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Acoustic and perceptual correlates of faster-than-habitual speech produced by speakers with Parkinson's disease and Multiple Sclerosis

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Abstract

Acoustic-perceptual characteristics of a faster-than-habitual rate (Fast condition) were examined for speakers with Parkinson's disease (PD) and Multiple Sclerosis (MS). Judgments of intelligibility for sentences produced at a habitual rate (Habitual condition) and at a faster-than-habitual rate (Fast condition) by 46 speakers with PD or MS as well as a group of 32 healthy speakers revealed that the Fast condition was, on average, associated with decreased intelligibility. However, some speakers' intelligibility did not decline. To further understand the acoustic characteristics of varied intelligibility in the Fast condition for speakers with dysarthria, a subgroup of speakers with PD or MS whose intelligibility did not decline in the Fast condition (No Decline group, $n = 8$) and a subgroup of speakers with significantly declined intelligibility (Decline group, $n = 8$) were compared. Acoustic measures of global speech timing, suprasegmental characteristics, and utterance-level segmental characteristics for vocalics were examined for the two subgroups. Results suggest acoustic contributions to intelligibility under rate modulation are complex. Potential clinical relevance and implications for the acoustic bases of intelligibility are discussed.

Keywords

Dysarthria; intelligibility; rate; acoustics

1. Introduction

Rate change has been shown to affect the spectral characteristics of speech (see also review in Tsao, Weismer, & Iqbal, 2006). For healthy speakers, for example, a faster-than-habitual rate has been associated with a decrease in vowel acoustic contrast and vowel acoustic

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working space (e.g., Lindblom, 1963; Lindblom, 1990; Perkell et al., 2004; Tsao et al., 2006) although other studies have demonstrated a variable relationship between a faster-than-habitual rate and vowel spectral characteristics (e.g., Fourakis, 1991; Gay, 1978; Van Son & Pols, 1990). In comparison, a slower-than-habitual rate has been associated with enhanced vowel spectral characteristics (e.g., Ferguson & Kewley-Port, 2007; Tjaden & Wilding, 2004). For speakers with dysarthria, similarly, a faster-than-habitual rate has been associated with a decrease in vowel acoustic contrast and vowel space (e.g., Hustad & Lee, 2008; McRae, Tjaden, & Schoonings, 2002; Tjaden, Rivera, Wilding, & Turner, 2005; Turner, Tjaden, & Weismer, 1995; Weismer et al., 2000), and a slower-than-habitual rate has been associated with an increase in the size of the acoustic vowel space (e.g. McRae et al., 2002; Tjaden et al., 2005; Tjaden & Wilding, 2004; Weismer, Laures, Jeng, Kent, & Kent, 2000).

Evidence of enhanced segmental acoustic contrast for a slower-than-habitual rate would seem to support improved intelligibility for healthy speakers and speakers with dysarthria alike, but slower-than-habitual rate has been shown to variably impact intelligibility for speakers with dysarthria despite an increase in vowel space area (McRae et al., 2002; Turner et al., 1995; Weismer et al., 2000). Nonetheless, rate control, usually in the form of a slower-than-habitual rate, is commonly recommended as a therapeutic technique to improve intelligibility for speakers with dysarthria (Duffy, 2013; Yorkston, Hakel, Beukelman, & Fager, 2007).

On the other hand, evidence of degraded segmental articulation in the form of reduced acoustic contrast at a faster-than-habitual rate would seem to suggest that a faster-than-habitual rate would likely contribute to compromised speech intelligibility (e.g., Tsao et al., 2006). However, studies have shown that a faster-than-habitual rate is not always accompanied by a reduction in intelligibility despite a decrease in vowel acoustic working space (e.g., McRae et al., 2002; Weismer et al., 2000). In addition, Turner et al. (1995) reported variable effects of a faster-than-habitual rate on intelligibility and vowel space area for speakers with dysarthria secondary to Amyotrophic Lateral Sclerosis (ALS). Thus, the disparate findings to date suggest the relationship between segmental acoustic changes accompanying rate manipulation and intelligibility warrants further attention.

It is noteworthy that a faster-than-habitual rate has been shown to facilitate speech naturalness or speech acceptability at least for some speakers, with or without dysarthria (Dagenais, Brown, & Moore, 2006; Logan, Roberts, Pretto, & Morey, 2002), and these perceptual constructs are strongly associated with intelligibility (see also discussion in Sussman & Tjaden, 2012). The perceptual constructs of speech naturalness or acceptability are further thought to reflect global, suprasegmental aspects of speech (Sussman & Tjaden, 2012). Wingfield's (1975) study on time-compressed speech also demonstrated the importance of prosody to intelligibility. Much of what is known about the suprasegmental contributions to intelligibility comes from the normal speech literature (e.g., Bradlow, Toretta, & Pisoni, 1996; Bunton, Kent, Kent, & Duffy, 2001; Krause & Braid, 2004; Laures & Weismer, 1999; Miller, Schlauch & Watson, 2010; Spitzer, Liss & Mattys, 2007), and there is a scarcity of dysarthria studies investigating the contribution of suprasegmental variables to intelligibility (Weismer, 2008). Even more limited are studies of rate

manipulation reporting suprasegmental measures such as fundamental frequency (F0) or vocal intensity. One study by D'Innocenzo and colleagues (2006) reported measures of mean sound pressure level (SPL) for sentences produced at a faster-than-habitual rate by a speaker with dysarthria secondary to traumatic brain injury. Intelligibility for this speaker did not decline at a faster-than-habitual rate. D'Innocenzo and colleagues further reported that a faster-than-habitual rate was associated with an increase in vocal intensity. The finding of an increased SPL at a faster-than-habitual rate has also been reported for healthy speakers (Dromey & Ramig, 1998; Wohler & Hammen, 2000). Relatedly, an increase in mean SPL has been reported to be beneficial for intelligibility in studies investigating speaking strategies other than rate manipulation, such as studies investigating an increased vocal intensity as well as clear speech (Ferguson & Kewley-Port, 2007; Sapir, Spielman, Ramig, Story, & Fox, 2007; Smiljanić & Bradlow, 2009).

Rate manipulation also may impact utterance level F0 characteristics. One study has reported an increase in utterance-level F0 variability for a faster-than-habitual rate (Dromey & Ramig, 1998). Conversely, Tjaden and Wilding (2011) found that a slower-than-habitual rate for speakers with Multiple Sclerosis (MS) and PD was associated with reduced F0 modulation (e.g., F0 range and F0 rate of change). Similar associations between a slower-than-habitual rate and reduced F0 modulation have also been reported for neurologically normal speakers (Cooper & Sorensen, 1981; Ladd, Faulkner, Faulkner & Schepman, 1999). Given that a decrease in utterance-level F0 variability has been shown to be detrimental to intelligibility (e.g., Bunton et al., 2001; Laures & Weismer, 1999; Watson & Schlauch, 2008), one implication is that increased F0 modulation for a faster-than-habitual rate may have the potential to facilitate intelligibility.

In summary, the acoustic consequences of rate modulation for speakers with dysarthria and their relationship to intelligibility warrant further investigation, as this knowledge has potential clinical implications and theoretical importance (Kim, Kent, & Weismer, 2011; Smiljanić & Bradlow, 2009; Weismer, 2008; Weismer, et al., 2008). Dysarthria studies to date have largely focused on the contribution of segmental variables to intelligibility. How segmental and suprasegmental variables interact to impact intelligibility is only beginning to be understood (e.g., Bunton, 2006; Spitzer et al., 2007). Importantly, rate modulation affords the opportunity for an examination of segmental and suprasegmental characteristics associated with variations in intelligibility (e.g. Turner et al., 1995; Weismer et al. 2000; McRae et al. 2002; D'Innocenzo et al., 2006) and therefore can help to advance conceptual understanding of intelligibility.

1.2 Purpose and Design

The goal of the current study was to investigate acoustic variables associated with variations in intelligibility at a faster-than-habitual rate for speakers with mild dysarthria. The interest in a faster-than-habitual rate was motivated by two primary findings that emerged from the above review. First, a slower-than-habitual rate has yielded variable intelligibility outcomes despite its wide acceptance as a therapeutic technique, and there does not appear to be strong evidence that a faster-than-habitual rate is indeed detrimental to intelligibility. Second, a

faster-than-habitual rate has been associated with suprasegmental changes that are potentially beneficial for intelligibility.

For clarity, the study is organized and presented as two related experiments. Experiment I reports judgments of intelligibility for sentences produced by a larger group of 78 speakers at a habitual (Habitual condition) and faster-than-habitual rate (Fast Condition). Experiment II reports segmental and suprasegmental acoustic measures for 16 speakers operationally identified from Experiment I, including eight speakers for whom the Fast condition was not associated with a decline in intelligibility relative to the Habitual condition (i.e., No Decline group) and eight speakers who demonstrated declined intelligibility in the Fast condition (i.e. Decline group). Detailed group definitions are discussed in Experiment II. This approach of contrasting operationally-defined speaker groups with varied intelligibility outcomes is similar to Ferguson and Kewley-Port's (2007) study comparing the impact of clear speech on acoustic characteristics of vowels produced by a group of talkers who improved intelligibility when speaking clearly ('big benefit talkers') and a group of speakers who did not improve intelligibility when speaking clearly ('no benefit talkers') (see also Hazan & Markham, 2004).

Acoustic measures of interest in Experiment II included articulation rate, speech rate, mean F0, F0 standard deviation (SD), minimum and maximum F0, F0 range, SPL, SPL SD, and F2 interquartile range (IQR) of vocalic segments. Acoustic measures were selected to span a range of speech production characteristics including global timing, suprasegmental and segmental characteristics, all of which have been suggested in the literature to bear on intelligibility (e.g., Kent & Kim, 2003). Moreover, the global speech timing measures were essential to document that speakers were able to implement a faster-than-habitual rate for the examination of rate changes associated with a faster-than-habitual rate. The suprasegmental measures of F0 and SPL were selected to capture the overall characteristics (i.e., means) and to quantify suprasegmental modulations (i.e., SD, minimum, maximum, and range measures).

F2 IQR was identified as a desirable segmental measure because of its potential for conceptual and practical contributions to advancing our knowledge of intelligibility. F2 IQR is associated with well-documented acoustic measures of F2 transition characteristics, which have been shown to be sensitive to articulatory integrity, particularly tongue functions (Yunusova et al., 2012), and intelligibility (e.g., Kent et al., 1989; Kim, Weismer, Kent, & Duffy, 2009; Weismer, Jeng, Laures, Kent, & Kent, 2001) (see also Weismer, Yunusova, & Bunton, 2012). Readers are also referred to the study by Yunusova, Weismer, Kent, and Rusche (2005) which first reported the measure. Second, F2 IQR is measured at the utterance level or over an operationally-defined period of time (e.g., Yunusova, Weismer, Kent, & Rusche, 2005). As such, F2 IQR reflects utterance-level segmental changes, as compared to the more conventional slice-in-time types of segmental measures, such as midpoint formant frequencies (e.g., Stevens & House, 1961). In this manner, F2 IQR shares a comparable unit of measurement with the suprasegmental measures of interest.

The present study addressed two research questions to understand potential acoustic contributions to different intelligibility outcomes at a faster-than-habitual rate. First, what is

the nature of the acoustic change(s) in the Fast as compared to Habitual condition? Second, what are the acoustic correlates of intelligibility variation at a faster-than-habitual rate? Given research reporting that increases in suprasegmental measures are associated with better intelligibility (e.g., Bunton et al., 2001; Ferguson & Kewley-Port, 2007; Smiljanić & Bradlow, 2009; Watson & Schlauch, 2008), it was hypothesized that measures of F0 and SPL would increase for the No Decline group in the Fast relative to Habitual condition. On the other hand, it was hypothesized that the Decline group would demonstrate variable patterns of change in F0 and SPL for the Fast condition. Given research suggesting that enhanced segmental contrast is associated with better intelligibility (e.g. McRae et al., 2002; Tjaden et al., 2005; Tjaden & Wilding, 2004; Weismer, et al., 2000), it was hypothesized that F2 IQR would increase for the No Decline group in the Fast relative to Habitual condition. For the Decline group, it was hypothesized that the Fast condition would yield variable changes in F2 IQR.

2. Experiment I

Judgments of intelligibility were obtained for Harvard sentences (IEEE, 1969) produced by speakers with PD and speakers with MS at habitual and faster-than-habitual rates. In this manner, the first experiment was a mechanism for identifying No Decline and Decline speakers who were the subject of Experiment II. For comparison purposes, judgments of intelligibility also were obtained for a group of healthy control speakers. A detailed account of the perceptual methods also may be found in Tjaden, Sussman and Wilding (2014 b).

2.1 Methods

2.1.1 Speakers—Sixteen speakers with idiopathic PD, 30 speakers with MS and 32 healthy speakers who are part of a larger project participated (e.g., Sussman & Tjaden, 2012; Tjaden, Lam, & Wilding, 2013; Tjaden et al., 2014b). PD speakers included eight men (55-78 years, $m = 67$) and eight women (48-78 years, $m = 69$). MS speakers included 10 men (29-60 years, $m = 51$) and 20 women (27-66 years, $m = 50$). Healthy speakers included 10 men (25-70 years, $M = 56$) and 22 women (27-77 years, $M = 57$). All speakers were native speakers of standard American English, had at least a high school degree or equivalent, and had visual acuity or corrected acuity adequate for reading printed materials. Hearing aid use was an exclusion criterion. Speakers also underwent puretone audiometric testing at the UB Speech and Hearing clinic for the purpose of providing participants with documentation of their auditory status, but no speaker was excluded on the basis of puretone thresholds. 72 of the 78 speakers had puretone thresholds of 40 dB or better in at least one ear at 1, 2 and 4 kHz (Ventry & Weinstein, 1983). For the six remaining speakers, including two in each group the mean puretone threshold at 1, 2 and 4 kHz in the right ear was 37.06 dB ($SD = 27$ dB) and the mean puretone threshold at 1, 2 and 4 kHz in the left ear was 36.11 dB ($SD = 24$ dB). With the exception of one male with MS, all speakers scored at least 26/30 on the Standardized Mini-Mental State Exam (Molloy, 1999). All speakers were paid \$10 per hour.

Speakers with MS and PD were taking a variety of disease-related medications, but had not undergone neurosurgical treatment. Speakers with PD ranged from two to 32 years post diagnosis ($m = 9$ years; $SD = 7.8$ years). Four of the female participants with PD also had

completed LSVT®. Speakers with MS ranged from two to 47 years post diagnosis ($m = 14$ years; $SD = 11$ years). Five speakers with MS had a primary progressive disease course, 18 had a relapsing remitting disease course, and seven had a secondary progressive disease course. Six speakers with MS had a history of dysarthria treatment, but had not received LSVT®.

A clinical measure of sentence intelligibility as well as scaled Speech Severity, an operationally-defined perceptual construct that aims to tap into speech naturalness and prosody were obtained. These perceptual metrics were the subject of the Sussman and Tjaden (2012) study and are reported here for the purpose of describing speaker participants. Readers are referred to this previous study for a more detailed treatment of the methods for obtaining these measures. Briefly, sentence intelligibility was assessed using Yorkston and Beukelman's (1996) Sentence Intelligibility Test (SIT). SIT sentences were pooled across speakers prior to being orthographically transcribed by 42 inexperienced student listeners using a customized computer program. Each listener heard a given SIT sentence once via headphones and then typed their response onto a computer. Transcriptions were first scored using the computer program. If the transcription was identical to the target stimulus, then the total number of correctly transcribed words in the sentence was tallied. When exact matches did not occur, two research assistants manually counted the number of words correctly transcribed. Spelling errors and homonyms were disregarded when determining a word match. For each speaker, the total number of correctly transcribed words was tallied, divided by the total number of target words and multiplied by 100 to yield an overall percent correct score.

Ten inexperienced student listeners also judged Speech Severity for the Grandfather Passage, using a 15 cm continuous computerized visual analog scale. Using a computer mouse, listeners indicated their response on the vertically-oriented scale shown on a computer monitor. After completing the entire task, software converted the position to numerical values ranging from 0.0 (no impairment) to 1.0 (severely impaired). Listeners judged all stimuli without knowledge of speaker identity/neurological diagnosis. Listeners also heard stimuli at the same sound pressure level at which they were naturally produced and were paid \$10 per hour.

Mean intelligibility on the SIT was 85 % ($SD = 10$ %) for PD speakers, 93 % for MS speakers ($SD = 4.5$ %) and 94% ($SD=2.7\%$) for Healthy speakers. Mean Speech Severity was 0.46 ($SD = 0.18$) for PD speakers, 0.42 ($SD = 0.21$) for MS speakers and .18 ($SD=.08$) for healthy speakers. Together, SIT scores and judgments of Speech Severity for the Grandfather Passage suggest mild dysarthria for most speakers with PD or MS (Yorkston et al. 2010).

2.1.2 Experimental Speech Stimuli and Speech Tasks—Experimental stimuli consisted of 25 Harvard Psychoacoustic Sentences (IEEE, 1969). Stimuli were audio-recorded using an AKG C410 head mounted microphone positioned 10 cm and 45 to 50 degrees from the left oral angle. The signal was pre-amplified, low pass-filtered at 9.8 kHz and digitized to computer hard disk at 22 kHz using TF32 (Milenkovic, 2005). A calibration tone also was recorded for each speaker for use in measuring vocal intensity.

Speakers first read Harvard sentences at their habitual rate (i.e., typical speech style, hereafter Habitual condition) followed by a faster-than-habitual rate (i.e., hereafter Fast condition). Sentences also were produced in three additional conditions and these conditions have been reported in other studies (e.g., Tjaden et al., 2013; Tjaden et al., 2014 b). Magnitude production was used to elicit the Fast condition wherein speakers were instructed to use a rate twice as fast as their typical rate (see also Turner et al., 1995; McRae et al. 2002). For each speaker, a unique random selection of the same 10 Harvard sentences produced in both the Fast and Habitual conditions was of interest here as well as in Experiment II. Thus, all perceptual and acoustic measures reported in the remainder of the paper are based on each speaker's unique random subset of 10 Harvard sentences. Speakers with PD were recorded one hour prior to taking medications.

Measures of articulatory rate were obtained to document that the magnitude production paradigm elicited the expected rate adjustments. Using conventional acoustic criteria, Harvard sentences were segmented into runs, defined as a stretch of speech bounded by silent periods between words of at least 200 ms (Turner & Weismer, 1993). Syllable counts and run durations were summed across the 10 sentences for each speaker and condition. Overall articulatory rate in syllables per second was computed by dividing total syllable count by total run duration for use in the statistical analysis.

2.1.3 Listeners—Fifty listeners judged intelligibility of Harvard sentences. Listeners passed a hearing screening at 20 dB SPL HL for octave frequencies from 250 to 8000 Hertz (Hz), bilaterally (ANSI, 2004). Listeners ranged in age from 18 to 30 years, were native speakers of standard American English, had at least a high school diploma or the equivalent, reported no history of speech, language, or hearing problems, and were unfamiliar with speech disorders. Listeners were paid \$10 per hour.

2.1.4 Stimuli Preparation and Perceptual Task—The majority of speakers had mildly reduced intelligibility, as indexed by the SIT. Thus, to increase task difficulty and prevent ceiling effects, stimuli were mixed with multi-talker babble, as in studies from other labs investigating intelligibility of neurologically normal speech (see Uchanski, 2005; Smiljani & Bradlow, 2009) as well as dysarthria (Bunton, 2006; McAuliffe, Schaefer, O'Beirne, & LaPointe, 2009). Sentences first were equated for peak amplitude using Goldwave Version 5 (Goldwave Inc., 2010) and then were mixed with twenty-person babble (Frank & Craig, 1984; Nilsson, Soli, & Sullivan, 1994) at a signal to noise ratio (SNR) of -3 dB. Pilot testing indicated that this SNR minimized ceiling and floor effects. This SNR also has been used previously (Ferguson & Kewley-Port, 2002; Maniwa, Jongman, & Wade, 2008; McAuliffe et al., 2009). Stimuli were presented at 75 dB SPL via headphones (SONY, MDR V300) in a double-walled audiometric booth.

Sentences for all speakers and conditions from the larger project were pooled and divided into 10 sets. Each sentence set was comprised of one sentence produced by each speaker in each condition. Five listeners were then randomly assigned to judge each set. Listeners judged intelligibility without knowledge of a speaker's neurological diagnosis or identity using a 150 mm continuous, computerized Visual Analog Scale, with scale endpoints labeled 'Understand everything' and 'Cannot understand anything'. Following completion

of the experiment, software converted listener responses to numerical values ranging from 0 to 1.0, with larger values indicating poorer intelligibility. Intelligibility judgments were averaged across listeners and sentences to provide a single, composite measure of intelligibility for each speaker and condition for use in the statistical analysis.

A random selection of 10 % of sentences was presented twice to determine intrajudge reliability. Pearson product moment correlation coefficients for the first and second presentation of sentences ranged from 0.60 to 0.88 across listeners, with a mean of .71 ($SD = 0.07$). Interjudge reliability was assessed using the Intraclass correlation coefficient (ICC) to determine the consistency of ratings among listeners. Following Neel (2009), ICCs were calculated separately for each of the 10 sentence sets using a two-way mixed effects model. The single measure ICC, which reflects reliability among listeners at the level of the individual sentence ranged from 0.59 to 0.68 ($m = 0.54$; $SD = 0.04$). The average measure ICC, which reflects the average agreement among all listeners and stimuli, ranged from 0.85 to 0.91 ($m = 0.85$; $SD = 0.02$) across sentence sets. Thus, listeners demonstrated good agreement on a per item basis and excellent agreement on average (Fleiss, 1986; Cichetti, 1994). All ICC's also were statistically significant ($p < 0.001$). These listener reliability metrics are comparable to those reported in previous dysarthria studies using scaling tasks to quantify intelligibility as well as studies employing orthographic transcription (e.g. Bunton et al., 2001; Neel, 2009; Tjaden, Kain & Lam, 2014 a; Van Nuffelen, De Bodt, Wuyts, & Van de Heyning, 2009; Yunusova, et al., 2005).

2.2 Results

The upper panel of Figure 1 indicates that, on average, the PD group increased rate by 22 % ($SD = 11\%$), the MS group increased rate by 32 % ($SD = 16\%$) and the healthy control group increased rate by 37% ($SD = 11\%$). A two-way mixed design repeated measures ANOVA indicated a significant effect of Condition $F(1, 75) = 377.88, p < .01$ but not Group. The Group $\times$ Condition interaction also was significant $F(2, 75) = 5.62, p < .01$, owing to the greater proportionate rate increase for controls.

The lower panel of Figure 1 indicates that, on average, intelligibility for the PD group was reduced by 0.07 ($SD = 0.10$) in the Fast condition. Similarly, intelligibility was reduced by 0.10 ($SD = 0.10$) for the MS group and by .08 ($SD=.11$) for healthy controls. Thus, across groups intelligibility was reduced in the Fast condition by 7 % to 10 %. A two-way mixed design repeated measures ANOVA further indicated significant main effects of Condition $F(1, 75) = 44.51, p < .01$ and Group $F(2, 75) = 18.91, p < .01$. Post hoc pairwise comparison with Bonferroni adjustment indicated poorer intelligibility for the MS and PD groups as compared to controls, with mean differences of .10 and .28 respectively ($p < .01$). The PD group also had poorer intelligibility compared to the MS group, with a mean difference of .18 ($p < .01$).

Figure 2 reports distributions of intelligibility difference scores for the PD and MS groups as a way of capturing the difference in intelligibility for the Habitual and Fast conditions. Each symbol corresponds to an individual speaker. Symbols near 0 indicate similar intelligibility for both conditions while larger difference scores (i.e. positive sign) indicate poorer intelligibility for the Fast condition.

2.2.1 Summary—All groups increased overall articulation rate for the Fast condition and, on average, had poorer sentence intelligibility relative to Habitual. The impact of the faster-than-habitual rate on intelligibility varied substantially for individual speakers with PD or MS (Figure 2).

3. Experiment II

Acoustic measures suggested to bear on intelligibility were obtained for two subsets of speakers with MS or PD from Experiment I, including speakers with no intelligibility decline and speakers with declined intelligibility in the Fast condition relative to Habitual. Acoustic changes for each group associated with the different intelligibility outcomes in the Fast condition were of interest.

3.1 Methods

3.1.1 Experimental Speaker Groups—Eight speakers with no reduction in intelligibility in the Fast condition relative to Habitual comprised the operationally defined No Decline group, and eight speakers with poorer intelligibility in the Fast condition relative to Habitual comprised the Decline group. An “improvement” group was not available for study as Experiment I demonstrated that most speakers had reduced intelligibility in the Fast condition (see also Figures 1 and 2). As indicated in Table 1, both groups included three speakers with PD and five speakers with MS as well as five males and three females. Numerical values in Table 1 closer to 0 for mean Habitual and Fast intelligibility indicate better intelligibility. Difference scores approximating zero indicate minimal change in intelligibility for the Fast condition relative to Habitual, while positive difference scores indicate poorer intelligibility in the Fast versus Habitual conditions. The No Decline group was comprised of individuals for whom the Fast condition was not detrimental to intelligibility, as indicated by an intelligibility difference score of zero (i.e., no change) or slightly below (i.e., improved). Further, the No Decline group had intelligibility difference scores between zero and -0.1 (Table 1). On the other hand, the Decline group consisted of speakers with intelligibility difference scores that were well above 0.1 (Table 1), indicating at least a 10 % reduction in intelligibility for the Fast versus Habitual condition. These operationally defined criteria ensured sufficient differences in intelligibility between the two groups in the Fast condition.

A multivariate analysis of variance (MANOVA) was performed to test for group differences in intelligibility difference score, intelligibility in the Fast condition, intelligibility in the Habitual condition, and SIT scores. Results indicated that intelligibility difference scores in Table 1 were significantly different for the No Decline and Decline groups [$F(1, 14) = 68.05, p < 0.001$]. The MANOVA also indicated that intelligibility in the Fast condition for the Decline group was significantly poorer [$F(1, 14) = 7.22, p = 0.02$]. Finally, the MANOVA indicated no difference in scaled Habitual intelligibility as well as no difference in SIT scores for No Decline and Decline groups, thus confirming that habitual intelligibility was not driving the direction and/or magnitude of change in intelligibility for the Fast condition. In sum, although habitual intelligibility was comparable, as indexed by the SIT as well as scaled intelligibility for the Habitual condition, the No Decline group was associated

with relatively unchanged intelligibility and the Decline group poorer intelligibility in the Fast condition.

3.1.2 Acoustic Analysis and Dependent Variables—Acoustic measures of global speech timing, suprasegmental characteristics, and a measure of segmental articulatory integrity for vocalics were obtained. The focus on vocalic segmental characteristics follows from previous research, but was also driven by the interest in suprasegmental characteristics. That is, a variety of studies have suggested a relationship between suprasegmental characteristics and perceptual impressions of vowels (e.g. Cheveigné, Kawahara, Tsuzaki, & Aikawa, 1997; Laures & Weismer, 1999; Barreda & Nearey, 2012). Moreover, vowels are thought to be particularly important for sentence-level intelligibility (e.g. Kent, Weismer, Kent, & Rosenbek, 1989; Fogerty, Kewley-Port, & Humes, 2012).

Global speech timing measures included articulation rate and speech rate. Procedures for measuring articulation rate were described in Experiment I. Speech rate, in syllables per second, was determined by counting the number of syllables produced in each sentence and dividing by sentence duration. Mean speech rate was obtained for each speaker and condition by averaging speech rates for individual sentences. These averages were used in the statistical analysis.

F0 traces were generated in TF32 and were visually inspected and corrected by trained research assistants. Computer-generated F0 tracking errors were manually corrected on a pitch period by pitch period basis. Summary statistics obtained for each speech run included F0 mean, F0 standard deviation (SD), F0 minimum (indexed by 10th percentile), F0 maximum (indexed by 90th percentile), and F0 range (frequency range spanning 10th to 90th percentile). The use of 10th and 90th percentiles as indices of F0 minima and maxima was a conservative approach that allowed for the exclusion of potential outliers. For each speaker and condition, F0 measures were averaged across runs for use in the statistical analyses. Mean sound pressure level (SPL) of each speech run was obtained from the Root-Mean-Squared (RMS) intensity trace in TF32. RMS voltages were converted to dB SPL in Excel with reference to each speaker's calibration tone. SPL values were averaged across runs to obtain a mean SPL for each speaker and condition. SPL SD was obtained directly from the RMS trace of TF32.

Second formant interquartile range (F2 IQR) was used to index utterance-level segmental characteristics for vocalics following Yunusova et al. (2005). F2 trajectories for vocalic segments comprised of vowels, liquids and glides were generated from pitch-synchronous Linear Predictive Coding (LPC)-based formant tracks in TF32 that were manually-corrected for tracking errors. Conventional acoustic criteria were used to identify vocalic segment onsets and offsets from the combined waveform and wideband (300-400 Hz) spectrographic displays. Although F2 was tracked for nasalized vowels, nasal consonants with sufficiently defined segment boundary cues were excluded. For each speaker and condition, F2 IQR values were averaged across the 10 sentences to yield a mean F2 IQR value for statistical analysis.

3.1.3 Acoustic Measurement Reliability—For each speaker and condition, three sentences were randomly selected for remeasurement of articulation rate, SPL and F0. Reliability was assessed using Pearson product moment correlations and mean absolute difference scores. For intrajudge reliability, the mean absolute difference scores for articulation rate was 0.06 syllables/second (Pearson $r = 0.98$) and for speech rate was 0.04 syllables/second ($r = 0.99$). The average difference score for mean SPL was 0.11 dB ($r = 0.99$). The difference score for mean F0 was 2.52 Hz ($r = 0.98$) and for F0 SD was 1.75 Hz ($r = 0.97$). The mean absolute difference score for F0 minimum was 5.15 Hz ($r = 0.95$) and for F0 maximum was 5.52 Hz ($r = 0.97$).

For interjudge reliability, the mean absolute difference scores for articulation rate was 0.08 syllables/second ($r = 0.96$) and for speech rate was 0.09 syllables/second ($r = 0.97$). The average difference score for mean SPL was 0.15 dB ($r = 0.99$). The mean absolute difference score for mean F0 was 2.77 Hz (Pearson $r = 0.98$) and for F0 SD was 1.78 Hz ($r = 0.96$). The mean absolute difference score for F0 minimum was 7.12 Hz ($r = 0.92$) and for F0 maximum was 7.95 Hz ($r = 0.95$).

Inter-judge and intra-judge reliability for F2 IQR was assessed by repeating the entire F2 IQR measure for 10 % (i.e. 32/320) of sentences. The mean signed difference in F2 IQR values between the original and replicate measures was -7.85 Hz, and the mean absolute difference was 30.01 Hz. Expressed as Pearson product moment correlation coefficients, intrajudge reliability for the original and replicate F2 IQR values was 0.98, and interjudge reliability for two experimenters was 0.98. The mean signed interjudge difference was 12.42 Hz, and the mean absolute interjudge difference was 37.02 Hz.

3.1.4 Data Analysis—Planned comparisons, in the form of paired, two-sample t-tests, were used to evaluate acoustic changes at a faster-than-habitual rate relative to habitual within each experimental speaker group. Each speaker group was assigned a significance level of $p = .05$ (Rothman, 1990; Keppel & Wickens, 2004; Streiner & Norman, 2011). Each of the four broad categories of acoustic variables including global speech timing, F0, SPL, and F2 IQR was treated as a family for analysis, and all tests within each family were evaluated at $p = .0125$ ($.05/4 = .0125$). Finally, to quantify the strength of association between acoustic changes in the Fast condition (i.e., differences in acoustic measures in the Fast versus Habitual condition) and changes in intelligibility, data were pooled for the No Decline and Decline groups and Pearson product-moment correlation coefficients were obtained.

3.2 Results

Descriptive statistics for acoustic measures are reported in Table 2. Statistically significant comparisons are denoted with asterisks.

3.2.1 Acoustic Changes at a Faster-than-Habitual Rate

3.2.1.1 Global speech timing: Table 2 suggests that the Fast condition was accompanied by adjustments in global speech timing for both No Decline and Decline groups. For the No Decline group, there was a statistically significant increase in articulation rate [$t(7) = -4.44$,

$p = 0.003$] as well as speech rate [$t(7) = -4.67$, $p = 0.002$] for the Fast condition relative to Habitual. These rate increases were present for each of the eight speakers in the No Decline group. For the Decline group, significant increases in articulation rate [$t(7) = -7.18$, $p < 0.001$] and speech rate [$t(7) = -7.75$, $p < 0.001$] for the Fast condition relative to Habitual were present. This pattern of rate increase held for all eight speakers in the Decline group.

3.2.1.2 Suprasegmental characteristics: As indicated in Table 2, the Fast condition was accompanied by statistically significant changes in mean F0 and mean SPL for the No Decline group, but only significant change in mean SPL for the Decline group. The analyses indicated significant increases in the Fast condition for the No Decline group for mean F0 [$t(7) = -4.20$, $p = 0.004$] and mean SPL [$t(7) = -5.71$, $p = 0.001$]. All speakers in the No Decline group followed these patterns of change. Measures of F0 SD, F0 minimum, F0 maximum, F0 range, and SPL SD did not yield statistically significant differences across rate conditions for the No Decline group. In comparison, for the Decline group, there was a statistically significant increase in mean SPL [$t(7) = -5.64$, $p = 0.001$]. All of the speakers in the Decline group followed this trend. Measures of mean F0, F0 SD, F0 minimum, F0 maximum, F0 range, and SPL SD did not yield statistically significant differences across rate conditions for the Decline group.

3.2.1.3 Segmental characteristics: For both groups, mean F2 IQR was not significantly different for the Fast condition relative to Habitual. Descriptive statistics in Table 2 illustrate the minimal differences between rate conditions for both groups.

3.2.2 Associations between Intelligibility and Acoustic Changes—Pearson product-moment correlation coefficients were obtained for acoustic changes and intelligibility difference scores (see also Table 1) pooled across the two experimental speaker groups. The acoustic changes are indexed by difference scores obtained in a similar fashion as the intelligibility difference scores. Hence, the acoustic changes are computed as the difference in a given acoustic measure for the Fast versus Habitual condition. The correlations are summarized in Table 3, which indicates moderate to strong correlations between variations in intelligibility and changes in global speech timing and suprasegmentals (Cohen, 1988). The direction of the association was such that greater increases in articulation rate tended to be associated with greater reduction in intelligibility. Greater increases in suprasegmental modulation also were associated with better intelligibility. Lastly, there appears to be a moderate correlation between F2 IQR change and intelligibility difference for the Fast versus Habitual condition (Cohen, 1988). The direction of the relationship was such that increases in F2 IQR were beneficial for intelligibility.

3.2.3 Summary—The Fast condition was associated with significantly increased articulation and speech rates as well as increased SPL for both No Decline and Decline groups. The No Decline group, however, modulated F0 to a greater extent than the Decline group. The correlation analysis further indicated the importance of suprasegmental modulations to intelligibility.

4. Discussion

The primary goal of this study was to advance understanding of the acoustic basis of intelligibility by employing rate modulation as a mechanism for doing so. Results also speak to the longstanding assumption that a faster-than-normal rate is detrimental to intelligibility for speakers with neurological diagnoses or dysarthria. Measures of global speech timing changed in the expected direction for the Fast condition for the larger group of 46 speakers with MS or PD as well as a group of 32 healthy speakers. On average, the Fast condition also was associated with poorer sentence intelligibility (Figure 1). The magnitude of intelligibility reduction of approximately 7 to 10% reported in Experiment I has been interpreted in other studies to be meaningful, and while modest, may be especially relevant in an adverse perceptual environment such as the multi-talker babble used in the present study (Van Nuffelen, de Bodt, Vanderwegen, van de Heyning, & Wuyts, 2010). However, in agreement with other studies investigating a Fast condition in dysarthria (e.g. McRae et al. 2002; Weismer et al., 2000), intelligibility outcomes varied, with a subset of speakers with MS or PD exhibiting minimal decline or in some cases even slightly improved intelligibility when instructed to use a faster-than-habitual rate (Table 1 and Figure 2). One implication is that there may be value in supplementing group results with a description of individual speaker trends in studies investigating the impact of rate modulation on intelligibility (see also Van Nuffelen et al., 2010).

As an example, Figure 3 illustrates individual speaker trends for measures of acoustic modulation that have been demonstrated in other studies to be important for intelligibility (e.g., Bunton et al., 2001; Dromey & Ramig, 1998; Kent & Kim, 2003). Two speakers from the No Decline group and two speakers from the Decline group who showed the most extreme intelligibility changes within the respective experimental speaker group are included (greatest intelligibility differences for Decline group and smallest intelligibility differences for No Decline group; see also Table 1). Figure 3 shows the overall patterns of relative acoustic changes for the Fast condition. The differences on the y axis should not be directly compared across acoustic measures owing to different units of measure. The figure demonstrates some variations in acoustic changes of interest for Decline speakers as compared to No Decline speakers that did not emerge from the group data analyses. There are differences in the magnitude of acoustic changes within experimental speaker groups (e.g., F2 IQR change between speakers) and across experimental groups (i.e., articulation rate). Moreover, these speaker “profiles” appear to suggest potential interplay among acoustic changes and intelligibility. For example, both No Decline and Decline groups increased rate significantly in the Fast condition, but the most extreme speakers in the two groups as illustrated in Figure 3 suggest that the magnitude of rate increase may bear on intelligibility. In regard to suprasegmental characteristics, the only statistically significant result that differentiated the No Decline versus Decline groups was an increase in mean F0 in the Fast condition for the No Decline group. Figure 3, however, suggests that the contribution of other suprasegmental characteristics to intelligibility may entail additional speaker-related factors that warrant further investigation. Finally, F2 IQR was not significantly different for the Fast versus Habitual condition for either group, but Figure 3 suggests that the interplay between segmental and suprasegmental contributions to

intelligibility variation remains unresolved. That is, the magnitude of change alone may be just one of many facets of the acoustic contributions to intelligibility. The following paragraphs offer further discussions on the current dataset as it relates to these issues.

Is it possible that relatively greater, voluntary increases in rate for speakers with mild dysarthria are more likely to be detrimental to intelligibility? For the No Decline group, the Fast condition was characterized by a significant increase in speech and articulation rates, with the magnitude of the increase, on average, being approximately 20 %. Similarly, the Decline group significantly increased speech and articulation rates in the Fast condition but with an average of 30% increase despite the comparable habitual global speech timing as well as intelligibility characteristics for the two groups. The notion that greater rate increase may be associated with intelligibility decline is further supported by the correlation analysis (Table 3). This is also consistent with previous work that has reported an effect of increased rate on speech perception, such as the “cutoff speaking rate” for the clear speech intelligibility benefit discussed by Krause and Braida (2002) (p.2172). Moreover, speech in a Fast condition, whether naturally (i.e., voluntary human production) or artificially (e.g., digitally processed) produced, is susceptible to compromised information processing time and load (e.g., Hustad & Sassano, 2002; Janse, 2004; Orr, 1968; Wingfield, 1975). Together, clinically, these results may suggest that at least for some speakers with mild dysarthria, monitoring global speech timing would facilitate maintaining their overall intelligibility.

There is much need for studies investigating the contribution of suprasegmental variables to intelligibility in dysarthria (Weismer, 2008; Weismer et al., 2008), and results from the present study suggest that appropriate adjustments to overall utterance-level suprasegmentals may be important for maintaining intelligibility under rate variation. Mean SPL for both groups significantly increased at a faster-than-habitual rate. Even with almost identical mean habitual SPLs (see Table 2), however, the magnitude of the increase was much greater for the No Decline (i.e. mean increase of 7dB) as compared to the Decline group (i.e. mean increase of 2 dB). A similar trend was noted for mean F0, although the increase was statistically significant only for the No Decline group (an increase of 25 Hz versus only 5 Hz for the Decline speakers). The types and extents of suprasegmental modulations that support improved intelligibility require additional research. In addition, relatively greater increases in rate were accompanied by relatively smaller increases in suprasegmental modulation for the Decline relative to No Decline group in the present study. This finding cautions that potential benefits for intelligibility from an increase in mean SPL and mean F0 (e.g., clear speech or increased vocal intensity), may interact with adjustments in global speech timing that can accompany these speech styles (see also Krause & Braida, 2002).

Neither experimental speaker group significantly adjusted utterance-level segmental modulation (Table 2) at a faster-than-habitual rate. Notably, descriptive statistics indicated that the majority of the Decline group decreased F2 IQR in the Fast condition. Half of the speakers in the No Decline group also reduced F2 IQR, but the decreased segmental modulation in the presence of smaller suprasegmental changes and greater increase in speech rate may have further affected intelligibility at least for some speakers (see also Figure 3). Research has suggested that segmental information plays a primary role in

intelligibility, but suprasegmental variables are thought to become increasingly important as segmental information becomes less reliable (Spitzer, et al., 2007; Weismer, 2008). The relative contributions of segmental and suprasegmental characteristics to intelligibility warrant further study (e.g., De Bodt, Huici, Van De Heyning, 2002; Tjaden et al., 2014a).

4.1 Limitations and Future Directions

Several factors should be considered when interpreting the current results. First, due to stringent inclusionary criteria related to intelligibility characteristics for both habitual and faster-than-habitual rates, the No Decline and Decline groups contained a limited number of speakers. Although similar speaker numbers have been used in other studies investigating the acoustic basis of intelligibility (e.g., Dromey, 2003; Neel, 2009), a bigger sample size is recommended in future research to strengthen generalization of results. Another consideration is the degree of speech impairment or dysarthria severity. Speakers had only mildly reduced sentence intelligibility as measured by the SIT, but were perceived to have reduced speech naturalness and prosodic adequacy for a longer, connected speech task (Table 1) compared to a group of healthy controls. Findings therefore should not be generalized to speakers with more severe dysarthria. The inclusion of speakers with more severe speech impairment would be important for future investigations, and these studies are likely to reveal a different relationship between acoustic measures and intelligibility, perhaps especially for segmental articulation (e.g., F2 measures) and intelligibility. Relatedly, the inclusion of speaker groups exhibiting greater differences in intelligibility with rate variation may be of interest. In particular, it would be of value to study speakers who demonstrate improved intelligibility as compared to declined intelligibility.

An important future research question pertains to characteristics or predictors of speakers who maintain intelligibility at a faster-than-habitual rate. No Decline and Decline groups in this study had comparable habitual speech characteristics (Table 1). Whether there is a subset of speakers with mild dysarthria for whom a faster-than-habitual rate might be used clinically to enhance suprasegmental modulation and possibly intelligibility remains to be determined.

Use of a transcription task to quantify intelligibility and an associated analysis of listener errors also may help to pinpoint acoustic measures that are most sensitive to production differences underlying intelligibility variation. Furthermore, intelligibility judgments were obtained for sentences mixed with multi-talker babble. This is arguably an ecologically valid perceptual environment not unlike a restaurant or family gathering. The importance of investigating intelligibility in dysarthria in adverse listening conditions further was noted by Yorkston et al. (2007). Although the topic has long been the focus of studies of neurologically normal speech (e.g., Binns & Culling, 2007; Festen & Plomp, 1990), intelligibility in background noise is only beginning to be reported in published dysarthria studies (Bunton, 2006; Cannito et al., 2012; Tjaden et al., 2014 b). Unpublished data further suggest that background noise may impact intelligibility in dysarthria in a slightly different way than for neurologically normal talkers and may differ depending upon the perceptual characteristics of the dysarthria (McAuliffe, Good, Beirne, & LaPointe, 2008; McAuliffe et

al., 2009). Thus, comparisons to other populations or perceptual environments should be made with the appropriate degree of caution.

Finally, only a single variant of faster-than-habitual rate, elicited using magnitude production was studied. The inclusion of a range or a continuum, of rate increases (e.g. twice as fast, three times as fast, fastest) may help to further advance understanding of the acoustic consequences of rate variation and the relationship to intelligibility.

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References

- American National Standards Institute. Specifications for audiometers (ANSI S3.6-2004). New York, NY: Author; 2004.
- Barreda S, Nearey TM. The direct and indirect roles of fundamental frequency in vowel perception. *Journal of the Acoustical Society of America*. 2012; 131:466–477. [PubMed: 22280608]
- Binns C, Culling JF. The role of fundamental frequency contours in the perception of speech against interfering speech. *Journal of the Acoustical Society of America*. 2007;1765–1776. [PubMed: 17927436]
- Bradlow AR, Torretta GM, Pisoni DB. Intelligibility of normal speech I: Global and fine-grained acoustic-phonetic talker characteristics. *Speech communication*. 1996; 20(3):255–272. [PubMed: 21461127]
- Bunton K. Fundamental frequency as a perceptual cue for vowel identification in speakers with Parkinson's disease. *Folia Phoniatrica et Logopaedica*. 2006; 58(5):323–339. [PubMed: 16966834]
- Bunton K, Kent RD, Kent JF, Duffy JR. The effects of flattening fundamental frequency contours on sentence intelligibility in speakers with dysarthria. *Clinical Linguistics & Phonetics*. 2001; 15:181–193.
- Cannito MP, Suiter DM, Beverly D, Chorna L, Wolf T, Pfeiffer RM. Sentence intelligibility before and after voice treatment in speakers with idiopathic Parkinson's Disease. *Journal of Voice*. 2012; 26(2):214–219. [PubMed: 22209057]
- Cicchetti DV. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychological Assessment*. 1994; 6:284–290.
- Cohen, J. Statistical power analysis for the behavioral sciences. 2nd. New Jersey: Lawrence Erlbaum; 1988.
- Cooper, WE.; Sorensen, JM. Fundamental frequency in sentence production. New York: Springer-Verlag; 1981.
- Dagenais PA, Brown GR, Moore RE. Speech rate effects upon intelligibility and acceptability of dysarthric speech. *Clinical Linguistics & Phonetics*. 2006; 20(2/3):141–148. [PubMed: 16428230]
- De Bodt MS, Hernández-Díaz Huici ME, Van De Heyning PH. Intelligibility as a linear combination of dimensions in dysarthric speech. *Journal of Communication Disorders*. 2002; 35(3):283–292. [PubMed: 12064788]
- De Cheveigné A, Kawahara H, Tsuzaki M, Aikawa K. Concurrent vowel identification. I. Effects of relative amplitude and F_0 difference. *Journal of the Acoustical Society of America*. 1997; 101(5): 2839–2847.
- D'Innocenzo J, Tjaden K, Greenman G. Intelligibility in dysarthria: Effects of listener familiarity and speaking condition. *Clinical Linguistics & Phonetics*. 2006; 20(9):659–675. [PubMed: 17342875]
- Dromey C, Ramig LO. Intentional changes in sound pressure level and rate: Their impact on measures of respiration, phonation, and articulation. *Journal of Speech, Language, and Hearing Research*. 1998; 41:1003–1018.

- Dromey C. Spectral measures and perceptual ratings of hypokinetic dysarthria. *Journal of Medical Speech Language Pathology*. 2003; 11(2):85–94.
- Duffy, JR. *Motor Speech Disorders: Substrates, Differential Diagnosis, and Management*. 3rd. St. Louis, Missouri: Mosby; 2013.
- Ferguson SH, Kewley-Port D. Vowel intelligibility in clear and conversational speech for normal-hearing and hearing-impaired listeners. *Journal of the Acoustical Society of America*. 2002; 112(1):259–271. [PubMed: 12141351]
- Ferguson SH, Kewley-Port D. Talker differences in clear and conversational speech: Acoustic characteristics of vowels. *Journal of Speech, Language, and Hearing Research*. 2007; 50:1241–1255.
- Festen JM, Plomp R. Effects of fluctuating noise and interfering speech on the speech-reception threshold for impaired and normal hearing. *Journal of the Acoustic Society of America*. 1990; 88:1725–1736.
- Fleiss, JL. *The Design and Analysis of Clinical Experiments*. New York: Wiley; 1986.
- Fogerty D, Kewley-Port D, Humes LE. The relative importance of consonant and vowel segments to the recognition of words and sentences: Effects of age and hearing loss. *Journal of the Acoustical Society of America*. 2012; 132(3):1667–1678. [PubMed: 22978895]
- Fourakis M. Tempo, stress, and vowel reduction in American English. *Journal of the Acoustical Society of America*. 1991; 90(4):1816–1827. [PubMed: 1960277]
- Frank T, Craig CH. Comparison of the auditec and rintelmann recordings of the NU-6. *Journal of Speech and Hearing Disorders*. 1984; 49:267–271. [PubMed: 6748621]
- Gay T. Effect of speaking rate on vowel formant movements. *Journal of the Acoustical Society of America*. 1978; 63(6):223–230. [PubMed: 632415]
- Goldwave Inc. Goldwave (Version 5). 2010. [Software] Available from <http://www.goldwave.com/release.php>
- Hazan V, Markham D. Acoustic-phonetic correlates of talker intelligibility for adults and children. *Journal of the Acoustical Society of America*. 2004; 116:3108–3118. [PubMed: 15603156]
- Hustad KC, Lee J. Changes in speech production associated with alphabet supplementation. *Journal of Speech, Language, and Hearing Research*. 2008; 51:1438–1450.
- Hustad KC, Sassano K. Effects of rate reduction on severe spastic dysarthria in cerebral palsy. *Journal of Medical Speech Language Pathology*. 2002; 10(4):287–292.
- IEEE. Institute of Electrical and Electronic Engineers. New York: 1969. IEEE recommended practice for speech quality measurements.
- Janse E. Word perception in fast speech: artificially time-compressed vs. naturally produced fast speech. *Speech Communication*. 2004; 42(2):155–173.
- Kent RD, Kent JF, Weismer G, Martin RE, Sufit RL, Brooks BR, Rosenbek JC. Relationships between speech intelligibility and the slope of second-formant transitions in dysarthric subjects. *Clinical Linguistics & Phonetics*. 1989; 3(4):347–358.
- Kent RD, Weismer G, Kent J, Rosenbek J. Toward phonetic intelligibility testing in dysarthria. *Journal of Speech and Hearing Disorders*. 1989; 54:482–499. [PubMed: 2811329]
- Keppel, G.; Wickens, TD. *Design and Analysis: A Researcher's Handbook*. Upper Saddle River, NJ: Pearson Prentice Hall; 2004.
- Kim YJ, Kent RD, Weismer. An acoustic study of the relationships among neurologic disease, dysarthria type and severity of dysarthria. *Journal of Speech, Language, and Hearing Research*. 2011; 54:417–429.
- Kim Y, Weismer G, Kent RD, Duffy JR. Statistical models of F2 slope in relation to severity of dysarthria. *Folia Phoniatrica et Logopaedica*. 2009; 61(6):329–335. [PubMed: 19864914]
- Krause JC, Braida LD. Investigating alternative forms of clear speech: The effects of speaking rate and speaking mode on intelligibility. *The Journal of the Acoustical Society of America*. 2002; 112(5): 2165–2172. [PubMed: 12430828]
- Krause JC, Braida LD. Acoustic properties of naturally produced clear speech at normal speaking rates. *Journal of the Acoustical Society of America*. 2004; 115(1):362–378. [PubMed: 14759028]

- Ladd DR, Faulkner D, Faulkner H, Schepman A. Constant “segmental anchoring” of F0 movements under changes in speech rate. *The Journal of the Acoustical Society of America*. 1999; 106:1543. [PubMed: 10489710]
- Laures JS, Bunton K. Perceptual effects of a flattened fundamental frequency at the sentence level under different listening conditions. *Journal of Communication Disorders*. 2003; 36:449–464. [PubMed: 12967739]
- Laures JS, Weismer G. The effects of a flattened fundamental frequency on intelligibility at the sentence level. *Journal of Speech, Language, Hearing Research*. 1999; 42:1148–1156.
- Lindblom B. Spectrographs Study of Vowel Reduction. *Journal of the Acoustical Society of America*. 1963; 35(11):1773–1781.
- Lindblom, B. Explaining Phonetic Variation: A Sketch of the H&H Theory. In: Hardcastle, WJ.; Marchal, A., editors. *Speech Production and Speech Modeling*. The Netherlands: Kluwer Academic Publishers; 1990. p. 403-439.
- Logan KJ, Roberts RR, Pretto AP, Morey MJ. Speaking Slowly: Effects of Four Self-Guided Training Approaches on Adults' Speech Rate and Naturalness. *American Journal of Speech-Language Pathology*. 2002; 11(2)
- Maniwa K, Jongman A, Wade T. Perception of clear fricatives by normal-hearing and simulated hearing-impaired listeners. *Journal of the Acoustical Society of America*. 2008; 123(2):1114–1125. [PubMed: 18247912]
- McAuliffe, MJ.; Schaefer, M.; O'Beirne, GA.; LaPointe, LL. Effect of noise upon the perception of speech intelligibility in dysarthria. Poster presented at the American Speech-Language and Hearing Association Convention. 2009. <http://hdl.handle.net/10092/3410>
- McRae PA, Tjaden K, Schoonings B. Acoustic and perceptual consequences of articulatory rate change in Parkinson Disease. *Journal of Speech, Language, and Hearing Research*. 2002; 45:35–50.
- Milenkovic, P. TF32. Madison, WI: University of Wisconsin-Madison; 2005. Computer software
- Miller SE, Schlauch RS, Watson PJ. The effects of fundamental frequency contour manipulations on speech intelligibility in background noise. *Journal of the Acoustical Society of America*. 2010; 128(1):435–443. [PubMed: 20649237]
- Molloy, D. *Standardized Mini-Mental State Examination*. Troy, NY: New Grange Press; 1999.
- Neel AT. Effects of loud and amplified speech on sentence and word intelligibility in Parkinson Disease. *Journal of Speech, Language, and Hearing Research*. 2009; 52:1021–1033.
- Nilsson M, Soli S, Sullivan J. Development of the hearing in noise test for the measurement of speech reception thresholds in quiet and in noise. *Journal of the Acoustical Society of America*. 1994; 95:1085–1099. [PubMed: 8132902]
- Orr DB. Time compressed speech—a perspective. *Journal of Communication*. 1968; 18(3):288–292.
- Perkell JS, Matthies ML, Tiede M, Lane H, Zandipour M, Marrone N, Stockmann E, Guenther FH. The distinctness of speakers'/s/-/S/contrast is related to their auditory discrimination and use of an articulatory saturation effect. *Journal of Speech, Language, and Hearing Research*. 2004b; 47:1259–1269.
- Rothman KJ. No adjustments are needed for multiple comparisons. *Epidemiology*. 1990; 1(1):43–46. [PubMed: 2081237]
- Sapir S, Spielman J, Ramig L, Story B, Fox C. Effects of intensive voice treatment (the Lee Silverman Voice Treatment [LSVT]) on vowel articulation in dysarthric individuals with idiopathic Parkinson's disease: Acoustic and perceptual findings. *Journal of Speech, Language, and Hearing Research*. 2007; 50:899–912.
- Smiljani R, Bradlow AR. Speaking and hearing clearly: Talker and listener factors in speaking style changes. *Language and Linguistics Compass*. 2009; 3(1):236–264. [PubMed: 20046964]
- Spitzer SM, Liss JM, Mattys SL. Acoustic cues to lexical segmentation: A study of resynthesized speech. *Journal of the Acoustical Society of America*. 2007; 122(6):3678–3687. [PubMed: 18247775]
- Stevens KN, House AS. An acoustical theory of vowel production and some of its implications. *Journal of Speech and Hearing Research*. 1961; 4(4):303. [PubMed: 13917066]

- Streiner DL, Norman GR. Correction for multiple testing: Is there a resolution? [Commentary]. *Chest*. 2011; 140(1):16–18. [PubMed: 21729890]
- Sussman JE, Tjaden K. Perceptual measures of speech from individuals with Parkinson's Disease and Multiple Sclerosis: Intelligibility and beyond. *Journal of Speech, Language, and Hearing Research*. 2012; 55:1208–1219.
- Tjaden K, Lam J, Wilding G. Vowel acoustics in Parkinson's Disease and Multiple Sclerosis: Comparison of Clear, Loud, and Slow speaking conditions. *Journal of Speech, Language and Hearing Research*. 2013; 56(5):1485.
- Tjaden, K.; Kain, A.; Lam, J. *Journal of Speech, Language and Hearing Research*. 2014a. Hybridizing conversational and clear speech to investigate the source of increased intelligibility in Parkinson's disease.
- Tjaden K, Rivera D, Wilding G, Turner GS. Characteristics of the lax vowel space in dysarthria. *Journal of Speech, Language, and Hearing Research*. 2005; 48(3):554–566.
- Tjaden, K.; Sussman, J.; Wilding, G. *Journal of Speech, Language and Hearing Research*. 2014b. Impact of clear, loud and slow speech on scaled intelligibility and speech severity in Parkinson's disease and Multiple sclerosis.
- Tjaden K, Wilding GE. Rate and loudness manipulations in dysarthria: Acoustic and perceptual findings. *Journal of Speech, Language, and Hearing Research*. 2004; 47:766–783.
- Tjaden K, Wilding G. Rate and loudness manipulations in dysarthria: Acoustic and perceptual findings. *Journal of Speech, Language, and Hearing Research*. 2011; 47(4):766–783.
- Tsao YC, Weismer G, Iqbal K. Interspeaker variation in habitual speaking rate: Additional evidence. *Journal of Speech, Language, and Hearing Research*. 2006; 49:1156–1164.
- Turner GS, Tjaden K, Weismer G. The influence of speaking rate on vowel space and speech intelligibility for individuals with Amyotrophic Lateral Sclerosis. *Journal of Speech and Hearing Research*. 1995; 38:1001–1013. [PubMed: 8558870]
- Turner GS, Weismer G. Characteristics of speaking rate in the dysarthria associated with Amyotrophic Lateral Sclerosis. *Journal of Speech and Hearing Research*. 1993; 36:1134–1144. [PubMed: 8114480]
- Uchanski, RM. Clear speech. In: Pisoni, DB.; Remez, R., editors. *The handbook of speech perception*. Malden, MA: Blackwell; 2005. p. 207-235.
- Van Nuffelen G, De Bodt Marc, Vanderwegen J, Van de Heyning P, Wuyts F. Effect of rate control on speech production and intelligibility in dysarthria. *Folia Phoniatica et Logopaedica*. 2010; 62:110–119. [PubMed: 20424466]
- Van Nuffelen G, De Bodt M, Wuyts F, Van de Heyning P. The effect of rate control on speech rate and intelligibility of dysarthric speech. *Folia Phoniatica et Logopaedica*. 2009; 61(2):69–75. [PubMed: 19287175]
- Van Son RJH, Pols LCW. Formant frequencies of Dutch vowels in a text, read at normal and fast rate. *Journal of the Acoustical Society of America*. 1990; 88(4):1683–1693.
- Ventry IM, Weinstein BE. Identification of elderly people with hearing problems. *Asha*. 1983; 25(7):37–42. [PubMed: 6626295]
- Watson PJ, Schlauch RS. The effect of fundamental frequency on the intelligibility of speech with flattened intonation contours. *American Journal of Speech-Language Pathology*. 2008; 17(4):348–355. [PubMed: 18840699]
- Weismer, G. Speech intelligibility. In: Ball, MJ.; Perkins, MR.; Muller, N.; Howard, S., editors. *The handbook of clinical linguistics*. Oxford, England: Blackwell; 2008. p. 568-582.
- Weismer G, Barlow S, Smith A, Caviness J, Finan D, Liss J. Driving critical initiatives in motor speech. *Journal of Medical Speech-Language Pathology*. 2008; 16(4):283–295. [PubMed: 19421339]
- Weismer G, Jeng JY, Laures JS, Kent RD, Kent JF. Acoustic and intelligibility characteristics of sentence production in neurogenic speech disorders. *Folia Phoniatica et Logopaedica*. 2001; 53(1):1–18. [PubMed: 11125256]
- Weismer G, Laures JS, Jeng JY, Kent RD, Kent JF. The effect of speaking rate manipulations on acoustic and perceptual aspects of the dysarthria in amyotrophic lateral sclerosis. *Folia Phoniatica et Logopaedica*. 2000; 52:201–219. [PubMed: 10965174]

- Weismer G, Yunusova Y, Bunton K. Measures to evaluate the effects of DBS on speech production. *Journal of Neurolinguistics*. 2012; 25(2):74–94. [PubMed: 24932066]
- Wingfield A. Acoustic redundancy and the perception of time-compressed speech. *Journal of Speech, Language, and Hearing Research*. 1975; 18(1):96–104.
- Wohlert AB, Hammen VL. Lip muscle activity related to speech rate and loudness. *Journal of Speech, Language, and Hearing Research*. 2000; 43:1229–1239.
- Yorkston, K.; Beukelman, D. Sentence Intelligibility Test for Windows. Lincoln: NE: Tice Technologies; 1996.
- Yorkston K, Hakel M, Beukelman DR, Fager S. Evidence for effectiveness of treatment of loudness, rate, or prosody in dysarthria: A systematic review. *Journal of Medical Speech-Language Pathology*. 2007; 15:11–36.
- Yunusova Y, Green JR, Greenwood L, Wang J, Pattee GL, Zinman L. Tongue movements and their acoustic consequences in amyotrophic lateral sclerosis. *Folia Phoniatrica et Logopaedica*. 2012; 64(2):94–102. [PubMed: 22555651]
- Yunusova Y, Weismer G, Kent RD, Rusche NM. Breath-group intelligibility in dysarthria: Characteristics and underlying correlates. *Journal of Speech, Language, and Hearing Research*. 2005; 48:1294–1310.

Highlights

- Intelligibility outcome at a faster-than-habitual rate varies across speakers.
- The acoustic correlates of intelligibility associated with rate change are complex.
- Suprasegmental adjustments in non-habitual speaking conditions may have facilitative effects on intelligibility.

Figure 1.

Means and standard deviations of articulation rate (top panel) and scaled intelligibility (bottom panel) by group and condition. Means are indicated by speaker group abbreviations, and error bars indicate one standard deviation. For brevity, the Fast condition is denoted as 'Fast' in this figure.

Figure 2. Distribution of intelligibility difference scores by speaker group. Dots represent individual speakers. Each dot indicates a difference score obtained by subtracting a speaker's mean scaled intelligibility in the Habitual condition from that in Fast.

Figure 3.

Faster-than-habitual speech profiles of selected acoustic measures for two speakers in the No Decline group and two speakers in the Decline group with the most extreme scaled intelligibility changes. All measures are presented as difference scores (Fast minus Habitual). Note that F2 IQR is shown in an unconventional unit of decahertz solely for graphing purposes.

Table 1

Summary of speaker characteristics.

Speaker ^a	Experimental Group Characteristics			Speaker Characteristics			
	Mean Intelligibility Difference ^b	Mean Habitual Intelligibility	Mean Fast Intelligibility	Age	Scaled Speech Severity ^d	Years Post Dx	History of Tx ^e
<i>No Decline</i>							
PDF05	-0.06	0.46	0.40	74	0.55	2	Yes
PDM01	-0.08	0.64	0.56	76	0.34	12	None
PDM07	-0.01	0.68	0.67	67	0.45	32	None
MSF08	-0.08	0.23	0.15	53	0.23	9	None
MSF13	-0.01	0.37	0.36	53	0.34	5	None
MSM02	-0.04	0.33	0.29	56	0.39	18	None
MSM05	-0.10	0.64	0.54	55	0.38	6	None
MSM07	<0.00 ^c	0.53	0.53	48	0.40	4	None
<i>Mean (SD)</i>	<i>-0.05 (0.04)</i>	<i>0.49 (0.17)</i>	<i>0.44 (0.17)</i>	<i>60.25 (10.58)</i>	<i>0.39 (0.09)</i>	<i>11 (9.90)</i>	<i>n/a</i>
<i>Decline</i>							
PDF04	0.30	0.52	0.82	48	0.52	11	Yes
PDM06	0.11	0.62	0.73	66	0.24	3	None
PDM08	0.14	0.55	0.69	78	0.46	4	Yes
MSF04	0.17	0.42	0.59	62	0.44	9	None
MSF05	0.25	0.26	0.51	49	0.24	24	None
MSM04	0.12	0.61	0.73	63	0.62	22	None
MSM09	0.15	0.30	0.45	47	0.70	8	Yes
MSM10	0.16	0.42	0.58	60	0.30	40	None
<i>Mean (SD)</i>	<i>0.18 (0.07)</i>	<i>0.46 (0.14)</i>	<i>0.64 (0.13)</i>	<i>59.13 (10.70)</i>	<i>0.44 (0.17)</i>	<i>15.13 (12.65)</i>	<i>n/a</i>
<i>91.25 (3.62)</i>							
<i>92.25 (2.71)</i>							

Note.

^aSpeaker code expresses the neurological diagnosis followed by the sex of the speaker. F = female and M = male.^bDifference scores reflect difference between faster-than-habitual and habitual rates.^cUnrounded difference = -0.001.

^d Scaled Severity for Grandfather Passage as reported in Sussman and Tjaden with higher scale values indicating greater impairment.

^e History of prior experience with speech and/or language therapy.

Table 2

Summary of experimental speaker group descriptive statistics.

	<i>No Decline</i>		<i>Decline</i>	
	<u>Habitual</u>	<u>Fast</u>	<u>Habitual</u>	<u>Fast</u>
Scaled Intelligibility	0.48 (0.17)	0.44 (0.17)	0.46 (0.14)	0.64 (0.13)
Dependent Variables	Habitual	Fast	Habitual	Fast
Articulation Rate _{syllables/sec}	3.69 (0.47)	4.41* (0.72)	3.74 (0.40)	4.81* (0.71)
Speech Rate _{syllables/sec}	3.62 (0.44)	4.38* (0.75)	3.61 (0.46)	4.72* (0.76)
Mean F0 _{Hz}	122.63 (24.36)	147.60* (36.35)	124.55 (32.28)	129.03 (21.15)
F0 SD _{Hz}	24.34 (9.08)	28.64 (9.63)	27.43 (11.98)	25.69 (10.51)
F0 Minimum _{Hz}	59.29 (14.93)	72.80 (19.28)	53.08 (21.87)	64.28 (24.11)
F0 Maximum _{Hz}	173.53 (37.37)	203.85 (49.58)	186.01 (48.65)	180.28 (29.00)
F0 Range _{Hz}	114.24 (41.79)	131.05 (46.59)	132.94 (57.62)	116.00 (39.21)
SPL _{dB}	71.64 (2.81)	78.37* (4.36)	71.33 (3.07)	73.01* (3.81)
SPL SD _{dB}	8.77 (1.06)	9.46 (1.38)	8.40 (0.72)	8.02 (0.80)
F2 IQR _{Hz}	532.25 (117.86)	521.63 (102.32)	522.08 (94.33)	489.52 (115.29)

Note. Values are group means. Standard deviations are shown in parentheses. Asterisks indicate statistically significant change from Habitual to Fast condition.

Table 3

Summary of correlation analysis for each acoustic measure.^a

Articulation Rate (syllables/se cond)		Speech Rate (syllables/second)	Mean F0 (Hz)	F0 SD (Hz)	F0 Minimum (Hz)	F0 Maximum (Hz)	F0 Range (Hz)	SPL (dB)	SPL SD (dB)	F2 IQR (Hz)
<i>r</i>	0.61* ^b	0.59*	-0.62*	-0.55*	0.1	-0.62*	-0.76*	-0.78*	-0.75*	-0.33
<i>P</i>	0.01	0.02	0.01	0.03	0.70	0.01	<0.001	<0.001	<0.001	0.21

Note.

^aBased on all speaker means across two speaker groups (*N* = 16).

^bAsterisks indicate significance at *p* = .05.