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Research Article

Effect of Dysarthria Type, Speaking Condition, and Listener Age on Speech Intelligibility

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Purpose: The aim of this study was to examine the effect of loud and slow speech cues on younger and older listeners' comprehension of dysarthric speech, specifically, (a) whether one strategy, as opposed to the other, promoted greater intelligibility gains for different speaker groups; (b) whether older and younger listeners' understandings were differentially affected by these strategies; and (c) which acoustic changes best predicted intelligibility gain in individual speakers.
Method: Twenty younger and 40 older listeners completed a perceptual task. Six individuals with dysarthria produced phrases across habitual, loud, and slow conditions. The primary dependent variable was proportion of words correct; follow-up acoustic analyses linked perceptual outcomes to changes in acoustic speech features.
Results: Regardless of dysarthria type, the loud condition produced significant intelligibility gains. Overall, older listeners' comprehension was reduced relative to younger listeners. Follow-up analysis revealed considerable interspeaker differences in intelligibility outcomes across conditions. Although the most successful speaking mode varied, intelligibility gains were strongly associated with the degree of change participants made to their vowel formants.
Conclusions: Perceptual outcomes vary across speaking modes, even when speakers with dysarthria are grouped according to similar perceptual profiles. Further investigation of interspeaker differences is needed to inform individually tailored intervention approaches.

Both clinically and in research, increased vocal loudness and reduced speech rate are commonly used to improve intelligibility for those with dysarthria. However, neither technique provides uniform positive changes. Indeed, inconsistent treatment outcomes for individuals with dysarthria are a substantial issue in clinical practice and research. Both within and across studies, research has regularly demonstrated that groups of participants with the same neurological etiology or dysarthria subtype do not always achieve similar intelligibility improvements in treatment or stimulability studies (Hammen, Yorkston, & Minifie, 1994; Neel, 2009; Pilon, McIntosh, & Thaut, 1998; Tjaden & Wilding, 2004; Turner, Tjaden, & Weismer, 1995; Van Nuffelen, De Bodt, Vanderwegen, & Van de Heyning, 2010; Van Nuffelen, De Bodt, Wuyts, & Van de Heyning, 2009; Yorkston, Hammen, Beukelman, & Traynor, 1990).

A recent investigation suggested that heterogeneity in the baseline speech characteristics of individuals with dysarthria may be linked to the lack of treatment effects commonly reported in group-based treatment studies (Feenaughty, Tjaden, & Sussman, 2014). Although this appears logical, there has been limited research conducted from this viewpoint. Examining how various treatment cues affect speech intelligibility when participants with dysarthria are clustered on the basis of their speech features appears a logical starting point. However, intelligibility is dependent on the interaction of speaker and listener. Hence, inherent variability among listeners, as well as speakers, may be an important consideration when reviewing treatment effects. Although the listener is crucial to understanding treatment outcomes, there has been limited study of how listener differences affect intelligibility in response to behavioral treatment cues. One salient issue is listener age—older listeners are common communication partners

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of individuals with dysarthria, yet to our knowledge, there have been no studies examining older listeners' processing of dysarthric speech that has been modified through common speech-cueing strategies. Therefore, we have a limited understanding of whether older and younger listeners will achieve similar intelligibility benefits when listening to dysarthric speech that has been modified by behavioral cuing—or whether certain behavioral speech modifications might result in greater intelligibility gain for certain listeners (e.g., older listeners may benefit more when individuals with dysarthria are cued to speak "loud" relative to younger listeners).

The current study brings speaker and listener viewpoints together. We investigate whether a loud or slow speech cue is most effective in enhancing intelligibility across two speaker groups—one with ataxic and another with hypokinetic dysarthria. In measuring intelligibility, the study includes both younger and older listeners to determine whether either group benefits substantially from one cue compared with another. Follow-up analyses focus on individual speakers with dysarthria, linking their intelligibility changes across speech conditions to changes in acoustic variables.

Research using treatment simulation approaches has commonly investigated changes to intelligibility through the use of two techniques: increased vocal loudness and reduced speech rate. These studies have demonstrated improvements in blinded listeners' comprehension of dysarthric speech; however, effects generally vary across speakers and studies (Hammen et al., 1994; Neel, 2009; Patel, 2002; Patel & Campellone, 2009; Pilon et al., 1998; Tjaden & Wilding, 2004; Turner et al., 1995; Van Nuffelen et al., 2009, 2010; Yorkston et al., 1990). For example, Tjaden and Wilding (2004) found that a loud speech cue resulted in a statistically significant improvement to scaled intelligibility in a group of 12 speakers with Parkinson's disease (PD). Ten of the 12 speakers exhibited improved intelligibility in a loud speaking condition; however, for the remaining two individuals, the slow speech cue resulted in the largest improvement in scaled intelligibility. For speakers involved in the same study but with a diagnosis of multiple sclerosis, neither cue resulted in significant changes to intelligibility at group level. Similarly, McAuliffe, Kerr, Gibson, Anderson, and LaShell (2014), with speech samples provided by a group of five speakers with hypokinetic dysarthria, reported that both slow and loud cues resulted in improved intelligibility—although in contrast to Tjaden and Wilding (2004), intelligibility was optimized through the use of a slow speech cue.

Similar variability has been reported in other studies that have examined the effects of either a slow or loud speech cue on intelligibility. Neel (2009) reported that four of five participants with hypokinetic dysarthria demonstrated significantly improved intelligibility when using loud speech. In the case of slow cued speech, Turner et al. (1995) found that only four of nine speakers with amyotrophic lateral sclerosis and dysarthria exhibited their largest intelligibility estimate in a slow speaking condition (achieved through direct magnitude estimation). In contrast, Hammen et al. (1994) reported that all five participants with PD exhibited higher speech intelligibility relative to a habitual condition in a paced reading task. Similarly, Yorkston et al. (1990) reported considerable intelligibility gain for groups of speakers with both ataxic (n = 4) and hypokinetic (n = 4) dysarthria when a slow speech cue was used. Overall, the slow speech cue resulted in an approximately 33% improvement in intelligibility for speakers with ataxic dysarthria and an approximately 21% improvement for those with hypokinetic dysarthria. Although all participants demonstrated improved intelligibility with these cues, the magnitude of effect varied considerably by speaker.

Overall, there is evidence that both speech treatment techniques may be effective in improving the intelligibility of individuals with dysarthria—yet the picture is far from complete. At present, we are unable to conclude which treatment approach will provide optimal intelligibility gains for certain speakers. Indeed, even among speakers who exhibit the same type of dysarthria, there is no obvious choice of which behavioral modification produces the best outcomes. A number of factors likely contribute to the varied outcomes, including differences in speech characteristics exhibited by individuals in the treatment groups (e.g., Tjaden & Wilding, 2004) and variations in speech disorder severity within the groups (Tjaden & Wilding, 2004; Turner et al., 1995). If we could examine the effects of these behavioral modifications using speakers with similar perceptual profiles and a defined intelligibility range, perhaps a clearer picture of treatment outcomes would emerge. Furthermore, regardless of perceptual profile, it is also clear that individuals with dysarthria enact acoustic changes to varying degrees in response to behavioral cuing (e.g., Darling & Huber, 2011). However, we do not have a clear sense of how these acoustic changes differ across individuals—or which acoustic changes are most important for altering intelligibility. As a further step toward improving the evidence base for behavioral intervention in dysarthria, a clearer understanding of these issues is required. In examining these issues, we begin by focusing on participants with hypokinetic and ataxic dysarthria.

Classically, speakers with hypokinetic dysarthria exhibit monopitch and loudness, reduced stress, consonant imprecision, breathiness, and a variable speaking rate (Darley, Aronson, & Brown, 1969). These changes are evidenced in degraded acoustic cues that challenge listener expectations and result in deteriorations in speech intelligibility. If increased loudness is achieved through behavioral intervention, then improved intelligibility is the likely outcome. Indeed, techniques using increased loudness are the current gold standard in the treatment of hypokinetic dysarthria (Ramig et al., 2001; Sapir, Ramig, & Fox, 2011). However, whether this approach is optimal relative to a slow speaking cue for those with hypokinetic dysarthria is debatable—and likely dependent on the individual speaker. For example, the cue to speak slowly was recently shown to result in greater intelligibility gains than a cue to speak louder in individuals with hypokinetic dysarthria who exhibited a faster speaking rate (McAuliffe et al., 2014). Thus, although the weight of clinical evidence suggests that a loud speech cue will result in the largest intelligibility gain for those with hypokinetic dysarthria, this remains to be determined.

In contrast, ataxic dysarthria is diagnosed in individuals who exhibit a cluster of speech features including imprecise consonant and vowel articulation, irregular articulatory breakdown, excess and equal stress, and vocal harshness (Darley et al., 1969). In speakers with ataxic dysarthria, we posit that a slow speech cue will provide optimal intelligibility gains. Slow speech is likely to result in increased distinctiveness of vowels and consonants, often shown to account for significant amount of variance in intelligibility for speakers with dysarthria (e.g., Kim, Kent, & Weismer, 2011; Turner et al., 1995). Moreover, the possibility of increased pauses at word boundaries may further enhance intelligibility. This notion fits with the findings of Yorkston et al. (1990), who showed that a slowed speech rate provided larger intelligibility gains for speakers with ataxic dysarthria than those with hypokinetic dysarthria.

When considering listeners' responses to various cuing techniques, one aspect of processing commonly neglected is the age of the listener. Older listeners are common communication partners of those with dysarthria, and thus far, most studies examining listeners' perception of dysarthric speech have measured performance on the basis of the perception of young, healthy listeners. The few studies that have included older listeners have focused on general intelligibility rather than the outcomes of treatment or listeners' responses to behavioral cues. Furthermore, although it might be assumed that older listeners would perform more poorly in the comprehension of dysarthric speech than younger listeners, study findings have been equivocal. When proportion of words correct was used as a dependent variable, a number of studies have found that older participants exhibit significantly lower scores than younger listeners (Dagenais, Adlington, & Evans, 2011; Garcia & Hayden, 1999; Jones, Mathy, Azuma, & Liss, 2004), yet others have reported no significant differences between the two groups (Dagenais, Watts, Turnage, & Kennedy, 1999; McAuliffe, Gibson, Kerr, Anderson, & LaShell, 2013).

To our knowledge, no study has examined whether younger and older listeners perform similarly in their attempts to comprehend dysarthric speech that has been modified through treatment or behavioral cuing. However, there is reason to believe that certain dysarthria types and behavioral cues may differentially affect older listeners. For example, Pennington and Miller (2007) found that, when listening to speakers with cerebral palsy and dysarthria, younger and older listeners performed similarly in a comprehension task. However, older men demonstrated greater difficulty relative to other listener groups when listening to the speech of individuals with PD. Recently, McAuliffe et al. (2013) demonstrated that older and younger listeners exhibited a similar ability to understand hypokinetic dysarthric speech, but they showed evidence of differences in their listening approach: Older participants appeared less reliant on syllabic stress patterns to inform speech segmentation than younger listeners. Impaired stress production is salient in the dysarthrias and may also be influenced by behavioral modifications used in treatment programs. Hence, if older listeners are indeed less reliant on stress cues to inform perception, it is possible that they might exhibit differences in the way they comprehend certain types of speech disorder and respond to changes resulting from behavioral cueing relative to younger listeners.

This article explores intelligibility changes in response to two common treatment strategies: reduced rate and increased loudness, as measured by both younger and older listener groups. Speakers with ataxic and hypokinetic dysarthria provided the speech samples, and the speakers within the two groups exhibited relatively perceptually homogenous speech features and dysarthria severities. On this basis, the study aimed to determine (a) which, of a loud or slow speech modification strategy, promoted the greatest intelligibility gain across speaker groups with ataxic and hypokinetic dysarthria respectively; (b) whether the performance of younger and older listeners was differentially affected by these speech changes; and (c) whether an individual speaker's degree of intelligibility change across conditions was linked to changes in various acoustic measures of speech production.

Method

The study received ethical approval from the Upper South A Regional Ethics Committee, Ministry of Health, New Zealand. All individuals provided written consent to participate.

Listener (Experimental) Participants

A total of 60 listeners completed the perception experiment—20 younger participants (all female) and 40 older participants (24 women, 16 men). The average age of the younger participants was 19.65 years (SD = 1.79, range = 18 to 24 years). The average age of the older participant group was 71.75 years (SD = 4.06, range = 66 to 80 years). All participants were native speakers of New Zealand English and reported no history of language, learning, or cognitive disabilities. They had not participated in any earlier published research from our laboratory. All younger listeners passed a pure-tone hearing screen at 20 dB HL for 1,000, 2,000, and 4,000 Hz and of 30 dB HL at 500 Hz bilaterally. We accepted all interested participants for the older listener group—with a range of hearing profiles and age-related hearing loss—provided they did not wear hearing aids. Their hearing thresholds were determined using behavioral pure-tone audiometry at 500, 1,000, 2,000, and 4,000 Hz in both the left and right ears. The average high-frequency pure-tone average of the older listeners in their better ear was 26.1 dB HL (SD = 11.9, range = 11.7 to 55.0). All listeners received a $30 NZD voucher as compensation for their participation.

Speech Stimuli Acquisition and Selection

Speaker Participants

Speech stimuli were collected from six individuals with dysarthria, all native speakers of New Zealand English. According to our operational criteria, three speakers exhibited ataxic dysarthria (two men, one woman), and a further three exhibited hypokinetic dysarthria (three men). Hypokinetic dysarthria was operationally defined as a perceptual impression of a fast rate of speech, monopitch, monoloudness, consonant imprecision, and a weak and/or breathy voice. In contrast, ataxic dysarthria was defined as exhibiting a slow rate of speech, tendency toward excess and equal stress, irregular articulatory breakdown, and excess loudness variation (Liss, Spitzer, Caviness, Adler, & Edwards, 2000). Perceptual analysis and categorization were conducted by two experienced speech-language pathologists via a consensus rating procedure and on the basis of speakers' recordings of the Grandfather Passage. Biographical and speech details of the six speakers are provided in Table 1.

Speech Recording Procedure

Speaker participants attended a single recording session, with digital recordings and signal calibration undertaken using our standard laboratory procedures, full details of which are provided in McAuliffe et al. (2014). During the assessment, speakers were recorded reading the Grandfather Passage and a list of 80 experimental phrases. The Grandfather Passage was used for classification of dysarthria type, whereas the experimental phrases were used in the listening experiment and are described in further detail in subsequent sections.

Speaker participants were recorded saying the 80 experimental phrases in three conditions—habitual, loud, and slow. In the habitual condition, speakers were asked to read the phrases using their everyday speaking voice, as if talking with a family member or friend. The slow and loud conditions were elicited using magnitude scaling (Tjaden & Wilding, 2004). For the loud condition, speakers were asked to say each phrase "at a level that feels like twice as loud as normal," and in the slow condition, speakers were asked to read each phrase at "what feels like half your normal speed." The habitual condition was conducted first, with the subsequent slow and loud conditions randomized across speakers. Any recordings of stimuli that contained errors were repeated.

Table 1. Biographical details of the six speakers with dysarthria.

Participant	Age	Sex	YPD	Dysarthria
A1	48	F	26	Ataxic
A2	55	M	36	Ataxic
A3	53	M	2	Ataxic (spastic)[a]
H1	75	M	NA	Hypokinetic
H2	71	M	17	Hypokinetic
H3	77	M	26	Hypokinetic

Note. YPD = years post diagnosis or injury.

[a]A3 exhibited salient speech features that resulted in a primary classification of ataxic dysarthria. The presence of vocal harshness was deemed to be related to a spastic component to this speaker's dysarthria.

Experimental Stimuli: Composition

The 80 experimental phrases were adapted from Liss, Spitzer, Caviness, Adler, and Edwards (1998). All phrases contained six syllables, were between three and five words in length, and alternated phrasal stress pattern. Approximately half the stimuli exhibited a weak-strong phrasal stress pattern (iambic), and the remaining half exhibited a strong-weak stress pattern (trochaic). All phrases were semantically anomalous, which served to limit the contribution of semantic processing to listener comprehension. Phrases were also syntactically correct. Example phrases include "push her equal culture" (trochaic) and "address her meeting time" (iambic). Further details regarding composition, and a full list of phrases, are provided in McAuliffe et al. (2014).

Experimental Stimuli: Perceptual Selection and Acoustic Verification

A phrase selection and verification procedure was undertaken, consistent with prior research (Borrie et al., 2012; Liss et al., 1998; McAuliffe et al., 2014). This process aimed to select phrases from each speaker that exhibited, most strongly, the perceptual features of hypokinetic and ataxic dysarthria. First, two experienced speech-language pathologists selected a subset of the speakers' habitual phrases that most strongly conformed to the perceptual criteria. A pilot listening experiment, conducted with six healthy young listeners, was then undertaken to further reduce the stimuli pool of habitual speech phrases to those that exhibited midrange intelligibility—that is, approximately 50% words correct. Considerable variation may exist in the intelligibility of a single speaker's phrases across any data set (e.g., Feenaughty et al., 2014), so we aimed to include a relatively homogenous group of phrases with respect to their intelligibility level. Following perceptual screening and the pilot listening experiment, a total of 54 phrases from the habitual condition were ultimately selected for the perception experiment (i.e., nine from each of the six speakers with dysarthria). The number of words spoken by each speaker with dysarthria was also matched across speakers, with phrase selection ensuring that between 35 and 37 words were included from each person with dysarthria.

Next, each loud and slow token that corresponded to an individual speaker's selected habitual phrase was screened. This process was to ensure that (a) tokens were free of recording error, (b) loud tokens exhibited perceptual evidence of louder and more effortful speech production relative to the habitual token, and (c) slow tokens were perceived to exhibit a reduced rate of speech relative to the habitual condition. This resulted in a final stimulus list containing 162 phrases—54 from the habitual condition and their matched tokens from the loud and slow conditions, respectively.

Acoustic analysis of the selected phrases was undertaken (a) to confirm, prior to competing the perception experiment, that the loud and slow conditions had the desired effect on measures of dB sound pressure level and phrase duration, respectively, and (b) to produce acoustic data for later examination of the relationship between change in acoustic variables and intelligibility gain. Acoustic analysis of selected measures of speech rate (phrase duration and articulation rate), rhythm (nPVIv), prosody (F0 and amplitude SD), and articulation (FCR) were completed. To do so, all phrases were segmented to phoneme level using the Hidden Markov Model Toolkit (HTK; Young et al., 2002). All automatically derived boundaries were visually checked for accuracy using standard criteria (Peterson & Lehiste, 1960). Custom Praat (Boersma & Weenink, 2009) scripts extracted (a) mean intensity (calibrated mean intensity, dB sound pressure level, across the phrase), (b) total phrase duration (in seconds), (c) articulation rate (syllables per second; calculated as per Robb, Maclagan, & Chen, 2004); (d) normalized vocalic Pairwise Variability Index for vowel duration (nPVIv; calculated as per Grabe & Low, 2002), (e) pitch variation (standard deviation of fundamental frequency across the phrase), (f) intensity variation (standard deviation of intensity variation across the phrase), and (g) formant centralization ratio (FCR; calculated using the mean formant values of the temporal midpoint of F1 and F2 of the START [ɐː], FLEECE [iː], and THOUGHT [oː] vowels from selected words[1] across the phrases, adapted for use for New Zealand English and as described in Fletcher, McAuliffe, Lansford, & Liss, 2015).

Table 2 contains results of the first acoustic analysis—that is, determining whether the loud and slow conditions had the desired effect on measures of dB sound pressure level and phrase duration, respectively, in the speakers with dysarthria. Data in Table 2 demonstrate that both groups with dysarthria produced their longest phrase durations in the slow condition and their greatest speech intensity in the loud condition. This indicated that the speaker group achieved the required manipulations of rate and loudness. For all acoustic analysis, Cronbach's alpha was used as a measure of reliability, with intrarater reliability values of greater than .86 and interrater reliability values greater than .84 on rechecking 20% of the experimental stimuli.

Procedure

The perception experiment was programmed using custom-written software (O'Beirne, 2009) and took approximately 50 min to complete. During the experiment, participants were seated in front of a laptop computer, and the experimental phrases were presented through Sennheiser HD280 Pro circumaural headphones via an InSync Buddy USB 6G sound card. Prior to commencing the perception experiment, a passage from a control speaker was presented, and the participants were instructed to use the on-screen sliding scale to adjust the presentation level until it was at a comfortable listening level. After adjusting the level, participants carried out a practice task. On completion of the practice task, participants were once again allowed to adjust the presentation level, but this time they heard the same passage read by dysarthric speakers, to familiarize listeners with dysarthric speech. This level was maintained for the remainder of the experiment. Written task instructions were presented on the laptop screen.

Consistent with our prior studies, participants were instructed that they would hear a series of phrases and that each of the phrases would be composed of real English words; however, the phrases may not make sense. They were asked to verbally repeat each of the phrases exactly as they heard them, and they were encouraged to respond with their best guess if they did not understand what was said. If participants felt they were unable to make a reasonable guess, they reported the word *something* each time they were unsure of the word.

Listener responses were audio recorded and transcribed in real time during the experiment by a trained research assistant, and the listeners had the opportunity to confirm the correct transcription (McAuliffe et al., 2013, 2014).

Each of the 60 listeners heard 162 phrases (54 distinct phrases, repeated across habitual, loud, and slow conditions). The phrases were presented in three blocks of 54 distinct phrases. All three blocks contained an equal number of phrases from each speaker and each condition. That is, the first block contained 54 unique phrases, three phrases from each condition produced by each of the six speakers. The second block also contained the same 54 phrases, but they were spoken in a different condition to block one (e.g., if the listeners heard the phrase "beside a sunken bat" spoken by Speaker A in the habitual condition in Block 1, then they heard Speaker A produce the phrase "beside a sunken bat" in either the loud or slow condition in Block 2). The

Table 2. Comparison of phrase duration and speech intensity across dysarthria type (ataxic, hypokinetic) and speech condition (habitual, loud, and slow).

Measure	Dysarthria	Habitual	Loud	Slow
Phrase duration (seconds)	Hypokinetic	1.49 *(0.29)*	1.65 *(0.36)*	2.22 *(0.66)*
	Ataxic	2.29 *(0.32)*	2.73 *(0.42)*	3.32 *(0.65)*
Speech intensity (dB SPL)	Hypokinetic	82.45 *(2.02)*	89.91 *(3.87)*	79.64 *(4.12)*
	Ataxic	81.52 *(2.59)*	92.78 *(4)*	78.08 *(4.69)*

Note. Mean values are presented, with standard deviations underneath in parentheses. db SPL = sound pressure level in decibels.

[1][ɐː] words were *apart*, *baskets*, *darker*, *embark*, *rather*, and *target*. /i/ words were *cheap*, *defeat*, *meeting*, *retreat*, *seat*, and *sheet*. /ɔ/ words were *award*, *fortune*, *report*, *roared*, *sort*, and *support*.

remaining phrases were presented in Block 3. No speaker, dysarthria type (ataxic or hypokinetic), or condition (habitual, loud, and slow) occurred more than twice in a row within a block. The construction of the blocks varied between participants—some participants heard the habitual production of a phrase in the initial block and then the slow production in the next block; other participants heard the loud production and then the habitual. Listeners were provided with the opportunity to take a short break between blocks.

Data Analysis: Error Coding

The final data set consisted of 60 sets of phrase transcriptions—20 from the younger listeners and 40 from older listeners. The transcripts were analyzed by a rater blinded to listener group allocation, speaker dysarthria, and phrase condition. The primary dependent variable—words correct—was judged according to existing protocols (Borrie et al., 2012; Liss et al., 1998; McAuliffe et al., 2014). Correct words matched the target exactly, differed only in the suffix by tense *ed* or the plural *s*, or involved a substitution of *a* and *the*. Spearman's rho was used as a measure of reliability, with intrarater and interrater values of .99 for the percentage words correct measure.

Results

Table 3 presents the percentage of words correctly understood by each of the two listener groups (younger and older) by dysarthria type (ataxic and hypokinetic) and speech condition (habitual, loud, and slow). To analyze these data statistically, we ran a series of linear mixed-effects models. The analysis began with a full model that included the fixed effects of group (younger and older), condition (habitual, loud, and slow), dysarthria type (ataxic and hypokinetic), and trial. Trial was allowed to be nonlinear through the use of a restricted cubic spline and varied through two points.[2] A maximized random effects structure was created for listener participants, which included the random effects of listener and speaker nested in phrase number. Random slopes were also included for the effect of condition. This allowed for mean values for each listener and phrase to vary and for the possibility that certain speakers within our dysarthric groups exhibited variable effects by condition. This approach reduces the probability of Type I error, and readers are directed to Barr, Levy, Scheepers, and Tily (2013) and Cunnings (2012) for further details regarding the statistical approach. Model evaluation proceeded in a backward-stepwise iterative fashion. The intent was to reduce from the full model to a model that contained only significant fixed effects (with alpha at .05). Model fitting was independently supported by fitness comparisons.

[2]Trial number is commonly included in perception experiments to account for learning effects evidenced by participants across the duration of an experiment.

Table 3. Percentage of words correctly understood by the younger and older listener groups across dysarthria type and speech condition.

	Older Listeners (n = 40)	Younger Listeners (n = 20)
Ataxic		
Habitual	54.80 (12.32)	64.94 (8.73)
Loud	66.79 (13.35)	78.13 (8.91)
Slow	73.50 (11.66)	83.42 (7.16)
Hypokinetic		
Habitual	43.28 (14.18)	53.52 (12.85)
Loud	60.52 (21.64)	69.67 (20.17)
Slow	49.54 (25.33)	57.77 (25.41)

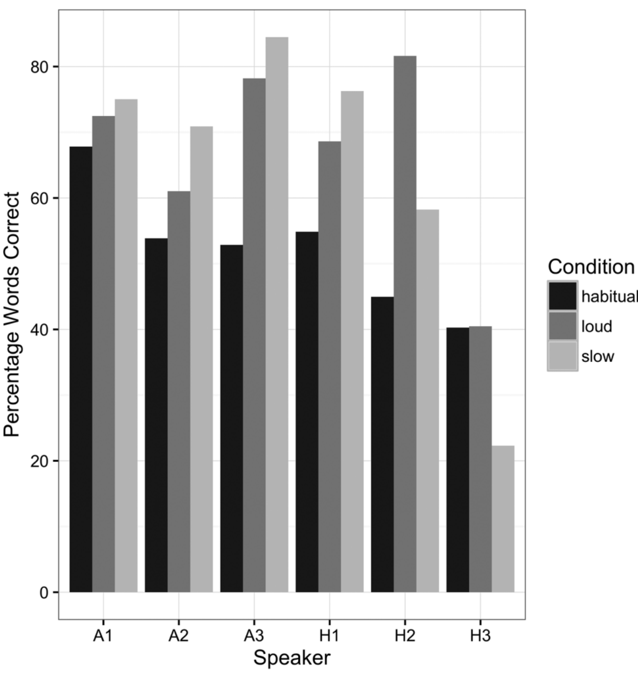
Note. The first value presented is the mean percentage words correct, with standard deviations in parentheses.

The final model revealed a significant effect of group, with younger participants significantly outperforming older participants (β = 6.36 [2.54], $p < .05$). Furthermore, listener accuracy was significantly increased in the loud relative to habitual (β = 15.05 [5.35], $p < .05$) condition. There was no significant increase in listeners' accuracy in the slow relative to the habitual condition (β = 11.81 [6.92], $p > .05$). To compare the loud and slow conditions against each other, the model was releveled and the slow condition mapped to the intercept. There was no significant difference between transcript accuracy in the loud and slow conditions (β = −3.24 [6.16], $p > .05$). The significance of the remaining results was unchanged from the original model.

As expected in longer perception experiments such as this, the effect of trial was significant, with improving accuracy observed in the first half (β = 0.14 [0.01], $p < .001$) of the experiment and performance declining in the second half (β = −0.05 [0.02], $p < .01$) of the experiment. The effect of trial number also interacted with listener group such that younger participants in the first half of the experiment improved their performance at a faster rate than older participants did (β = 0.06 [0.03], $p < .01$). There was no significant difference between the two groups in the second half of the experiment.

Although the results presented in Table 3 appeared to suggest that speakers with hypokinetic and ataxic dysarthria differed in their degree of intelligibility gain across conditions, this was not supported statistically. Speaker-based variability was a considerable contributor to this null result, further motivating speaker-specific data analysis. Figure 1 depicts the percentage of words correct across condition plotted by speaker and collapsed across the two listener groups. We chose to collapse data across the listener groups given the absence of an interaction between groups and condition—older listeners performed generally more poorly than younger listeners, but this was a uniform

Figure 1. Mean percentage words correct for the six speakers with dysarthria across the three speaking conditions. Speakers identified with an "A" are Speakers 1, 2, and 3 with ataxic dysarthria. Speakers identified with an "H" are Speakers 1, 2, and 3 with hypokinetic dysarthria.



reduction in performance across conditions and dysarthria types.

Figure 1 shows that the effects of speaking condition patterned relatively consistently within the group of speakers with ataxic dysarthria. For these speakers, improvement occurred in both the loud and slow conditions, but the slower speaking rate provided the greatest perceptual benefit. However, within the hypokinetic speaker group, there was considerable variation—listener's responses to all three speakers varied. For Speaker H1, the slow condition provided the greatest perceptual benefit. For Speaker H2, the loud condition provided a near doubling of words correct, and for Speaker H3, there was no change to intelligibility in the loud condition and a considerable decline in intelligibility in the slow condition.

To investigate further, we undertook a case-by-case analysis in which individual speaker's acoustic data were compared with their intelligibility outcomes (see Table 4). As demonstrated in Table 4, all speakers increased their vocal intensity in the loud condition and reduced articulatory rate in the slow condition. However, the degree to which participants spoke louder, or slower, did not appear to relate to intelligibility improvement at an individual level. To investigate this further, the strength of association between change in intelligibility and change in the acoustic measures across loud and slow speech conditions were examined.

Correlation analyses revealed no significant relationship between change in intelligibility and vocal intensity (R^2 = .003, p = .88), with the change in vocal intensity accounting for less than 1% of the variance in speakers' intelligibility improvement. That is, the act of speaking with increased vocal intensity was not associated with increased intelligibility. Similarly, a general reduction in articulation rate was minimally, but not significantly, associated with intelligibility change (R^2 = .20, p = .14). Here, the act of simply slowing speech down was only minimally associated with enhanced intelligibility. The same was shown for both changes to prosodic and rhythmic measures. Standard deviations of intensity (R^2 = .02, p = .7) and F0 (R^2 = .003, p = .87) accounted for only 1% or 2% of the differences in treatment outcome. Changes to PVIv in the slow and loud conditions accounted for about 10% (R^2 = .10, p = .32) of the variance. Indeed, there was only one acoustic measure that exhibited a statistically significant relationship to intelligibility change: vowel centralization as measured by FCR. Changes to FCR in the loud and slow condition were strongly associated with improved intelligibility (R^2 = .63, p = .002). The association between these variables is plotted in Figure 2. Figure 2 demonstrates that reductions in FCR that occurred in the loud and slow condition were positively correlated with speakers' intelligibility gains.

Discussion

The current investigation aimed to determine, within two groups of speakers with perceptually similar speech patterns (ataxic and hypokinetic dysarthria, respectively) and intelligibility levels, which treatment strategy—increased loudness or reduced speech rate—provided optimal gains for listener perception and, second, if older and younger listener participants differed in their ability to resolve this degraded signal. Third, the study examined the relationship between individual speakers' degree of intelligibility change and the variation in acoustic measures across conditions. In general, the study found that both treatment strategies improved listeners' ability to comprehend the speech of individuals with dysarthria, with overall analysis indicating that the cue to speak loud provided the greatest intelligibility benefit. Although older listeners' responses were less accurate, this involved a simple scaling down of accuracy as opposed to a difference in ability to resolve either a type of dysarthria or speech cue. Follow-up analysis at the speaker level showed considerable variation in the relative benefit of the two speech modification cues. Increased intelligibility was strongly associated with degree of vowel centralization, not the extent of increased vocal intensity or reduced speech rate. Findings are discussed in more detail below.

The first analysis showed that when dysarthric speakers were cued to speak louder, listeners exhibited a statistically significant improvement in their ability to comprehend the speech signal. However, the slow speech condition did not result in significant gains to speech intelligibility across the group. Instead, a loud speech cue appeared to provide generalized benefits to intelligibility regardless of dysarthria type. Although the current study used only a small number of speakers with dysarthria, the findings provide further

Table 4. Change to individual speaker's percentage words correct and acoustic measures as a result of loud and slow speaking cues.

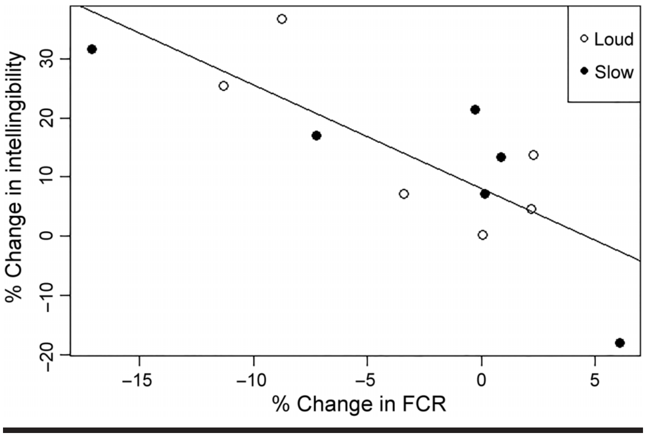
Speaker/condition	PWC	Intensity	Phrase dur	AR	PVI(v)	Int. *SD*	F0 *SD*	FCR
A1								
Slow	7.21	NA	−23.28	−14.28	−0.86	19.61	−0.59	0.17
Loud	4.64	7.90	−15.90	−9.44	−31.02	21.28	66.45	2.20
A2								
Slow	17.05	−0.60	−31.78	−21.53	−11.02	22.17	−10.97	−7.24
Loud	7.19	11.70	−5.40	−4.02	−25.37	16.97	17.15	−3.39
A3								
Slow	31.62	−7.90	−82.53	−35.47	−0.27	49.25	18.92	−17.10
Loud	25.33	16.00	−37.25	−27.05	−7.20	34.95	120.30	−11.29
H1								
Slow	21.43	0.10	−28.82	−20.61	−6.26	50.66	13.36	−0.26
Loud	13.76	6.50	−1.61	−0.55	2.77	21.41	73.25	2.29
H2								
Slow	13.29	−6.80	−49.93	−30.06	−21.42	22.76	−31.81	0.84
Loud	36.67	5.80	−23.79	−17.27	−21.93	29.42	−27.86	−8.74
H3								
Slow	−17.96	−3.50	−60.69	−17.82	−25.99	72.27	−9.37	6.05
Loud	0.19	14.90	−5.34	−5.77	−3.21	13.78	34.07	0.06

Note. Intelligibility is expressed as the overall percentage change from the habitual condition (i.e., a value of 7.21 in the slow condition indicates that intelligibility rose by 7.21% in response to a slow speech cue). All acoustic measures are expressed as a percentage of the speaker's baseline speech (e.g., an AR value of −14.28 in the slow condition indicates that the participant's articulation rate reduced by 14.28% relative to the habitual condition in response to a slow speech cue). PWC = percentage words correct; dur = duration; AR = articulation rate; PVI(v) = pairwise variability index for vowels; Int. *SD* = standard deviation of intensity; F0 *SD* = standard deviation of fundamental frequency; FCR = formant centralization ratio; NA = not available.

support for the use of increased loudness as a general rehabilitative strategy for individuals with dysarthria. It appears that the use of this cue need not be limited to those with hypokinetic dysarthria associated with PD but may be useful, at the very least, to individuals with similar salient speech features to those included in the current study.

The lack of significant intelligibility gain associated with a slow speech cue, relative to the habitual speech condition, was not expected, particularly given the careful stimulus selection procedure. Prior studies have noted improvements to speech intelligibility when both speakers with hypokinetic and ataxic dysarthria are cued to slow their rate of speech (Hammen et al., 1994; Yorkston et al., 1990). However, follow-up speaker-based analysis revealed considerable variability in intelligibility improvement among the six speakers when cued to speak using a slow speech rate. In particular, Speaker H3 exhibited substantial reductions in intelligibility when producing speech with a slower rate (see Figure 1), which may have played some role in the lack of significant findings. Varied outcomes in response to a slow speech cue are not uncommon (e.g., Pilon et al., 1998; Turner & Weismer, 1993; Van Nuffelen et al., 2009, 2010), and why this particular cue may be particularly susceptible to varied outcomes is not known.

Figure 2. Relationship between percentage change in formant centralization ratio (FCR) value and percentage change in intelligibility in the loud and slow speaking modes.



Our analysis also found that dysarthria type was not a significant predictor of whether intelligibility gains would be achieved through the use of particular strategy (i.e., there was no interaction between dysarthria type and speech condition). Kim et al. (2011), in an extensive study of acoustic predictors of intelligibility in speakers with dysarthria, found that grouping participants by dysarthria type did not provide the same level of classification accuracy as grouping participants by disease type or severity of speech involvement. The authors concluded that "blocking of participants on dysarthria type…may not provide additional insight into interpretation of speech production or perception data obtained by speakers with dysarthria" (p. 426). Although the current study included only a small number of participants with dysarthria, the findings lend support to this interpretation. Overall, it appears possible that variation in speech features and baseline intelligibility may be better predictors of intelligibility outcomes. Hence, future studies that investigate treatment or treatment simulation outcomes should consider classification on the basis of the presence of certain speech features in a habitual speech condition. It seems possible that approach may present a way forward in the examination of speech treatment outcomes.

The second component of this analysis investigated whether older and younger listeners would exhibit differential outcomes based on dysarthria type and speech condition. Findings revealed that older listeners exhibited a significantly reduced ability to comprehend dysarthric speech relative to younger listeners. However, this was a generalized dampening down of performance; different speech conditions or dysarthria types did not differentially affect older listeners relative to younger listeners. In this study, the older listeners exhibited a range of hearing profiles, but all listeners were able to adjust the listening level to a comfortable level. Even with the ability to adjust the listening level, older listeners still exhibited reduced performance relative to younger listeners. These findings add to prior literature indicating that older listeners have greater difficulty understanding speech of individuals with dysarthria relative to younger listeners (e.g., Dagenais et al., 2011; Garcia & Hayden, 1999; Jones et al., 2004). It is highly likely that hearing thresholds contributed directly to performance—hearing acuity generally accounts for the majority of variance in perception in older listeners (Akeroyd, 2008). However, the cognitive function (e.g., Benichov, Cox, Tun, & Wingfield, 2012) and vocabulary knowledge (e.g., McAuliffe et al., 2013) of listeners are also likely to have affected performance.

It should also be noted that the current study used semantically anomalous phrases for the perception experiment. Older listeners have been shown to exhibit reliance on semantic and contextual information in difficult listening conditions (Pichora-Fuller, Schneider, & Daneman, 1995; Sheldon, Pichora-Fuller, & Schneider, 2008; Sommers & Danielson, 1999). Hence, our approach meant that older listeners did not receive benefit from semantic predictability. As a result, this may have exacerbated the difficulties of the older listeners in comprehending dysarthric speech. Follow-up studies that examine the relative contributions of hearing and cognition to the older listeners' performance are warranted. Furthermore, examination of the relative benefits of semantically predictable information or conversational speech in younger and older listeners may also prove fruitful.

A by-product of our primary statistical analysis was the finding that older listeners were slower in their perceptual learning across the first half of the experiment relative to younger listeners. It has previously been demonstrated that older listeners were slower to adapt to time-compressed speech in the early phases of a perception trial (Peelle & Wingfield, 2005). Although the clinical implications of this particular finding are minimal, learning across the course of the experiment is a feature of experiments of this type. We suggest that future studies should also attempt to control for the effects of learning in both design and/or statistical analysis.

The third component of this study examined the relationship between individual speaker's intelligibility outcomes and their change in various acoustic variables across the two conditions. Through careful stimulus selection, we ensured that all speakers made the requested speech modifications. That is, each participant produced speech with greater intensity in the loud condition and with a reduced speech rate in the slow condition (see Table 4). Despite this, and as shown in Figure 1, the loud and slow speech enacted by different participants did not result in homogenous changes to listeners' ability to comprehend speech.

To investigate further, we examined which acoustic indices were most strongly correlated with intelligibility improvement across the speaker group. From this analysis, it appeared that the amount speakers changed their vocal intensity or speech rate was unrelated to their degree of intelligibility change. Similarly, measures of speech rhythm accounted for very little variance in intelligibility outcomes. However, distinctiveness of vowel production, as shown by lower FCR values, was strongly associated with a positive change to intelligibility. The finding of a relationship between vowel space and intelligibility is consistent with other reports (e.g., Lansford & Liss, 2014). In the current study, changes to the FCR following speech modification accounted for 63% of variance in speakers' intelligibility improvement. The decrease in FCR values that many speakers experienced following cues to speak louder or reduce speech rate indicated that their formant values became more clearly separated across the three vowels. This likely reflected greater movements of the tongue and jaw during vowel production, suggestive of improved articulation.

Although the number of participants in this data set was small, it appeared that degree of increase in vocal intensity or reduction in speech rate were not the primary indicators of improved intelligibility. Instead, the greatest improvement in intelligibility was associated with speech conditions that promoted enhanced articulatory distinctiveness. Follow-up research is needed to determine if this finding holds across a larger data set. However, it does raise the question of what our therapy targets should be—and suggests that clear pronunciation in a loud or slow condition may be more important than the degree of change to vocal intensity or speech rate achieved by a speaker.

In summary, the current study found that a loud speech cue produced significant improvements in listeners' ability to comprehend dysarthric speech, but the slow condition did not. Dysarthria subtype did not play a role in outcomes—neither dysarthria subtype produced differential gains through one condition over another. Older listeners exhibited significantly reduced ability to comprehend dysarthric speech relative to younger listeners, but differential effects by speech condition or dysarthria type were not observed. The current study served to highlight the degree of individual variation in intelligibility outcomes associated with the two speech cues. It appeared that speakers' degree of intelligibility improvement was not related to the change in intensity or reduction in speech rate that the cuing conditions induced. Instead, a clear relationship between degree of vowel distinctiveness and increases in intelligibility was observed.

This study was limited by the small number of speaker participants. In addition, it reflects the results of stimulability, not treatment effects themselves. However, the analyses suggest that a "one-size-fits-all" approach to behavioral speech modification is not conducive to optimized intelligibility outcomes. Instead, it appears that speech modification that results in enhanced vowel space/articulatory distinctiveness may produce the greatest intelligibility gains for speakers with dysarthria. Future studies that include larger numbers of speakers with dysarthria (with greater variation in etiology and, perhaps most importantly, a greater range of salient speech features) are required to investigate why some participants exhibit marked improvement in certain conditions whereas others do not. Ideally, we suggest that studies should aim to predict the outcomes of various behavioral speech cues on the basis of a speaker's habitual speech profile.

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