quantifying differences between OC and YC participants as well as people with PD with and without STN-DBS, and (c) quantifying differences between sentence reading and monologues.

Group Differences Across Speech Rate Conditions

Changes in Acoustically Derived Speech Rates

Few studies have examined more than two rate manipulation conditions in dysarthria (Tjaden, 2000, 2003), and none of these multirate studies explored changes in intelligibility. Evidence from multirate studies in young, healthy talkers suggests that individuals do not modify their speaking rate in a linear fashion (Adams et al., 1993; Tsao & Weismer, 1997; Tsao et al., 2006). Rather, healthy speakers tend to make smaller adjustments on the faster end of the rate continuum and larger adjustments on the slower end, resulting in a quadratic or more complex nonlinear relationship between intended and actual speech rate (Adams et al., 1993). This pattern was supported by the finding of greater magnitudes of change (larger absolute estimated differences) in speech rate in slower conditions compared to the faster conditions, displayed in Appendix A. These patterns were most dramatic in the younger talkers but held in the older controls and the PD groups, as well. These findings open the question to explore differences in the mechanisms in psychophysical rate adjustments in healthy aging, as well.

Changes in Intelligibility

In general, for most talkers, slower speech conditions were not associated with gains in intelligibility. This was the case for both the YC and OC participants as well as the PD-Med group. The PD-DBS group, however, did see gains in the slow speech conditions, and these gains were magnified in the monologue compared to the sentence readings. Slow speech conditions did not, at any point along the continuum, demonstrate a clear intelligibility benefit for the PD-Med group, a finding that supports recent literature suggesting that slow speech is often associated with minimal or no gains in speech intelligibility for people with PD (Fletcher et al., 2017; Kuo et al., 2014; McAuliffe et al., 2017; Tjaden & Wilding, 2004; Van Nuffelen et al., 2010, 2009). To the authors' knowledge, talkers with DBS have not previously been included in studies of speech rate manipulation, likely because of the heterogeneity in speech symptoms and changes following STN-DBS surgeries (Aldridge et al., 2016) that pose a challenge when controlling for experimental variables. Findings in this study emphasize that their inclusion in future studies of behavioral modification is warranted and suggest they may stand to benefit from such strategies in ways that differ from talkers with PD undergoing standard pharmaceutical treatment.

A critical outstanding question from the current study is to determine how underlying speech adjustments were used by speakers to achieve the varied rates and how these adjustments impacted intelligibility. While the purpose of this study was to characterize changes in intelligibility across varied rates of speech, discussion of the variety of strategies speakers may have used is warranted. Individual talkers vary considerably in the ways in which they modify their vocal tracts in order to obtain different rates of speech. For example, faster rates of speech may be obtained by reducing pauses, increasing articulatory velocities, and modifying movement extents, while slow rates may be achieved by increasing pauses, increasing segment durations, or a combination of multiple adjustments (Adams et al., 1993; Dromey & Ramig 1998).

Rate changes likely induce changes in acoustic parameters of articulation, prosody, and voice characteristics that could have contributed to the listeners' ability to understand the speech. A clear example from the literature is vowel space, which has been shown (generally) to increase in slow speech and decrease in fast speech in both healthy talkers and those with dysarthria (D'Innocenzo et al., 2006; Tjaden et al., 2013; Tjaden & Wilding, 2004; Turner et al., 1995). Expanded vowel space, along with dynamic acoustic metrics of vowel production such as the slope of the second formant, has been shown to contribute to speech intelligibility (Feenaughty et al., 2014; Kim et al., 2011; Lansford & Liss, 2014). Further investigations of how acoustic speech properties vary along the rate adjustments in this study are underway.

Task-based differences in intelligibility were also found. Lower speech intelligibility was found for the monologue task compared to the sentence reading task, and group differences were greater in the monologue task. These findings are consistent with previous accounts of extemporaneous speech being rated as less intelligible than more structured speech tasks, such as reading for people with PD (Kempler & Van Lancker, 2002; Kent, 1996; Weismer, 1984; Yorkston & Beukelman, 1981), but differs from others that have found no differences in intelligibility ratings between monologue and paragraph reading (Bunton, 2008; Tjaden & Wilding, 2011). In this study, not only was intelligibility found to be overall lower for more extemporaneous speech (i.e., the monologue task), but the relationship between speech rate and intelligibility differed in its extremity across the two speech tasks. The most extreme differences occurred for the PD-DBS talkers, who saw substantially steeper gains in intelligibility during slower rates of speech in the monologue task. The PD-Med speakers saw a flatter but continuous rise in intelligibility during slow monologue speech, compared to a small rise that tapered off (and eventually declined) in the sentence reading task. At faster rates, the PD-DBS talkers saw a clearer trend toward "increased" intelligibility in the monologue task that was not apparent in the sentence reading, indicating that rate modulation in "both" directions led to improvements in speech for this group. The relationship between speech rate and intelligibility was relatively preserved across tasks for both healthy control groups, though steeper declines in intelligibility at faster rates were more evident in the sentences.

Spontaneous speech, which requires more cognitive–linguistic planning than read speech, has been shown to be characterized by reduced spectral space and the presence of filled pauses, hesitations, repetitions, and disfluencies (Nakamura et al., 2008; Shinozaki & Furui, 2002). It is possible that these differences were enhanced in this study given the added cognitive–linguistic demands of the rate manipulation task. Furthermore, this study compared objective rates in the sentence task, but not in the monologue task. Though the task was designed to be maximally supportive of maintaining each talker's target rate during the experiment (i.e., through the use of visual, audio prompts and the elicitation of the monologue task at the end of a rate condition), it is possible that actual rates differed to a wider degree during the monologue task. Further study of the differences in how modified rates were achieved acoustically across tasks (e.g., differences in acoustic–articulatory configurations and pause durations) would aid in understanding the underlying reasons for these differences.

The PD-DBS group also demonstrated lower overall intelligibility in general, especially at their habitual rates of speech. This difference was widened in the monologue task, which was associated with lower intelligibility for both PD groups. This pattern is visible in Figure 3. These findings again support previous accounts of higher intelligibility scores for structured speech tasks for talkers with PD (Bunton, 2008; Kempler & Van Lancker, 2002; Kent, 1996; Tjaden & Wilding, 2011; Weismer, 1984; Yorkston & Beukelman, 1981). Mounting evidence suggests that STN-DBS is associated with worsening of speech symptoms in PD (Aldridge et al., 2016; Iulianella et al., 2008; Krack et al., 2003; Skodda et al., 2012), a trend also supported by this study.

Previous research has suggested that gains in intelligibility that result from global behavioral strategies, including slow speech, can be predicted from baseline speech features (Fletcher et al., 2017). Specifically, talkers with PD with more severe speech impairment and greater temporal variation in their speech may show greater benefits in slow speech (Fletcher et al., 2017). The PD-DBS group in this study was not selected for their speech characteristics, but their lower baseline intelligibility is consistent with this as a possibility. More work is warranted to determine whether severity and other baseline speech characteristics are predictive of intelligibility gains in individual speakers.

Speech Rate Adjustments

Slow Speech Conditions

The primary aim of this study was to explore changes in intelligibility across a wide range of self-selected speech rates. As can be seen in the left panel of Figure 3, the PD-Med speakers showed a modest (nonsignificant) trend for increased intelligibility at the 2× slower rate condition, but slowing down further did not yield additional benefit. In fact, intelligibility began to decrease again in the 4× slower rate condition. This pattern also held for the control speakers, though, given that controls were rated as highly intelligible to begin with, this effect was very small. This pattern is consistent with what Yorkston et al. (1999) theorized when predicting the likely trade-off between speech intelligibility and naturalness. The PD-DBS talkers, however, saw a continued rise in intelligibility. Notably, for the PD-DBS talkers, improvements were most evident at the 3× slower condition (in sentence reading) and the 2× slower condition (in spontaneous speech). This is consistent with two previous studies that incorporated multiple slow rate targets, demonstrating that having speakers slow to 60% of their habitual rate of speech offered greater gains in sentence intelligibility compared to slowing to 80% (Hammen et al., 1994; Yorkston et al., 1990). This pattern was more prominent in the monologues compared to sentence reading, as exhibited in Figure 3. This difference was likely also driven by the PD-DBS group, who showed markedly lower habitual speech intelligibility in the monologue task compared to in sentence reading. This baseline difference between speech tasks is supported by previous literature that shows more structured speech tasks are often associated with higher intelligibility ratings for talkers with PD (Bunton, 2008; Kempler & Van Lancker, 2002; Kent, 1996; Tjaden & Wilding, 2011; Yorkston & Beukelman, 1981). This finding also highlights the importance of including spontaneous speech tasks when assessing changes in intelligibility resulting from behavioral speech modifications.

Fast Speech Conditions

In contrast to slower speech, faster speech conditions were generally associated with predictable decreases in intelligibility for all groups. This patterns with findings from one previous study that elicited faster rates of speech for talkers with PD (Kuo et al., 2014). The PD-Med group showed steeper declines compared to the PD-DBS group in both tasks. That is, there was an asymmetric effect of rate modification for the PD-Med group, whereby they saw little change in intelligibility at slower rate conditions and substantially worse intelligibility at faster rate conditions. The PD-DBS group, on the other hand, saw similar magnitudes of change for the sentence task (i.e., the effect of rate on intelligibility was more linear for the PD-DBS group) and actually saw nonsignificant "increases" in intelligibility at faster rate conditions in the monologue task. This pattern has been observed in talkers with PD once before. Kuo et al. (2014) showed that not "all" speakers demonstrated declines in speech intelligibility at faster rates. The trend for intelligibility to rise for the PD-DBS group lends more support to this observation (Kuo et al., 2014; McRae et al., 2002; Weismer et al., 2000). It is not yet clear why the PD-DBS talkers not only did not get more difficult to understand in the faster rate conditions but, at least in some cases, became more understandable. Anecdotally, some participants were observed to increase their effort and loudness during the fast speech tasks. Acoustic analyses related to the observations are ongoing and needed in order to draw conclusions surrounding the underlying bases of intelligibility changes across the speech rate range.

With regard to individual speakers, this study employed current diagnostic criteria (Postuma et al., 2015) by an expert clinician but allowed for a lenient inclusion criteria with regard to the age of PD onset (i.e., two participants had onset at < 40 years) in an attempt to gather a more representative sample of the Parkinson's population. As is often observed with talkers with PD, considerable individual variability existed in this sample. Individual intelligibility curves are displayed in Appendix D. Some specific cases are worth noting. As reported in Tables 1 and 2, three participants scored less than 21/30 on the Montréal Cognitive Assessment (PD-Med 02, PD-DBS 02, and PD-DBS 06), a suggested cutoff for screening for dementia in PD (Dalrymple-Alford et al., 2010). These participants were all capable of participating in the task (though PD-DBS 02 did not complete the final fast condition due to fatigue, as noted above), and inspection of their individual data did not illuminate any obvious patterns that deviated from the general group trends. Two participants (PD-Med 04 and PD-Med 09) were diagnosed prior to 40 years of age, indicating cases of young-onset PD (Quinn et al., 1987). These participants were noted to demonstrate lower intelligibility at baseline and sharper intelligibility declines in fast speech conditions but also did not stand out as clear outliers relative to other patterns in the group. While previous work has demonstrated the ability to predict intelligibility gains from loud and slow speech modifications in PD (Fletcher et al., 2017), it is not presently known how other contributors to individual variability factor in. Future work should investigate individual patterns of responses to rate interventions to determine whether there are predictive factors that may help better identify candidacy for these and other behavioral techniques.

In summary, these findings suggest that the relationship between (self-selected) speech rate, speech task, and intelligibility is complex and varied. Talkers with PD and STN-DBS were more likely to benefit from rate reduction compared to talkers with PD without STN-DBS and less likely to deteriorate when increasing their speech rate. A deeper exploration into the acoustic changes associated with speech rate modifications and their potential impact on intelligibility are necessary to understand the speech changes responsible for the perceptual differences.

Limitations and Future Directions

The findings of this study should be interpreted carefully and in the context of several limitations worth noting. These can be broadly classified into speaker limitations, listener limitations, and methodological decisions. While speakers were generally effective at modifying their actual rate of speech, rate modification as a form of clinical intervention would involve more extensive training in how to achieve a target rate. Therefore, these results capture a snapshot of the effects of intelligibility on a wide variety of speech rates but may not generalize to clinical practice with more supports in place to facilitate motor learning. With regard to individual speakers, this study employed lenient inclusion criteria in an attempt to gather a more representative sample of the Parkinson's population. Future work should attempt to delineate differences in speech rate modifications as they relate to additional factors, including disease considerations, cognitive decline, or specific clusters of speech symptoms.

Listeners were asked to rate intelligibility on a scale of "low" to "high" and were not provided with exemplar tokens. While previous research suggests that similar scalar metrics of intelligibility of dysarthric speech are highly correlated with more objective measures such as orthographic transcription (Abur et al., 2019; Stipancic et al., 2016), it is possible that other scalar anchors such as *cannot understand anything* to *can understand everything* (e.g., Tjaden et al., 2014) may have elicited different patterns. Listeners also heard all speech stimuli with minimal postprocessing. For example, utterances were scaled to 70 dB SPL but were not mixed with noise. The decision to present unadulterated speech samples rather than increase the difficulty of the listening task by mixing with noise was made in order to avoid a potential floor effect in the clinical talkers, given the extensive nature of the speech modifications across the rate continuum. Furthermore, previous research suggests that rating speech intelligibility in noise may reflect a different process than in quiet (Chiu et al., 2019, 2020). Future related work should seek to establish these differences in relation to speech rate adjustments, as well as explore other listener perceptions such as speech naturalness or listener effort.

Speech rate condition, rather than actual, acoustically derived speech rate in WPM, was entered as the independent variable in the primary models in this study. That is, "faster" and "slower" speech in this study corresponds to individuals' psychophysical self-scaling of speaking rate (elicited with supports in place to facilitate true adjustments to actual rates of speech). This was an intentional choice in order to preserve the relationship of modified rates to each individual's habitual rate; however, an examination of acoustically derived speech rate would have the potential to strengthen the findings by avoiding overlap across rate conditions and preserving nuance by treating rate as a continuous, rather than categorical variable. More importantly, however, the use of actual speech rate would allow researchers to identify specific rates (as well as, eventually, other acoustic parameters such as pause characteristics and spectral measures) at which intelligibility may be expected to increase or decrease in a clinically meaningful way (as has been done for amyotrophic lateral sclerosis; Rong et al., 2015). Further exploration of a more fine-grained measure of rate, such as articulatory rate of speech (in which pauses are accounted for) or syllables per minute (instead of words), would also shed more light on the articulatory–acoustic processes at play when a talker modifies their rate of speech to such degrees.

Conclusions

The findings of this study suggest a complex relationship between speech rate modifications, speech task, and speech in talkers with PD. The results support previous findings that slower-than-habitual speech is often not associated with increases in intelligibility for many talkers with PD; however, gains were more readily observed in talkers with PD and STN-DBS. Conversely, while faster self-selected speech rates were associated with general declines in intelligibility, there was a trend for increased intelligibility for some talkers. Findings also supported previous claims of task differences, notably reduced intelligibility in extemporaneous speech, but speech rate adjustments magnified this difference. Overall, this study points toward a need to include more ecologically valid speech tasks and more representative samples of talkers with PD in order to continue to improve our understanding of speech rate modification and the implications on speech treatment.

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Appendix A

Pairwise Comparisons of Speech Rates Across Successive Rate Conditions for Each Group

Contrast	Group	Estimate	*SE*	*df*	*t* ratio	*p*
S4–S3	YC	–28.854	2.814	139.286	–10.254	.000
S3–S2	YC	–41.661	4.263	139.286	–9.773	.000
S2–H1	YC	–87.786	7.395	140.219	–11.871	.000
H1–F2	YC	–49.741	9.267	141.172	–5.367	.000
F2–F3	YC	–40.851	10.884	141.172	–3.753	.005
F3–F4	YC	–29.003	12.183	141.172	–2.381	.215
S4–S3	OC	–31.693	3.596	140.267	–8.813	.000
S3–S2	OC	–33.015	4.853	140.267	–6.804	.000
S2–H1	OC	–59.239	6.959	141.281	–8.513	.000
H1–F2	OC	–24.994	8.152	141.281	–3.066	.041
F2–F3	OC	–30.188	9.260	141.281	–3.260	.023
F3–F4	OC	–17.999	10.204	141.281	–1.764	.574
S4–S3	PD-Med	–23.029	3.071	139.258	–7.500	.000
S3–S2	PD-Med	–40.626	4.323	139.258	–9.398	.000
S2–H1	PD-Med	–52.812	5.954	140.709	–8.870	.000
H1–F2	PD-Med	–37.023	7.283	140.709	–5.083	.000
F2–F3	PD-Med	–18.669	8.122	141.451	–2.299	.252
F3–F4	PD-Med	–11.660	8.807	141.451	–1.324	.840
S4–S3	PD-DBS	–37.203	5.005	141.827	–7.432	.000
S3–S2	PD-DBS	–28.071	6.092	141.827	–4.608	.000
S2–H1	PD-DBS	–41.901	7.787	140.393	–5.381	.000
H1–F2	PD-DBS	–20.101	9.075	140.393	–2.215	.294
F2–F3	PD-DBS	–16.853	10.348	146.180	–1.629	.664
F3–F4	PD-DBS	6.372	10.900	157.875	0.585	.997

Note. Estimates reflect estimated differences in words per minute. *SE* = standard error; *df* = degrees of freedom; S4 = 4× slower; S3 = 3× slower; YC = younger healthy controls; S2 = 2× slower; H1 = habitual rate; F2 = 2× faster; F3 = 3× faster; F4 = 4× faster; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation.

Appendix B

Pairwise Comparisons for Sequential Speech Rate Conditions Within Each Group for the Sentence Reading Task

Group	Contrast	Estimate	*SE*	*z* ratio	*p*
YC	H1–S4	1.0	0.4	2.478	.167
	H1–S3	0.2	0.2	1.003	.954
	H1–S2	−0.1	0.2	−0.440	.999
	H1–F2	1.4	0.5	2.776	*.081*
	H1–F3	3.8	1.2	3.265	**.019**
	H1–F4	11.6	3.1	3.691	**.004**
	S4–S3	−0.7	0.4	−1.757	.578
	S3–S2	−0.3	0.3	−1.133	.918
	F2–F3	2.5	1.1	2.209	.291
	F3–F4	7.8	3.0	2.609	.123
OC	H1–S4	1.0	0.5	2.139	.330
	H1–S3	0.6	0.4	1.542	.719
	H1–S2	0.1	0.3	0.384	1.000
	H1–F2	1.6	0.6	2.631	.117
	H1–F3	3.7	1.2	3.036	**.039**
	H1–F4	8.6	2.6	3.282	**.018**
	S4–S3	−0.5	0.5	−0.875	.976
	S3–S2	−0.4	0.4	−1.065	.938
	F2–F3	2.1	1.2	1.732	.594
	F3–F4	4.8	2.6	1.879	.494
PD-Med	H1–S4	−0.4	0.9	−0.407	1.000
	H1–S3	−0.3	0.8	−0.432	1.000
	H1–S2	−1.7	0.7	−2.464	.172
	H1–F2	6.7	1.7	3.967	**.001**
	H1–F3	15.8	3.0	5.218	**.000**
	H1–F4	21.6	4.2	5.164	**.000**
	S4–S3	0.0	1.1	0.012	1.000
	S3–S2	−1.3	0.9	−1.431	.785
	F2–F3	9.1	3.1	2.942	*.051*
	F3–F4	5.8	4.6	1.252	.873
PD-DBS	H1–S4	−1.7	2.4	−0.694	.993
	H1–S3	−6.1	1.8	−3.314	**.016**
	H1–S2	−2.9	1.8	−1.556	.711
	H1–F2	2.4	2.6	0.914	.970
	H1–F3	9.1	4.1	2.232	.278
	H1–F4	7.6	5.1	1.481	.757
	S4–S3	−4.4	2.7	−1.605	.679
	S3–S2	3.2	2.2	1.459	.769
	F2–F3	6.7	4.7	1.430	.786
	F3–F4	−1.5	6.4	−0.228	1.000

Note. Estimates and standard errors are reported on the response scale and converted to a percentage (0–100). Bolded values reflect $p < .05$. Italicized values reflect $p < .1$. *SE* = standard error; YC = younger healthy controls; H1 = habitual rate; S4 = 4× slower; S3 = 3× slower; S2 = 2× slower; F2 = 2 × faster; F3 = 3× faster; F4 = 4× faster; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation.

Appendix C

Pairwise Comparisons for Sequential Speech Rate Conditions Within Each Group for the Monologue Task

Group	Contrast	Estimate	*SE*	*z* ratio	*p*
YC	H1–S4	1.3	0.6	2.071	.370
	H1–S3	0.5	0.4	1.148	.913
	H1–S2	0.3	0.4	0.707	.992
	H1–F2	1.4	0.7	2.146	.326
	H1–F3	2.0	0.9	2.191	.300
	H1–F4	3.8	1.6	2.435	.184
	S4–S3	−0.8	0.7	−1.176	.903
	S3–S2	−0.2	0.5	−0.466	.999
	F2–F3	0.5	1.0	0.540	.998
	F3–F4	1.8	1.6	1.125	.921
OC	H1–S4	1.1	0.9	1.202	.894
	H1–S3	0.0	0.7	0.009	1.000
	H1–S2	0.0	0.7	−0.010	1.000
	H1–F2	0.0	0.8	0.023	1.000
	H1–F3	0.5	1.0	0.556	.998
	H1–F4	1.9	1.5	1.275	.863
	S4–S3	−1.1	1.0	−1.102	.928
	S3–S2	0.0	0.8	−0.017	1.000
	F2–F3	0.5	1.1	0.483	.999
	F3–F4	1.3	1.6	0.813	.984
PD-Med	H1–S4	0.0	1.8	−0.025	1.000
	H1–S3	1.5	1.9	0.807	.984
	H1–S2	2.0	1.9	1.044	.944
	H1–F2	6.4	2.5	2.558	.139
	H1—F3	10.9	3.3	3.314	**.016**
	H1–F4	18.2	4.5	4.040	**.001**
	S4–S3	1.6	2.2	0.721	.991
	S3–S2	0.4	2.2	0.196	1.000
	F2–F3	4.6	3.7	1.238	.880
	F3–F4	7.3	5.1	1.422	.790
PD-DBS	H1–S4	−9.0	4.4	−2.051	.382
	H1–S3	−9.7	3.9	−2.473	.169
	H1–S2	−11.0	3.8	−2.923	*.054*
	H1–F2	0.6	4.7	0.121	1.000
	H1–F3	1.2	5.5	0.229	1.000
	H1–F4	5.1	6.8	0.743	.990
	S4–S3	−0.7	4.5	−0.146	1.000
	S3–S2	−1.4	3.9	−0.349	1.000
	F2–F3	0.7	6.2	0.109	1.000
	F3–F4	3.8	7.9	0.482	.999
	F3–F4	−1.5	6.4	−0.228	1.000

Note. Estimates and standard errors are reported on the response scale and converted to a percentage (0–100). Bolded values reflect $p < .05$. Italicized values reflect $p < .1$. *SE* = standard error; YC = younger healthy controls; H1 = habitual rate; S4 = 4× slower; S3 = 3× slower; S2 = 2× slower; F2 = 2× faster; F3 = 3× faster; F4 = 4× faster; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation.

Appendix D

Empirical Data Representing Intelligibility Ratings Along the Speech Rate Conditions for Each Participant, Arranged by Group

Intelligibility ratings are averaged over both sentence reading and monologue tasks. YC = younger healthy controls; OC = older healthy controls; PD-Med = people with Parkinson's disease without deep brain stimulation; PD-DBS = people with Parkinson's disease with deep brain stimulation; S4 = 4× slower; S3 = 3× slower; S2 = 2× slower; H1 = habitual rate; F2 = 2× faster; F3 = 3× faster; F4 = 4× faster.