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From Speech Acoustics to Communicative Participation in Dysarthria: Toward a Causal Framework

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ABSTRACT

Purpose: We proposed and tested a causal instantiation of the World Health Organization's International Classification of Functioning, Disability and Health (ICF) framework, linking acoustics, intelligibility, and communicative participation in the context of dysarthria.
Method: Speech samples and communicative participation scores were collected from individuals with dysarthria (n = 32). Speech was analyzed for two acoustic metrics (i.e., articulatory precision and speech rate), and an objective measure of intelligibility was generated from listener transcripts. Mediation analysis was used to evaluate pathways of effect between acoustics, intelligibility, and communicative participation.
Results: We observed a strong relationship between articulatory precision and intelligibility and a moderate relationship between intelligibility and communicative participation. Collectively, data supported a significant relationship between articulatory precision and communicative participation, which was almost entirely mediated through intelligibility. These relationships were not significant when speech rate was specified as the acoustic variable of interest.
Conclusion: The statistical corroboration of our causal instantiation of the ICF framework with articulatory acoustics affords important support toward the development of a comprehensive causal framework to understand and, ultimately, address restricted communicative participation in dysarthria.

The neurological speech disorder of dysarthria manifests in degraded speech acoustics (e.g., H. Kim et al., 2011; Liss et al., 2009) and, often, impaired intelligibility (e.g., Dykstra et al., 2007; Weismer et al., 2001). More recently, dysarthria has been (and continues to be) associated with restrictions in communicative participation (e.g., Dickson et al., 2008; Walshe & Miller, 2011). This multidimensional experience of dysarthria can be framed within the World Health Organization's International Classification of Functioning, Disability and Health (WHO ICF) framework, which specifies co-consideration of body structures or functions (e.g., compromised articulator movement and associated degraded speech acoustics), activities (e.g., impaired intelligibility), and communicative participation (e.g., restricted engagement in communication interactions), and also takes into account relevant contextual factors (WHO, 2001). The ICF framework posits interdependence and associations between all dimensions of health, and these assumptions have extended to the clinical management of dysarthria, where maximizing communicative participation is considered the ultimate, overarching goal.

In the dysarthria literature, there is a (relatively) rich body of literature examining relationships between speech acoustics and intelligibility, with the evidence collectively revealing that some acoustics predict intelligibility more robustly than others (e.g., Fletcher et al., 2017; Kent et al.,

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1989; H. Kim et al., 2011; Liu et al., 2005; Weismer & Martin, 1992; Weismer et al., 2000; Yorkston & Beukelman, 1981). However, studies linking both acoustics and intelligibility to communicative participation are sparse. To our knowledge, a single study has examined whether an acoustic feature tracks with communicative participation. Dykstra et al. (2015) found no significant correlation between habitual speech intensity and communicative effectiveness in individuals with hypophonia and Parkinson's disease (PD). Recently, a few studies have reported a positive relationship between intelligibility and communicative participation in populations with dysarthria, including PD (Barnish et al., 2017; Spencer et al., 2020) and amyotrophic lateral sclerosis (Sixt Börjesson et al., 2021). More research is needed to substantiate these preliminary findings. The lack of studies examining the potential impact of speech acoustics and intelligibility on communicative participation in dysarthria is problematic. Clinical management of dysarthria is primarily focused on addressing speech subsystem impairment (e.g., articulation and phonation) and/or intelligibility deficits (Collis & Bloch, 2012; Miller & Bloch, 2017; see also Duffy, 2020). As Baylor and Darling-White comment, "clinicians certainly hope that improvements in these areas will generalize to improvements in life participation" (2020, p. 1337). Yet, there is minimal evidence that these traditional intervention targets influence communicative participation outcomes.

Toward a Causal Framework of Participation in Dysarthria

To rigorously test associations between acoustics, intelligibility, and communicative participation in persons with dysarthria, we propose an entry-level causal instantiation of the ICF framework. This instantiation is based on directed acyclic graphs as used in the causal inference literature across many other fields (e.g., Pearl, 2009; Suzuki et al., 2020; Williams et al., 2018) and is also commonly found in the mediation modeling literature (e.g., Hayes, 2017; MacKinnon et al., 2012). Our proposed instantiation is illustrated in Figure 1. Here, the solid lines represent paths of interest: The *a*-path represents the effect of acoustics on intelligibility, and the *b*-path represents the effect of intelligibility on communicative participation. Taken together, these represent the indirect path between acoustics and communicative participation through intelligibility. The *c*-path represents the direct path between acoustics and communicative participation (i.e., the effect independent of intelligibility). Furthermore, as represented by the dashed line, we control for relevant contextual factors that may confound our three primary variables of interest. As aforementioned, existing literature has established positive relationships between acoustics and intelligibility in speakers with dysarthria and, to a much lesser extent, intelligibility and communicative participation. Novel here is the collective consideration of all three dysarthria dimensions into one holistic causal instantiation.

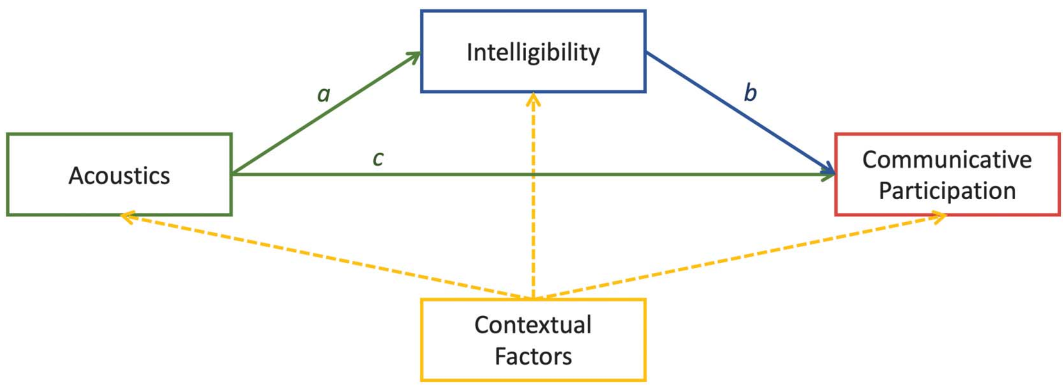
A causal instantiation of the ICF framework as it relates to the multidimensional experience of dysarthria affords important contributions. First, it is transparent about the assumptions of which variables are relevant and important, utilizing those informed by theory and existing empirical evidence. This allows for subsequent studies to highlight additional variables that are relevant to the relationships of interest that may afford greater statistical control. Second, the direction of each relationship is made explicit, allowing for the debate of alternate possibilities (if any). Third, the conceptual instantiation naturally informs the modeling approach, which inherently leads to statistical estimates that are more likely to represent reality.

Finally, if statistically corroborated, this instantiation yields high clinical application, key being that it would allow for the use of counterfactual reasoning to evaluate the downstream impact of current treatment targets (e.g., improving articulation and/or intelligibility) on communicative participation. Given the consequences that restrictions in communicative participation can have on individual well-being, including social isolation, loss of employment, and challenges in accessing services (e.g., Eadie et al., 2006; Walshe & Miller, 2011), there is rapidly growing awareness that dysarthria management must facilitate (directly or indirectly) improvements in the participatory aspects of communication (e.g., Brady et al., 2011; Yorkston, Baylor, & Britton, 2017).

This Study

In this study, we test our proposed causal instantiation of the ICF framework within the context of dysarthria. In the initial testing of this instantiation, we address a fundamental research question: What is the relationship between habitual acoustics, intelligibility, and communicative participation? To empirically test this, we use two models examining different acoustic measures: articulatory precision and speech rate. Articulatory precision was selected because there is ample evidence that acoustic metrics that capture articulatory behavior have important and robust contributions to the intelligibility of speakers with dysarthria (e.g., Fletcher et al., 2017; Kent et al., 1989; H. Kim et al., 2011; Y. Kim et al., 2009; Liu et al., 2005; Weismer & Martin, 1992; Weismer et al., 2001). Thus, we hypothesized that articulatory precision would predict communicative participation and that this relationship will be primarily mediated through its relationship with intelligibility. Habitual speech rate, on the other hand, has not been robustly associated with intelligibility of speakers with dysarthria (Barnish et al., 2017; Yorkston & Beukelman, 1981). Furthermore, related speech rate manipulation literature has yielded inconclusive findings regarding intelligibility outcomes associated with explicit rate changes (e.g.,

Figure 1. Entry-level causal instantiation of the International Classification of Functioning, Disability and Health framework, linking acoustics, intelligibility, and communicative participation in the context of dysarthria. The solid lines represent paths of interest. The dashed lines represent paths controlled for within the model.



Kuo et al., 2014; McAuliffe et al., 2017; Weismer et al., 2000; Yorkston et al., 1990). Thus, we hypothesized that speech rate would not predict our functional communication outcomes. Testing a metric like speech rate, which is not expected to conform to model expectations, affords additional insight into the utility of the proposed causal instantiation, highlighting the significance of utilizing suitably motivated acoustic variables in such designs. In both models, we control for contextual factors of age, gender, and cognition, given prior evidence that these person parameters may (or may not) influence acoustics, intelligibility, and/or communicative participation (e.g., Barnish et al., 2017; McAuliffe et al., 2017; Spencer et al., 2020). Although our study was not designed to explicitly examine paths of effect between contextual factors and the three primary dimensions of dysarthria, including them as control variables increases the objectivity of the statistical models. The acoustic metric of articulatory precision used here is relatively novel, quantifying the match between the expected and observed spectral acoustics for phoneme productions (Stegmann et al., 2020). Accordingly, the measure affords a more gestalt (and automated) representation of articulation relative to the traditional (and largely manual) vowel-based measures. Certainly, the automated articulatory precision metric is entirely novel in terms of its relationship with intelligibility. As such, a secondary contribution of this study is a validation of the measure of articulatory precision relative to the listeners' ability to understand speakers with dysarthria.

Method

Overview

Data for this study were collected as part of a larger study examining speech of individuals with dysarthria. There were two phases to the data collection: speaker phase and listener phase. The speaker phase involved eliciting speech stimuli from individuals with dysarthria and analyzing the speech signal for the acoustic measures of articulatory precision and speech rate. The listener phase involved obtaining orthographic transcripts of the dysarthric speech stimuli from neurotypical listeners and analyzing the transcripts for an objective measure of intelligibility: percent words correct (PWC). These phases are discussed in detail below. This data collection method was approved by Utah State University (USU) Institutional Review Board.

Speaker Phase

Speaker Participants

Thirty-two speakers (22 males; 10 females) between the ages of 32 and 89 years (M = 68, SD = 12) participated in the study. All speakers were native speakers of American English with a diagnosis of dysarthria ranging from mild to severe. Perceptual classification of severity and dysarthria subtype designations were made by two experienced speech-language pathologists via consensus judgments. Table 1 reports the speakers' demographic and diagnosis details, including medical etiology. If cognitive or language disorders prevented individuals from independently reading aloud written text or providing answers regarding communicative participation, the individual was excluded from the study. Based on that exclusion criterion, one potential participant was excluded from the study. Speaker participants were recruited from a Utah-based rehabilitation hospital and community-based neurological disease and injury support groups.

Speaker Procedure

Speech Stimuli

The speech stimuli used in this study were elicited using "The Caterpillar" passage, a contextual passage

Table 1. Demographic and diagnosis information of speakers with dysarthria.

Sex	Age (years)	Medical etiology	Dysarthria severity	Dysarthria subtype
M	41	Brain tumor	Moderate	Ataxic
F	32	Brain tumor	Moderate	Ataxic
M	70	Multiple sclerosis	Mild–moderate	Mixed
M	67	Parkinson's disease	Mild	Hypokinetic
M	77	Parkinson's disease	Mild	Hypokinetic
F	70	Parkinson's disease	Mild	Hypokinetic
M	77	Parkinson's disease	Mild	Hypokinetic
F	63	Parkinson's disease	Mild	Hypokinetic
F	61	Parkinson's disease	Mild	Hypokinetic
F	75	Parkinson's disease	Mild	Hypokinetic
M	86	Parkinson's disease	Mild–moderate	Hypokinetic
M	59	Parkinson's disease	Mild–moderate	Hypokinetic
M	70	Parkinson's disease	Mild–moderate	Hypokinetic
M	68	Parkinson's disease	Mild–moderate	Hypokinetic
M	64	Parkinson's disease	Mild–moderate	Hypokinetic
M	80	Parkinson's disease	Moderate	Hypokinetic
M	66	Parkinson's disease	Moderate	Hypokinetic
M	74	Parkinson's disease	Moderate	Hypokinetic
M	67	Parkinson's disease	Moderate	Hypokinetic
M	68	Parkinson's disease	Severe	Hypokinetic
M	71	Parkinson's disease	Severe	Hypokinetic
M	58	Stroke	Mild	Mixed
F	70	Stroke	Mild	Spastic
M	72	Stroke	Mild–moderate	Mixed
M	89	Stroke	Moderate	Mixed
M	59	Stroke	Moderate	Ataxic
M	71	Stroke	Moderate–severe	Ataxic
F	73	Stroke	Moderate–severe	Mixed
F	88	Stroke	Moderate	Mixed
F	57	Stroke	Severe	Mixed
M	50	Traumatic brain injury	Severe	Mixed
F	71	Undetermined	Mild	Hypokinetic

Note. M = male; F = female.

explicitly designed to inform the assessment of motor speech disorders (Patel et al., 2013). The passage consists of 16 sentences of varying length, sampling the entire phonetic repertoire. Contemporary vocabulary and simple syntax are used to minimize cognitive load. The sentence stimuli were presented, one at a time, via a computer monitor, and speakers were instructed to read the sentence aloud in their everyday speaking voice. Digital recordings of the sentence productions were made via a lavalier cardioid microphone positioned approximately 10 cm from the speakers' mouth with a sampling rate of 48 kHz and 16 bits of quantization. All speaker participants read and produced the sentence stimuli independently.

Additional Assessments

Speaker participants also completed two standardized assessments to obtain measures of cognition and communicative participation. Assessments were administrated using standard administration procedures. Cognition was assessed with the Montreal Cognitive Assessment (Nasreddine et al., 2005). This brief cognitive screening tool consists of a 30-point test with lower outcome scores indicating greater cognitive impairment.

Communicative participation was assessed using the General Short Form of the Communication Participation Item Bank (CPIB; Baylor et al., 2013). This patient-reported outcome instrument has participants score the extent to which their condition interferes with participation in 10 speaking situations. There are four scoring options: *Not at all* = 3, *A little* = 2, *Quite a bit* = 1, *Very much* = 0. As per the administration guidelines of Baylor et al. (2013), participants had to score the items themselves. However, if required, participants could have someone else read the situations and mark scores on the assessment form. Scores across the 10 items were summed to obtain a summary score, ranging from 0 to 30. The summary score was converted to a T-score (M = 50, SD = 10; Baylor et al., 2013). The range of possible T-scores on the general short form is 24.20–71.00. The higher the T-score, the less one perceives that their condition interferes with their ability to participate and engage in everyday speaking situations.

Acoustic Measures

Signal Preprocessing

A trained research assistant manually created TextGrids for the 511 sentence productions (16 sentences[1] from 32 speaker participants) using Praat (Boersma & Weenink, 2020). These TextGrids identified start/stop boundaries of the sentence production and included an orthographic transcript of what the speaker was saying. For use in the articulatory precision measure, sentences longer than 14 words were divided at natural breaking points into shorter speech segments. Although the sentences were elicited using the Caterpillar passage and thus predetermined targets were specified, the orthographic transcripts detailed any syllable repetition and word substitutions, ensuring accurate acoustic and perceptual analyses.

Articulatory Precision

Articulatory precision is measured as the match between the expected and observed acoustic features for phoneme productions (Borrie et al., 2020; Lubold et al., 2021; Stegmann et al., 2020; Tu et al., 2018). The automated precision algorithm assesses how well the spectral acoustics (represented by mel-frequency cepstral coefficients) of each observed phoneme correspond to the spectral acoustics of the expected phoneme as represented in a normative speech sample. To establish acoustic targets from the normative speech samples, we trained an acoustic model that learns acoustic representations of phonemes in context. Specifically, we trained a triphone model that considers the target phoneme in the context of all preceding and following phonemes. The acoustic features associated with the phoneme are encoded in the neural network. This model was trained using a publicly available corpus (approximately 1,000 hr) of read American English speech (Panayotov et al., 2015). When a new sample is provided as an input into the neural network, it produces a likelihood score of the observed phoneme and the expected phoneme. The ratio between the two quantities serves as a proxy for articulatory precision. The presumption here is that the more similar the dysarthric speaker's phonemes are to the expected phonemes of neurotypical speakers, the more precisely they were produced. Thus, a score of 0 represents precise speech, whereas negative scores reflect imprecise articulation, deviating from the expected neurotypical acoustic model. The articulatory precision scores for each phoneme and each segment were averaged across all segments produced by a speaker, resulting in one articulatory precision score per participant.

[1]Due to a recording malfunction, one sentence was missing from one of the participants. Thus, for that single speaker, only 15 sentence productions could be used for data analyses.

Speech Rate

Speech rate was measured as syllables per second. To generate this measure, the number of syllables for each sentence was identified from the orthographic transcripts, and the duration of each sentence was identified using the start/stop boundaries detailed in the TextGrids. The number of syllables per sentence was then divided by sentence duration. The speech rate scores for each sentence were averaged across all sentences produced by a speaker, resulting in one speech rate score per participant.

Listener Phase

Listener Participants

Listener transcripts were taken from a larger data set involving 192 listeners (46 males; 146 females) between the ages of 19 and 64 years (M = 24, SD = 8). All listener participants were native speakers of American English. Inclusion criteria required that listener participants had no prior experience with individuals with motor speech disorders (see Borrie et al., 2021, for empirical data on the influence of prior experience) and no past or present hearing impairment, as per self-disclosure. Listener participants were recruited from the student population at USU.

Listener Procedure

Interested listener participants were given a study weblink, directing them to a speech perception task hosted on a university-based web server.[2] After completing a short demographic survey, listeners were informed that they would be presented with sentences produced by adult speakers with an acquired speech disorder and that their task was to listen to each sentence and type out what they thought was being said. Participants could only listen to each sentence once but could take as much time as necessary to type their responses. The task was designed so that each listener heard 16 randomly ordered sentences, each a different sentence of the Caterpillar passage, and each produced by a randomly selected speaker with dysarthria. This randomization procedure reduced the confounding factors of two important variables: listener familiarity with a specific speaker with dysarthria (see Borrie & Lansford, 2021, for a comprehensive review) and individual variability in understanding dysarthric speech (e.g., Borrie, Baese-Berk, et al., 2017; Ingvalson et al., 2017). On average, this task took 10 min for listeners to complete.

Intelligibility Measure

Intelligibility is measured as PWC. Listener transcripts for each of the 511 sentences were scored using

[2]We have previously reported on the validity of online speech perception studies (Lansford et al., 2016).

Autoscore, an open-source, computer-based tool for automated scoring of orthographic transcripts (http://autoscore.usu.edu/; Borrie, Barrett, & Yoho, 2019).[3] We applied the same scoring rules used in previous studies of perception of dysarthric speech. Words were scored as correct if they matched the intended target exactly or differed only by tense or plurality. Homophones and obvious spelling errors were scored as correct using a preprogrammed default list of common misspellings. A PWC score for each speaker participant was tabulated by summing words correct from listener transcripts of all 16 sentences of the passage and dividing by the total number of words. Thus, each speaker's intelligibility score reflects a rigorous and robust intelligibility metric contributed by 16 different listeners.

Statistical Analysis

Using the causal instantiation of the ICF framework as our guide (see Figure 1), mediation analyses (a specific form of path analyses) were used to evaluate relationships between articulatory precision, intelligibility, and communicative participation. Mediation analysis allows us to estimate effects from one variable (articulatory precision) on an outcome (communicative participation) through an intermediate variable (intelligibility). The complete mediation model is built of a series of multiple regression models (Hayes, 2017, 2018) as expressed below:

$$Participation_i = b_0 + b_1 \times Intelligibility_i + \sum_{j=1} b_j \times covariate_{ji} + \epsilon_i, \quad \text{path } b \text{ model,} \tag{1}$$

$$Intelligibility_i = a_0 + a_1 \times Precision_i + \sum_{j=1} a_j \times covariate_{ji} + \lambda_i, \quad \text{path } a \text{ model,} \tag{2}$$

where a_1 is the estimate for the a-path and b_1 is the estimate for the b-path. This provides an estimate of how articulatory precision predicts changes in communicative participation through its hypothesized effect on intelligibility scores. Both regression models include the relevant control variables as covariates (i.e., age, gender, and cognition). By controlling for these, we are accounting for the possible confounding produced by these three variables in the overall model. When combined, the two regression models form the complete statistical form of the causal instantiation. This can be expressed in the "reduced form" of the regression by substituting the right-hand side of the path a model into the path b model:

$$Participation_i = b_0 + b_1 \times \left(a_0 + a_1 \times Precision_i + \sum_{j=1} a_j \times covariate_{ji} + \lambda_i \right) + \sum_{j=1} b_j \times covariate_{ji} + \epsilon_i \tag{3}$$

This reduced form shows that it is ultimately testing how articulatory precision impacts communicative participation through its effect on intelligibility (the "indirect effect"). As such, this specification (using mediation analyses) is able to estimate the effects of interest.

Notably, as shown in the path b model equation, we did not include articulatory precision (the path labeled c in Figure 1) in the path b model. This adjustment was due to statistical limitations caused by the extremely high correlation between articulatory precision and intelligibility. That is, the collinearity made it impossible to estimate the b-path with any accuracy when including articulatory precision within the model. Arguably, its exclusion in the path b model is necessary since any interpretation about the effect of intelligibility on communicative participation, holding articulatory precision constant, is, in essence, not meaningful. As such, estimation of the indirect effect (a x b) as generally defined in mediation analysis was not possible in these data. Instead, we report the individual paths and discuss the total effect of articulatory precision on communicative participation.

In addition, a second mediation analysis was run with speech rate to compare the findings of the initial mediation analysis. Similar to the mediation analysis with articulatory precision, this analysis has speech rate predicting intelligibility, which then predicts communicative participation. Unlike in the previous mediation analysis, there is no high collinearity between speech rate and intelligibility. As such, speech rate was also included in the path b model, and estimates were made of the indirect effect (a x b) and the direct effect of speech rate on communicative participation.

All analyses were performed in the R statistical environment (R Version 4.0.3; R Development Core Team, 2020). Data cleaning and visualization relied on the rio, tidyverse, and ggdist packages (Kay, 2021; Wickham et al., 2019). Statistical analyses relied on the furniture, lme4, lmerTest, and lavaan packages (Barrett & Brignone, 2017; Bates et al., 2015; Chan et al., 2021; Kuznetsova et al., 2017; Rosseel, 2012). All p values reported in conjunction with estimates of effect are based on Satterthwaite approximation to degrees of freedom.

Results

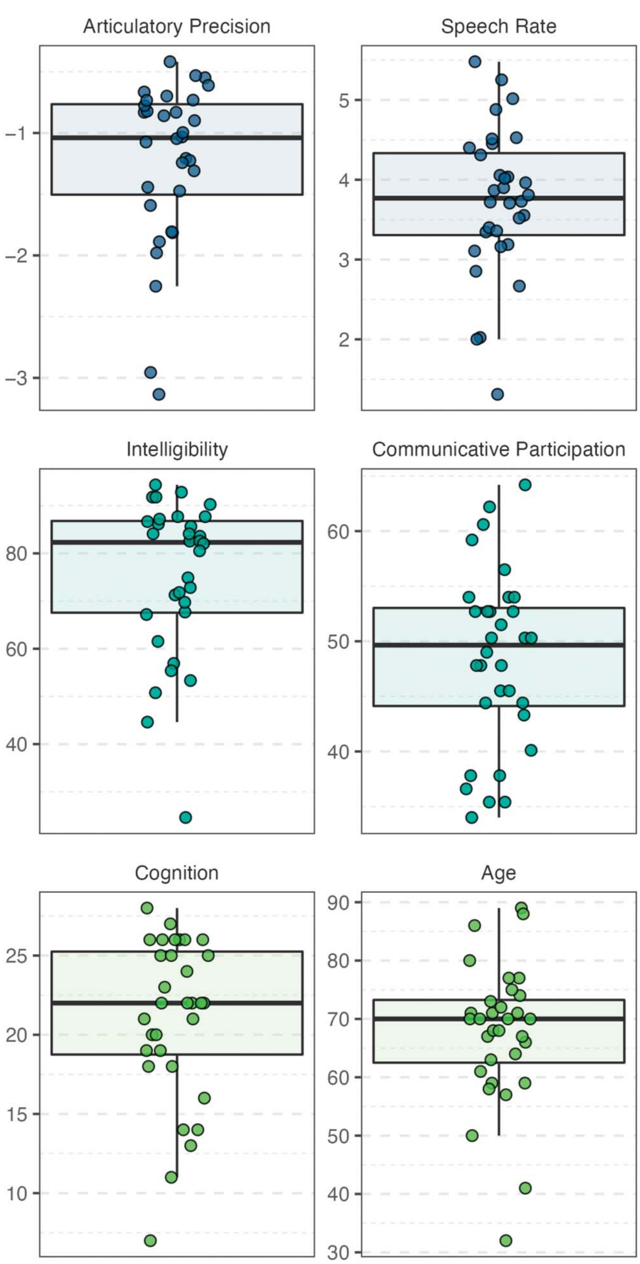
Descriptive Data

The mediation analyses described below included seven variables: articulatory precision (M = −1.2, SD = 0.7), speech

[3]The accuracy of Autoscore relative to human scorers has been rigorously validated (Borrie et al., 2019).

rate (M = 3.7, SD = 0.9), intelligibility (M = 75.1, SD = 16.4), communicative participation (M = 48.5, SD = 8.1), cognition (M = 21.1, SD = 5.1), age, and gender. Figure 2 provides details of the distribution of these variables. Pearson correlation coefficients (only $r > \pm .2$) between each variable are reported in Figure 3.

Figure 2. Distributions of the continuous variables used in this study. Each point is an observed value (jittered). "Articulatory precision" was measured as the match between the expected and observed acoustic features for phoneme productions, "speech rate" was measured as syllables per second, "intelligibility" was measured as percent words correct, "communicative participation" was measured as T-scores on the Communicative Participation Item Bank, "cognition" was measured as raw scores on the Montreal Cognitive Assessment score, and "age" was measured in years.



Articulatory Precision

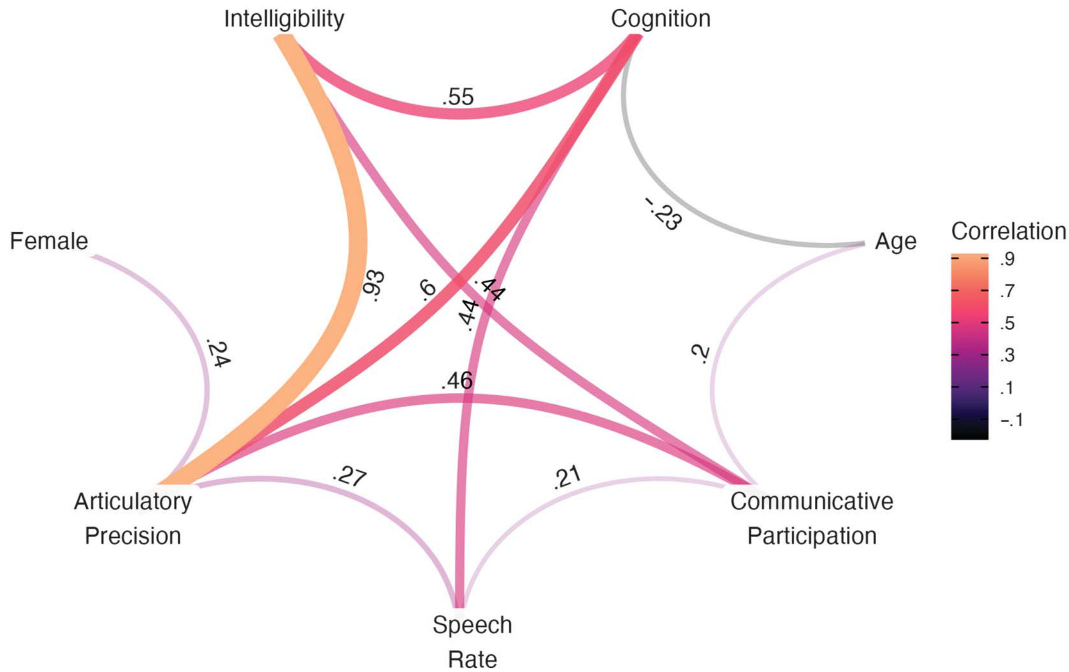
Multiple linear regression models were used to examine the relationship between articulatory precision, intelligibility, and communicative participation. Our first model explored path *a*, in which intelligibility is the dependent variable and articulatory precision is the primary predictor. Age, gender, and cognition were included as control variables. As indicated in Table 2, results show that intelligibility is significantly predicted by articulatory precision (b = 24, p < .001). This suggests that a 1-unit improvement in articulatory precision translates to a 24-percentage-point improvement in intelligibility. Furthermore, as illustrated in Figure 3, Pearson correlation analysis indicated a large effect size between the two variables (r = .93, p < .001; see also Figure 4). Thus, precision is predictive of and highly correlated with intelligibility.

In the next regression model, we examined path *b,* in which communicative participation is the dependent variable and intelligibility is the primary predictor. Age, gender, and cognition were again included as control variables. As indicated in Table 3, findings show that communicative participation is significantly predicted by intelligibility (b = .26, p = < .001). This suggests that approximately a 4-percentage-point improvement in intelligibility translates to a 1-unit improvement in communicative participation. As illustrated in Figure 3, Pearson correlation analysis shows a moderate effect size between the two variables (r = .44, p = .01).

Taken together, the path *a* and path *b* models describe a mediated relationship between articulatory precision and communicative participation. That is, much of the effect of articulatory precision on communicative participation appears to go through intelligibility. The high level of collinearity between articulatory precision and intelligibility leads to issues in estimating the indirect and direct relationships between precision and communicative participation with any degree of accuracy. Therefore, this analysis was not conducted. However, given the strong relationship between articulatory precision and intelligibility, it is likely that the relationship between articulatory precision and communicative participation is mostly or entirely mediated by intelligibility, and any direct relationship between these two variables, if present, is minimal.

Finally, we also note the total effect of articulatory precision on communicative participation. This was estimated in a separate regression model, still controlling for the same covariates, with communicative participation as the dependent variable and articulatory precision as the predictor of interest. Results of the model indicated a significant relationship between the two variables (b = 7.2,

Figure 3. Summary of correlations between each variable included in the analyses. Thicker lines represent stronger correlations between the variables connected by the line. Values represent the Pearson correlation between the connected variables. Only correlations larger than ± .2 are illustrated.



p = .007). This suggests that a 1-unit increase in articulatory precision translates to a 7.2-unit improvement in communicative participation, with much of this effect mediated through improved intelligibility. As illustrated in Figure 3, Pearson correlation analysis shows a moderate effect size between articulatory precision and communicative participation (r = .46, p = .01).

When collectively summarizing the results of the complete mediation analysis, our findings indicate that a 1-unit improvement in an acoustic metric of articulation (i.e., articulatory precision) results in a 24-percentage-point improvement in intelligibility (e.g., from 50% to 74% words correct), which results in a 6.2-unit improvement in communicative participation, as measured by CPIB scores. Notably, the remaining 0.9-unit increase (the difference between the 7.2-unit full effect and the 6.2-unit mediated effect) represents any effect that articulatory precision has on communicative participation that is unrelated to intelligibility. Given the high collinearity, it was not possible to statistically deconstruct this effect in more depth with any real precision. Importantly though, this shows that in this sample, 87.5% of the full effect of articulatory precision on communicative participation is mediated through intelligibility.

Table 2. Results of the path *a* regression model.

Variable	*b*	*SE*	z value	*p* value
Intercept	99.72	10.04	9.94	< .001***
Articulatory precision	24.00	2.01	11.97	< .001***
Age	0.06	0.06	0.96	.34
Gender	1.14	2.19	0.52	.60
Cognition	–0.06	0.30	–0.21	.84

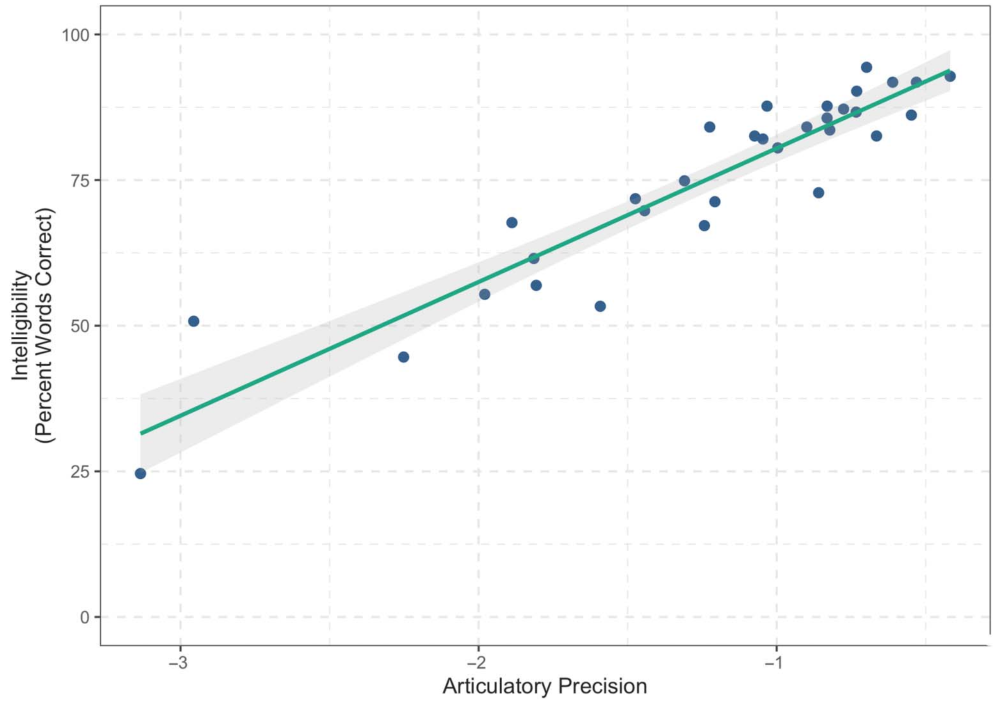
Note. *SE* = standard error.

***p < .001.

Speech Rate

A mediation analysis examining the relationships between speech rate, intelligibility, and communicative participation was also conducted. As before, the first model included intelligibility as the dependent variable and age, gender, and cognition as control variables. Here, speech rate was included as the primary predictor. Findings indicated that intelligibility was not significantly predicted by speech rate (b = −3.0, p = .41). Additionally, as shown in Figure 3, the raw correlation between speech rate and intelligibility is small and nonsignificant (r = .11, p = .55). In the second model, communicative participation was the outcome variable, and speech rate and intelligibility were the predictors. Again, age, gender, and cognition were included as control variables. The findings showed no significant relationship between communicative participation and speech rate (b = 2.10, p = .12), and the correlation between these two variables was small and nonsignificant

Figure 4. Scatter plot illustrating the strong positive relationship between articulatory precision and intelligibility.



($r = .21$, $p = .25$). Intelligibility was still predictive of communicative participation ($b = .27$, $p = .001$). Thus, the relationship between speech rate and communicative participation, either directly or indirectly through intelligibility, is not significant.

Discussion

The primary goal of this study was to test our proposed causal instantiation of the WHO ICF framework, in which we specify possible pathways of effect between acoustics, intelligibility, and communicative participation in dysarthria (controlling for age, gender, and cognition). In testing the initial association between acoustics and intelligibility, the results revealed that an automated acoustic measure of articulatory precision is significantly predictive of and highly correlated with intelligibility of persons with dysarthria. The relationship between degraded articulation and intelligibility impairment has been evidenced in prior studies employing more fine-grained acoustic measures of articulatory behavior such as vowel space area (e.g., Y. Kim et al., 2009; Weismer et al., 2001), spectral overlap degree among vowels (H. Kim et al., 2011), and formant centralization ratios (Fletcher et al., 2017). We add to that body of literature, extending the relationship to a more gestalt and automated measure of articulation, one that reflects clarity of phoneme production relative to an acoustic model target constructed from neurotypical speech.

Table 3. Results of the path *b* regression model.

Variable	*b*	*SE*	z value	*p* value
Intercept	25.69	12.54	2.05	.04*
Intelligibility	0.26	0.07	3.95	< .001***
Age	0.17	0.11	1.56	.12
Gender	−0.99	2.66	−0.37	.71
Cognition	−0.24	0.30	−0.79	.43

Note. *SE* = standard error.

*$p < .05$. ***$p < .001$.

Testing the complete model revealed that the acoustic measure of articulatory precision predicted communicative participation scores of persons with dysarthria, with the moderate relationship between the variables primarily mediated through intelligibility. Thus, we empirically validate our instantiation of the ICF framework in dysarthria. The relationship between intelligibility and communicative participation of persons with dysarthria has been previously identified (Barnish et al., 2017; Sixt Börjesson et al., 2021; Spencer et al., 2020). We thus confirm that relationship and further show that imprecise articulation also adversely impacts communicative participation (via its contribution to impaired intelligibility). As noted earlier, reduced communicative participation has been associated with a host of factors that negatively impact well-being (e.g., Eadie et al., 2006; Walshe &

Miller, 2011). As such, the need for intervention targets that support communicative participation has been well-recognized (see Baylor & Darling-White, 2020). Research on such targets in the context of a comprehensive causal framework will be necessary; however, the current findings afford some mechanistic support for possible communicative participation benefits following existing intervention approaches that aim to improve articulation and/or intelligibility in people with dysarthria.

Of further import is the strength of the predictive and correlative relationships between the metric of articulatory precision and intelligibility. The current findings suggest that this automated acoustic measure of articulatory precision may function as a proxy for intelligibility. Such a proxy benefits researchers and clinicians alike. There is mounting evidence that listeners vary widely in their ability to decipher speech, particularly in adverse listening conditions such as degraded speech (e.g., Borrie, Baese-Berk, et al., 2017; McLaughlin et al., 2018). Specific to the intelligibility of dysarthric speech, listener parameters such as age, vocabulary knowledge, and working memory likely play a meaningful role in the individual variability observed (Bent et al., 2016; Borrie, Lansford, & Barrett, 2017; Ingvalson et al., 2017; Lansford et al., 2018; Lee et al., 2014; McAuliffe et al., 2013). Additionally, prior experience, including clinical experience, with persons with dysarthria can significantly impact intelligibility scores (Borrie et al., 2021; Dagenais et al., 1999). With many listener parameters influencing intelligibility scores, the task of establishing speaker intelligibility can be inherently biased. To mitigate these issues, rigorous research and clinical evaluation of intelligibility of speakers with dysarthria should utilize designs and practices that draw from many listeners per speaker. However, achieving such rigor is both time consuming and resource intensive. An automated, objective measure that estimates speaker intelligibility without listener input affords a potential alternative solution. Continued validation of this gestalt metric of articulatory precision relative to intelligibility of dysarthric speech across a much larger and more heterogeneous cohort of speakers and dysarthria presentations, including varying prosodic presentations, should ensue.

When speech rate was specified as the acoustic variable of interest, the paths of effect between speech rate, intelligibility, and communicative participation were not significant. We hypothesized that the effect of acoustics on communicative participation would be primarily mediated through their effect on intelligibility. Thus, the absence of an association between speech rate and communicative participation here was not unexpected, given the current findings and previous (although notably scant) research reporting a nonsignificant relationship between habitual speech rate and intelligibility of dysarthric speech (Barnish et al., 2017; Yorkston & Beukelman, 1981). These findings do not negate the potential value that speech rate interventions may play in improving functional communication outcomes. A related body of literature has characterized intelligibility outcomes related to speech rate manipulations in speakers with dysarthria (e.g., Kuo et al., 2014; McAuliffe et al., 2017; Tjaden et al., 2014; Weismer et al., 2000; Yorkston et al., 1990). While aggregated group data have generally indicated no significant intelligibility benefits associated with explicit speech rate changes, under some circumstances, some individual speakers have been reported to produce more intelligible speech when prompted to speak at slower-than-habitual rates (e.g., Knowles et al., 2021; McAuliffe et al., 2017; Tjaden et al., 2014; Van Nuffelen et al., 2010). Such intelligibility changes for these individuals could then, in theory, influence communicative participation outcomes. However, in this study, we show that habitual speech rate was not significantly related (directly or indirectly) to communicative participation, which was in clear contrast to the articulatory precision results. Collectively, the study findings indicate that not all habitual acoustics exert the same influence on communicative participation in dysarthria.

Toward a Causal Framework: Limitations and Future Directions

The statistical corroboration of our instantiation of the ICF framework with an acoustic metric of articulation provides support toward the development of a theoretically informed, empirically situated causal framework to understand restricted communicative participation in dysarthria. We highlight the limitations of this study as critical discussion to move toward this type of comprehensive causal framework. Here, we targeted two acoustic measures: articulatory precision and speech rate. While measures of articulation have been revealed to contribute most strongly to intelligibility of dysarthric speech and measures of speech rate have not, other suitably motivated acoustic metrics that capture deviant speech features of dysarthria could be included in the model. Furthermore, the acoustic and intelligibility measures in this study were extracted from sentence productions of a reading passage elicited from speakers in a noninteractive context. However, communicative participation is a measure of performance in a social context which, by definition, includes more than one person and must involve a communicative exchange. Indeed, prior studies have confirmed that acoustic measures (including speech rate) and intelligibility of individuals with dysarthria, as measured in read sentences, changes in connected speech, and conversational settings (e.g., Barnish et al., 2017; Bunton & Keintz, 2008; Huber & Darling, 2011). Furthermore, preliminary findings suggest that intelligibility measures derived from more naturalistic speech tasks may be more sensitive to predicting the impact on communication participation (Spencer et al., 2020). Following interviews with community-dwelling adults with PD, Yorkston, Baylor, and Britton made an important distinction between *speech,* which is "the product of the production process," and *speaking,* which is "part of the active process of communication and cannot be separated from the social context" (2017, p. 567). As such, we advance that a causal framework to understand communicative participation in dysarthria should utilize measures from the *speaking* produced by individuals with dysarthria engaged in spoken dialogue. Relatedly, communicative participation scores, as quantified by the CPIB, are amalgamated from items relating to different speaking situations. As such, sampling speaking behaviors from various interactional contexts, including goal-oriented and rapport-building dialogue, with both familiar and unfamiliar communication partners, are warranted.

The need to consider the contribution of additional contextual factors in participation-focused frameworks has been recognized (Baylor & Darling-White, 2020). Indeed, there is a growing body of empirical data to support going beyond the measurement of acoustics and intelligibility to appreciate the complex construct of communicative participation fully. Studies examining self-report variables underpinning CPIB scores have revealed that, in addition to self-rated speech severity, self-rated measures of speech usage, speaking effort, fatigue, swallowing difficulties, cognitive and emotional problems, mental health, perceived social support, and resilience have been revealed as significant predictors of the variance in communicative participation (Jin et al., 2021; McAuliffe et al., 2017). Certainly, some of these self-report measures (e.g., speech usage and speaking effort) could be related to degraded acoustics and may function, like intelligibility, as mediators of the effect of acoustics on communicative participation. Indeed, the possible paths of influence with personal (e.g., personality and physical impairments) or environmental (e.g., support systems, attitudes, and policy) factors seem endless; however, a theoretically grounded causal framework developed and specified for dysarthria participation would enable systematic and hypothesis-driven investigations into the contextual factors that serve as facilitators of or barriers to communicative participation.

Furthermore, beyond the person with dysarthria, a most comprehensive causal framework of communicative participation should consider the speaking behaviors of the neurotypical communication partners. In an exploratory study utilizing the same automated measure of articulatory precision, Lubold et al. (2021) found that neurotypical communication partners engaged in significantly more precise speaking behavior when conversing with adults with dysarthria relative to other neurotypical adults. However, this hyperarticulated speaking behavior did not predict an objective measure of conversational success. The implications of this hyperarticulated speaking style exhibited by neurotypical communication partners on communicative participation for the communication partner with dysarthria have yet to be examined. However, studies examining the impact of elderspeak in conversations with older adults indicate that the infantilizing communication style is perceived as patronizing and can precipitate communication breakdowns (Kemper & Harden, 1999; Ryan et al., 1991). Thus, evidence supports the postulation that overly precise articulation exhibited by communication partners may adversely impact communicative participation outcomes. Crucially, the limiting factor in the complexity of a causal framework will be the size of the corpus. To advance this work and enable the statistical realization of a comprehensive causal framework communicative participation in dysarthria (which may or may not be impacted by unique dysarthria presentations), a much larger participant data set than utilized herein will be required.

Conclusions

In summary, this study has proposed and statistically corroborated a causal instantiation of the WHO ICF framework to understand and explain the paths of influence between the degraded acoustics, intelligibility impairment, and restricted communicative participation frequently experienced by individuals with dysarthria. We observed a moderate relationship between articulatory precision and communicative participation, which was almost entirely mediated through intelligibility. This finding was perhaps not surprising given the strong relationship between articulatory precision and intelligibility, suggesting that the automated acoustic metric of articulatory precision might be considered a proxy for intelligibility. The current findings provide important support and direction for the development of a comprehensive causal framework to advance understanding of restricted communicative participation in dysarthria and guide investigations of intervention targets that maximally support successful and satisfying communicative interactions for persons living with dysarthria, as well as their families, friends, and communities.

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References

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models Using lme4. *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Barrett, T. S., & Brignone, E. (2017). Furniture for quantitative scientists. *The R Journal, 9*(2), 142–148. https://doi.org/10.32614/RJ-2017-037

Barnish, M. S., Horton, S. M. C., Butterfint, Z. R., Clark, A. B., Atkinson, R. A., & Deane, K. H. O. (2017). Speech and communication in Parkinson's disease: A cross-sectional exploratory study in the UK. *BMJ Open, 7*(5), Article e014642. https://doi.org/10.1136/bmjopen-2016-014642

Baylor, C., & Darling-White, M. (2020). Achieving participation-focused intervention through shared decision making: Proposal of an age- and disorder-generic framework. *American Journal of Speech-Language Pathology, 29*(3), 1335–1360. https://doi.org/10.1044/2020_AJSLP-19-00043

Baylor, C., Yorkston, K., Eadie, T., Kim, J., Chung, H., & Amtmann, D. (2013). The Communicative Participation Item Bank (CPIB): Item bank calibration and development of a disorder-generic short form. *Journal of Speech, Language, and Hearing Research, 56*(4), 1190–1208. https://doi.org/10.1044/1092-4388(2012/12-0140)

Bent, T., Baese-Berk, M., Borrie, S. A., & McKee, M. (2016). Individual differences in the perception of regional, nonnative, and disordered speech varieties. *The Journal of the Acoustical Society of America, 140*(5), 3775–3786. https://doi.org/10.1121/1.4966677

Boersma, P., & Weenink, D. (2020). *Praat: Doing phonetics by computer* (Version 6.1) [Computer software]. http://www.praat.org

Borrie, S. A., Baese-Berk, M., Van Engen, K., & Bent, T. (2017). A relationship between processing speech in noise and dysarthric speech. *The Journal of the Acoustical Society of America, 141*(6), 4660–4667. https://doi.org/10.1121/1.4986746

Borrie, S. A., Barrett, T. S., & Yoho, S. E. (2019). Autoscore: An open-source automated tool for scoring listener perception of speech. *The Journal of the Acoustical Society of America, 145*(1), 392–399. https://doi.org/10.1121/1.5087276

Borrie, S. A., & Lansford, K. L. (2021). A perceptual learning approach for dysarthria remediation: An updated review. *Journal of Speech, Language, and Hearing Research, 64*(8), 3060–3073. https://doi.org/10.1044/2021_JSLHR-21-00012

Borrie, S. A., Lansford, K. L., & Barrett, T. S. (2017). Rhythm perception and its role in perception and learning of dysrhythmic speech. *Journal of Speech, Language, and Hearing Research, 60*(3), 561–570. https://doi.org/10.1044/2016_JSLHR-S-16-0094

Borrie, S. A., Lansford, K. L., & Barrett, T. S. (2021). A clinical advantage: Experience informs recognition and adaptation to a novel talker with dysarthria. *Journal of Speech, Language, and Hearing Research, 64*(5), 1503–1514. https://doi.org/10.1044/2021_JSLHR-20-00663

Borrie, S. A., Wynn, C. J., Berisha, V., Lubold, N., Willi, M. M., Coelho, C. A., & Barrett, T. S. (2020). Conversational coordination of articulation responds to context: A clinical test case with traumatic brain injury. *Journal of Speech, Language, and Hearing Research, 63*(8), 2567–2577. https://doi.org/10.1044/2020_JSLHR-20-00104

Brady, M. C., Clark, A. M., Dickson, S., Paton, G., & Barbour, R. S. (2011). Dysarthria following stroke: The patient's perspective on management and rehabilitation. *Clinical Rehabilitation, 25*(10), 935–952. https://doi.org/10.1177/0269215511405079

Bunton, K., & Keintz, C. K. (2008). The use of a dual-task paradigm for assessing speech intelligibility in clients with Parkinson disease. *Journal of Medical Speech-Language Pathology, 16*(3), 141–155.

Chan, C., Chan, G. C., Leeper, T. J., & Becker, J. (2021). *rio: A Swiss-army knife for data file I/O. R package version 0.5.26*.

Collis, J., & Bloch, S. (2012). Survey of UK speech and language therapists' assessment and treatment practices for people with progressive dysarthria. *International Journal of Language & Communication Disorders, 47*(6), 725–737. https://doi.org/10.1111/j.1460-6984.2012.00183.x

Dagenais, P. A., Brown, G. R., & Moore, R. E. (2006). Speech rate effects upon intelligibility and acceptability of dysarthric speech. *Clinical Linguistics & Phonetics, 20*(2–3), 141–148. https://doi.org/10.1080/02699200400026843

Dagenais, P. A., Watts, C. R., Turnage, L. M., & Kennedy, S. (1999). Intelligibility and acceptability of moderately dysarthric speech by three types of listeners. *Journal of Medical Speech-Language Pathology, 7,* 91–96.

Dickson, S., Barbour, R. S., Brady, M., Clark, A. M., & Paton, G. (2008). Patients' experiences of disruptions associated with post-stroke dysarthria. *International Journal of Language & Communication Disorders, 43*(2), 135–153. https://doi.org/10.1080/13682820701862228

Duffy, J. R. (2020). *Motor speech disorders: Substrates, differential diagnosis, and management* (4th ed.). Elsevier Mosby.

Dykstra, A. D., Adams, S. G., & Jog, M. (2015). Examining the relationship between speech intensity and self-rated communicative effectiveness in individuals with Parkinson's disease and hypophonia. *Journal of Communication Disorders, 56,* 103–112. https://doi.org/10.1016/j.jcomdis.2015.06.012

Dykstra, A. D., Hakel, M. E., & Adams, S. G. (2007). Application of the ICF in reduced speech intelligibility in dysarthria. *Seminars in Speech and Language, 28*(4), 301–311. https://doi.org/10.1055/s-2007-986527

Eadie, T. L., Yorkston, K. M., Klasner, E. R., Dudgeon, B. J., Deitz, J. C., Baylor, C. R., Miller, R. M., & Amtmann, D. (2006). Measuring communicative participation: A review of self-report instruments in speech-language pathology. *American Journal of Speech-Language Pathology, 15*(4), 307–320. https://doi.org/10.1044/1058-0360(2006/030)

Fletcher, A. R., McAuliffe, M. J., Lansford, K. L., & Liss, J. M. (2017). Assessing vowel centralization in dysarthria: A comparison of methods. *Journal of Speech, Language, and Hearing Research, 60*(2), 341–354. https://doi.org/10.1044/2016_JSLHR-S-15-0355

Hayes, A. F. (2017). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. Guilford Press.

Hayes, A. F. (2018). *Introduction to mediation, moderation, and conditional process analysis: A regression-based perspective* (2nd ed.). Guilford Press.

Huber, J. E., & Darling, M. (2011). Effect of Parkinson's disease on the production of structured and unstructured speaking tasks: Respiratory physiologic and linguistic considerations. *Journal of Speech, Language, and Hearing Research, 54*(1), 33–46. https://doi.org/10.1044/1092-4388(2010/09-0184)

Ingvalson, E. M., Lansford, K. L., Fedorova, V., & Fernandez, G. (2017). Cognitive factors as predictors of accented speech perception for younger and older adults. *The Journal of the Acoustical Society of America, 141*(6), 4652–4659. https://doi.org/10.1121/1.4986930

Jin, J. L., Baylor, C., & Yorkston, K. (2021). Predicting communicative participation in adults across communication disorders. *American Journal of Speech-Language Pathology, 30*(3S), 1301–1313. https://doi.org/10.1044/2020_AJSLP-20-00100

Kay, M. (2021). *ggdist: Visualizations of distributions and uncertainty*. R package version 3.0.0. https://doi.org/10.5281/zenodo.3879620
Kemper, S., & Harden, T. (1999). Experimentally disentangling what's beneficial about elderspeak from what's not. *Psychology and Aging, 14*(4), 656–670. https://doi.org/10.1037//0882-7974.14.4.656
Kent, R. D., Weismer, G., Kent, J. F., & Rosenbek, J. C. (1989). Toward phonetic intelligibility testing in dysarthria. *Journal of Speech and Hearing Disorders, 54*(4), 482–499. https://doi.org/10.1044/jshd.5404.482
Kim, H., Hasegawa-Johnson, M., & Perlman, A. (2011). Vowel contrast and speech intelligibility in dysarthria. *Folia Phoniatrica et Logopaedica, 63*(4), 187–194. https://doi.org/10.1159/000318881
Kim, Y., Weismer, G., Kent, R. D., & Duffy, J. R. (2009). Statistical models of F2 slope in relation to severity of dysarthria. *Folia Phoniatrica et Logopaedica, 61*(6), 329–335. https://doi.org/10.1159/000252849
Knowles, T., Adams, S. G., & Jog, M. (2021). Variation in speech intelligibility ratings as a function of speech rate modification in Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 64*(6), 1773–1793. https://doi.org/10.1044/2021_JSLHR-20-00593
Kuo, C., Tjaden, K., & Sussman, J. E. (2014). Acoustic and perceptual correlates of faster-than-habitual speech produced by speakers with Parkinson's disease and multiple sclerosis. *Journal of Communication Disorders, 52,* 156–169. https://doi.org/10.1016/j.jcomdis.2014.09.002
Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTestPackage: Tests in linear mixed effects models. *Journal of Statistical Software, 82*(13), 1–26. https://doi.org/10.18637/jss.v082.i13
Lansford, K. L., Borrie, S. A., & Bystricky, L. (2016). Use of crowdsourcing to assess the ecological validity of perceptual-training paradigms in dysarthria. *American Journal of Speech-Language Pathology, 25*(2), 233–239. https://doi.org/10.1044/2015_AJSLP-15-0059
Lansford, K. L., Luhrsen, S., Ingvalson, E. M., & Borrie, S. A. (2018). Effects of familiarization on intelligibility of dysarthric speech in older adults with and without hearing loss. *American Journal of Speech-Language Pathology, 27*(1), 91–98. https://doi.org/10.1044/2017_AJSLP-17-0090
Lee, Y., Sung, J. E., & Sim, H. (2014). Effects of listeners' working memory and noise on speech intelligibility in dysarthria. *Clinical Linguistics & Phonetics, 28*(10), 785–795. https://doi.org/10.3109/02699206.2014.904443
Liss, J. M., White, L., Mattys, S. L., Lansford, K., Lotto, A. J., Spitzer, S. M., & Caviness, J. N. (2009). Quantifying speech rhythm abnormalities in the dysarthrias. *Journal of Speech, Language, and Hearing Research, 52*(5), 1334–1352. https://doi.org/10.1044/1092-4388(2009/08-0208)
Liu, H.-M., Tsao, F.-M., & Kuhl, P. K. (2005). The effect of reduced vowel working space on speech intelligibility in Mandarin-speaking young adults with cerebral palsy. *The Journal of the Acoustical Society of America, 117*(6), 3879–3889. https://doi.org/10.1121/1.1898623
Lubold, N., Willi, M. M., Borrie, S. A., Barrett, T. S., & Berisha, V. (2021). Healthy communication partners modify their speech when conversing with individuals with Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 64*(5), 1539–1549. https://doi.org/10.1044/2021_JSLHR-20-00233
MacKinnon, D. P., Cheong, J., & Pirlott, A. G. (2012). Statistical mediation analysis. In H. Cooper, P. M. Camic, D. L. Long, A. T. Panter, D. Rindskopf, & K. J. Sher (Eds.), *APA handbooks in psychology. APA handbook of research methods in psychology, Vol. 2. Research designs: Quantitative, qualitative, neuropsychological, and biological* (pp. 313–331). American Psychological Association. https://doi.org/10.1037/13620-018
McAuliffe, M. J., Fletcher, A. R., Kerr, S. E., O'Beirne, G. A., & Anderson, T. (2017). Effect of dysarthria type, speaking condition, and listener age on speech intelligibility. *American Journal of Speech-Language Pathology, 26*(1), 113–123. https://doi.org/10.1044/2016_AJSLP-15-0182
McAuliffe, M. J., Gibson, E. M. R., Kerr, S. E., Anderson, T., & LaShell, P. J. (2013). Vocabulary influences older and younger listeners' processing of dysarthric speech. *The Journal of the Acoustical Society of America, 134*(2), 1358–1368. https://doi.org/10.1121/1.4812764
McLaughlin, D. J., Baese-Berk, M. M., Bent, T., Borrie, S. A., & Van Engen, K. J. (2018). Coping with adversity: Individual differences in the perception of noisy and accented speech. *Attention, Perception, & Psychophysics, 80*(6), 1559–1570. https://doi.org/10.3758/s13414-018-1537-4
Miller, N., & Bloch, S. (2017). A survey of speech-language therapy provision for people with post-stroke dysarthria in the UK. *International Journal of Language & Communication Disorders, 52*(6), 800–815. https://doi.org/10.1111/1460-6984.12316
Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society, 53*(4), 695–699. https://doi.org/10.1111/j.1532-5415.2005.53221.x
Panayotov, V., Chen, G., Povey, D., & Khudanpur, S. (2015). Librispeech: An ASR corpus based on public domain audio books. *Paper presented at the ICASSP, IEEE International Conference on Acoustics, Speech and Signal Processing Proceedings* (pp. 5206–5210).
Patel, R., Connaghan, K., Franco, D., Edsall, E., Forgit, D., Olsen, L., Ramage, L., Tyler, E., & Russell, S. (2013). "The Caterpillar": A novel reading passage for assessment of motor speech disorders. *American Journal of Speech-Language Pathology, 22*(1), 1–9. https://doi.org/10.1044/1058-0360(2012/11-0134)
Pearl, J. (2009). *Causality*. Cambridge University Press. https://doi.org/10.1017/CBO9780511803161
R Development Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/
Rosseel, Y. (2012). lavaan: An R package for structural equation modeling. *Journal of Statistical Software, 48*(2), 1–36. https://doi.org/10.18637/jss.v048.i02
Ryan, E. B., Bourhis, R. Y., & Knops, U. (1991). Evaluative perceptions of patronizing speech addressed to elders. *Psychology and Aging, 6*(3), 442–450. https://doi.org/10.1037/0882-7974.6.3.442
Sixt Börjesson, M., Hartelius, L., & Laakso, K. (2021). Communicative participation in people with amyotrophic lateral sclerosis. *Folia Phoniatrica et Logopaedica, 73*(2), 1–108. https://doi.org/10.1159/000505022
Spencer, K. A., Friedlander, C., & Brown, K. A. (2020). Predictors of health-related quality of life and communicative participation in individuals with dysarthria from Parkinson's disease. *International Journal of Neurodegenerative Disorders, 3*(1), Article 014. https://doi.org/10.23937/2643-4539/1710014
Stegmann, G. M., Hahn, S., Liss, J., Shefner, J., Rutkove, S., Shelton, K., Duncan, C. J., & Berisha, V. (2020). Early detection and tracking of bulbar changes in ALS via frequent and remote speech analysis. *npj Digital Medicine, 3*(1), Article 132. https://doi.org/10.1038/s41746-020-00335-x

Suzuki, E., Shinozaki, T., & Yamamoto, E. (2020). Causal diagrams: Pitfalls and tips. *Journal of Epidemiology, 30*(4), 153–162. https://doi.org/10.2188/jea.JE20190192

Tjaden, K., Sussman, J. E., & Wilding, G. E. (2014). Impact of clear, loud, and slow speech on scaled intelligibility and speech severity in Parkinson's disease and multiple sclerosis. *Journal of Speech, Language, and Hearing Research, 57*(3), 779–792. https://doi.org/10.1044/2014_JSLHR-S-12-0372

Tu, M., Grabek, A., Liss, J., & Berisha, V. (2018). Investigating the role of L1 in automatic pronunciation evaluation of L2 speech. *Proceedings of Interspeech, 2018,* 1636–1640. https://doi.org/10.21437/Interspeech.2018-1350

Van Nuffelen, G., De Bodt, M., Vanderwegen, J., Van de Heyning, P., & Wuyts, F. (2010). Effect of rate control on speech production and intelligibility in dysarthria. *Folia Phoniatrica et Logopaedica, 62*(3), 110–119. https://doi.org/10.1159/000287209

Walshe, M., & Miller, N. (2011). Living with acquired dysarthria: The speaker's perspective. *Disability and Rehabilitation, 33*(3), 195–203. https://doi.org/10.3109/09638288.2010.511685

Weismer, G., Jeng, J. Y., Laures, J. S., Kent, R. D., & Kent, J. F. (2001). Acoustic and intelligibility characteristics of sentence production in neurogenic speech disorders. *Folia Phoniatrica et Logopaedica, 53*(1), 1–18. https://doi.org/10.1159/000052649

Weismer, G., Laures, J. S., Jeng, J.-Y., Kent, R. D., & Kent, J. F. (2000). Effect of speaking rate manipulations on acoustic and perceptual aspects of the dysarthria in amyotrophic lateral sclerosis. *Folia Phoniatrica et Logopaedica*, 52(5), 201–219. https://doi.org/10.1159/000021536

Weismer, G., & Martin, R. E. (1992). Acoustic and perceptual approaches to the study of intelligibility. In R. D. Kent (Ed.), *Intelligibility in speech disorders: Theory, measurement and management* (pp. 68–118). John Benjamins. https://doi.org/10.1075/sspcl.1.04wei

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhm, M., Pedersen, T. L., Miller, E., Bache, S. M., Müller, K., Ooms, J., Robinson, D., Seidel, D. P., Spinu, V., . . . Yutani, H. (2019). Welcome to the tidyverse. *The Journal of Open Source Software, 4*(43), Article 1686. https://doi.org/10.21105/joss.01686

Williams, T. C., Bach, C. C., Matthiesen, N. B., Henriksen, T. B., & Gagliardi, L. (2018). Directed acyclic graphs: A tool for causal studies in paediatrics. *Pediatric Research, 84*(4), 487–493. https://doi.org/10.1038/s41390-018-0071-3

World Health Organization. (2001). *International Classification of Functioning, Disability and Health.* https://www.who.int/standards/classifications/international-classification-of-functioning-disability-and-health

Yorkston, K. M., Baylor, C., & Britton, D. (2017). Speech versus speaking: The experiences of people with Parkinson's disease and implications for intervention. *American Journal of Speech-Language Pathology, 26*(2S), 561–568. https://doi.org/10.1044/2017_AJSLP-16-0087

Yorkston, K. M., Baylor, C., & Mach, H. (2017). Factors associated with communicative participation in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research, 60*(6S), 1791–1797. https://doi.org/10.1044/2017_JSLHR-S-16-0206

Yorkston, K. M., & Beukelman, D. R. (1981). Communication efficiency of dysarthric speakers as measured by sentence intelligibility and speaking rate. *Journal of Speech and Hearing Disorders, 46*(3), 296–301. https://doi.org/10.1044/jshd.4603.296

Yorkston, K. M., Hammen, V. L., Beukelman, D. R., & Traynor, C. D. (1990). The effect of rate control on the intelligibility and naturalness of dysarthric speech. *Journal of Speech and Hearing Disorders, 55*(3), 550–560. https://doi.org/10.1044/jshd.5503.550