The association between longitudinal declines in speech sound accuracy and speech intelligibility in speakers with amyotrophic lateral sclerosis

Rowe, Hannah P., Ph.D., CCC-SLP[a], hrowe@mghihp.edu

Stipancic, Kaila L., Ph.D., CCC-SLP[b], klstip@buffalo.edu

Campbell, Thomas F., Ph.D., CCC-SLP[c], thomas.f.campbell@utdallas.edu

Yana, Yunusova, Ph.D., CCC-SLP[d,e,f], yana.yunusova@utoronto.ca

Green, Jordan R., Ph.D., CCC-SLP[a*], jgreen2@mghihp.edu

[a]*Department of Rehabilitation Sciences, MGH Institute of Health Professions, Boston, MA, USA*

[b]*Department of Communicative Disorders and Sciences, The State University of New York at Buffalo, Buffalo, NY, USA*

[c]*Callier Center for Communication Disorders, University of Texas at Dallas, Dallas, TX, USA*

[d]*Department of Speech-Language Pathology and Rehabilitation Sciences Institute, University of Toronto, Toronto, ON, Canada*

[e]*Hurvitz Brain Sciences Research Program, Sunnybrook Research Institute, Toronto, ON, Canada*

[f]*KITE – University Health Network, Toronto, ON, Canada*

Corresponding Author:
Hannah Rowe
hprowe@bu.edu
Department of Speech, Language, and Hearing Sciences
Boston University
Boston, MA, United States

ABSTRACT

The purpose of this study was to examine how neurodegeneration secondary to amyotrophic lateral sclerosis (ALS) impacts speech sound accuracy over time and how speech sound accuracy, in turn, is related to speech intelligibility. Twenty-one participants with ALS read the Bamboo Passage over multiple data collection sessions across several months. Phonemic and orthographic transcriptions were completed for all speech samples. The percentage of phonemes accurately produced was calculated across each phoneme, sound class (i.e., consonants versus vowels), and distinctive feature (i.e., features involved in Manner of Articulation, Place of Articulation, Laryngeal Voicing, Tongue Height, and Tongue Advancement). Intelligibility was determined by calculating the percentage of words correctly transcribed orthographically by naive listeners. Linear mixed effects models were conducted to assess the decline of each distinctive feature over time and their impact on intelligibility. The results demonstrated that overall phonemic production accuracy had a nonlinear relationship with speech intelligibility and that a subset of features (i.e., those dependent on precise lingual and labial constriction and/or extensive lingual and labial movement) were more important for intelligibility and were more impacted over time than other features. Furthermore, findings revealed that consonants were more strongly associated with intelligibility than vowels, but consonants did not significantly differ from vowels in their decline over time. These findings have the potential to (1) strengthen mechanistic understanding of the physiological constraints imposed by neuronal degeneration on speech production and (2) inform the timing and selection of treatment and assessment targets for individuals with ALS.

Keywords: phonemic analysis, intelligibility, neurodegenerative disease, speech impairment

WORD COUNT: 7090 words

Introduction

Amyotrophic lateral sclerosis (ALS) is a neurodegenerative disease that results in the degeneration of both upper and lower motor neurons, which causes progressive weakness and atrophy of muscles (Strong et al., 2017). Speech deficits are a common initial symptom of the disease and lead to loss in intelligibility and, eventually, of all verbal communication in 75-95% of individuals (Brownlee & Bruening, 2012; Carpenter et al., 1978). In progressive dysarthrias, such as those associated with ALS, deficits in intelligibility have been linked to a reduction in articulatory performance (De Bodt et al., 2002; Lee et al., 2014; Rong et al., 2015; Sidtis et al., 2011; Yunusova et al., 2008). Although clinicians use perceptual judgment to assess the state of bulbar disease, researchers have typically characterized the decline in articulatory precision using speech acoustics or kinematics (Kuruvilla et al., 2012; Rong & Green, 2019; Wang et al., 2018; Yunusova et al., 2012). Few studies have examined how these articulatory impairments constrain speech sound production (i.e., based on perceptual judgment) and how the resulting speech errors degrade intelligibility over time. This knowledge is needed to (1) optimize the timing and selection of treatment goals focused on prolonging oral communication and (2) strengthen our understanding of the physiological constraints secondary to neuronal degeneration.

To effectively manage progressive dysarthria, there is a pressing need to understand how speech sound accuracy deteriorates over time. The few studies that examined speech sound errors in progressive dysarthria secondary to ALS were conducted two to three decades ago (Bunton & Weismer, 2001; DePaul & Kent, 2000; Kent et al., 1989, 1990, 1991; Riddel et al., 1995). These studies found a high proportion of stop-nasal contrast errors (Kent et al., 1989, 1991) and a higher error rate for voiceless sounds than for voiced sounds (Riddel et al., 1995).

However, this research was largely cross-sectional (Bunton & Weismer, 2001; Kent et al., 1989, 1990; Riddel et al., 1995), with the exception of a few longitudinal case studies (DePaul & Kent, 2000; Kent et al., 1991). Furthermore, these studies primarily examined productions of isolated words rather than connected speech (Bunton & Weismer, 2001; DePaul & Kent, 2000; Kent et al., 1989, 1990, 1991; Riddel et al., 1995); although single-word speech batteries are efficient to administer and easier to experimentally control for confounds such as phonetic environment, longer utterances provide a more representative assessment of speech function (Allison et al., 2019).

A number of studies have examined the relative impact of different speech sound errors on intelligibility, which revealed a large effect of impaired consonants and, specifically, impaired fricatives and affricates (Ansel & Kent, 1992; Bunton et al., 2007; Hodge et al., 2013; Kim et al., 2010; McLeod et al., 2012; Platt et al., 1980). Many of these studies, however, have been conducted with speakers with non-progressive dysarthria secondary to cerebral palsy (CP), which precludes examining how declines in speech sound accuracy affect intelligibility *over time*. The need to assess longitudinal change is crucial because the capabilities and needs of patients with neurodegeneration change significantly as the disease progresses (Yorkston & Beukelman, 1991).

Moreover, prior work suggests that the spread of motor deterioration is not uniform across cranial nerve nuclei. That is, ALS may result in differential impairment of the speech mechanism over time (e.g., lingual muscles may be more impaired than labial muscles at different points across the disease) (DePaul et al., 1988; Kent et al., 1990; Langmore & Lehman, 1994; Lawyer & Netsky, 1953; Stipancic et al., 2021; Yunusova et al., 2008). Indeed, tongue weakness has been shown to be more prominent than weakness in other articulators (DePaul &

Brooks, 1993; Solomon et al., 2017; Wood et al., 1992). This differential impairment can affect different speech sounds to varying degrees and therefore can be evidenced, in part, by patterns of speech sound accuracy. For example, difficulty producing alveolars but not bilabials may indicate tongue tip weakness with spared upper and lower lip function. Similarly, difficulty producing velars but not alveolars could indicate tongue back weakness with spared tongue tip function.

In the current study, we investigated (1) the impact of speech errors on intelligibility in a paragraph-reading task and (2) the changes in speech error patterns over time in a cohort of 21 speakers with ALS. This study differs from prior work on speech error patterns in ALS (Bunton & Weismer, 2001; DePaul & Kent, 2000; Kent et al., 1989, 1990, 1991; Riddel et al., 1995) in that our focus was to characterize distinctive feature accuracy rather than the *types* of sound error (e.g., distortions, substitutions, deletions). Distinctive feature errors were of particular interest because they can provide insights into underlying physiological impairments. If we observe a preponderance of errors in alveolars but not in bilabials, we might posit that speakers are losing function over their tongue tip muscles prior to lip muscles; or if we observe a preponderance of errors in fricatives but not glides, we might posit that speakers are losing fine force control but can still achieve more coarse, low velocity movements.

To this end, the following research questions were addressed:

1. What is the overall effect of phonemic accuracy on speech intelligibility in speakers with ALS?
2. Which sound class (i.e., consonants versus vowels) and distinctive feature (e.g., fricatives) errors have the greatest impact on speech intelligibility in speakers with ALS?

3. Do different sound classes and distinctive features degrade similarly over time (as represented by data collection sessions) in a given speaker with ALS?

Materials and methods

Participants

Data were collected from twenty-one participants who were diagnosed with ALS by a neurologist using El Escorial criteria (Brooks et al., 2000) at the University of Texas, Dallas (UTD); MGH Institute of Health Professions (MGH IHP); and the University of Nebraska, Lincoln (UNL). This data was part of a multi-site, longitudinal study on bulbar degeneration in ALS. Table 1 provides demographic data for each participant, including age at the first data collection session, sex, the number of sessions each participant participated in, and the number of days between the first and last sessions. Intelligibility at the first session ranged from 37 to 100% (M = 84.14, SD = 18.54), while intelligibility at the last session ranged from 0 to 100% (M = 48.99, SD = 47.40). All participants spoke English as their native language, passed a bilateral hearing screening at 25 dB at 1000, 2000, and 4000 Hz, reported normal or correct-to-normal vision, and passed the Montreal Cognitive Assessment (MoCA).

Table 1. Demographic and speech characteristics of the ALS participants.

Subject	Sex	Age at First Session	Number of Data Collection Sessions	Days between First and Last Session (Timepoint 1 and Timepoint 2)	Intelligibility at First Session	Intelligibility at Last Session	Database
ALS01	M	46	3	243	83%	0%	UNL
ALS02	M	44	5	148	87%	0%	UNL
ALS03	M	51	6	133	90%	77%	UNL
ALS04	M	54	9	238	89%	0%	UNL
ALS05	F	64	8	245	90%	1%	UNL
ALS06	F	48	5	226	58%	0%	UNL
ALS07	M	77	4	196	90%	0%	UNL
ALS08	F	62	4	101	68%	0%	UNL

ALS09	F	62	7	238	37%	33%	UNL
ALS10	M	44	3	81	38%	33%	UNL
ALS11	M	53	4	542	98%	96%	UTD
ALS12	M	61	4	591	90%	100%	UTD
ALS13	M	52	3	428	92%	0%	UTD
ALS14	F	62	4	367	93%	0%	UTD
ALS15	M	44	3	444	100%	100%	UTD
ALS16	F	54	4	547	92%	100%	UTD
ALS17	M	42	3	386	100%	94%	UTD
ALS18	M	52	3	393	86%	100%	UTD
ALS19	F	57	3	295	100%	98%	UTD
ALS20	F	52	3	504	86%	100%	MGH IHP
ALS21	M	56	3	591	100%	98%	MGH IHP

Note. UNL = University of Nebraska, Lincoln; UTD = University of Texas, Dallas; MGH IHP = MGH Institute of Health Professions.

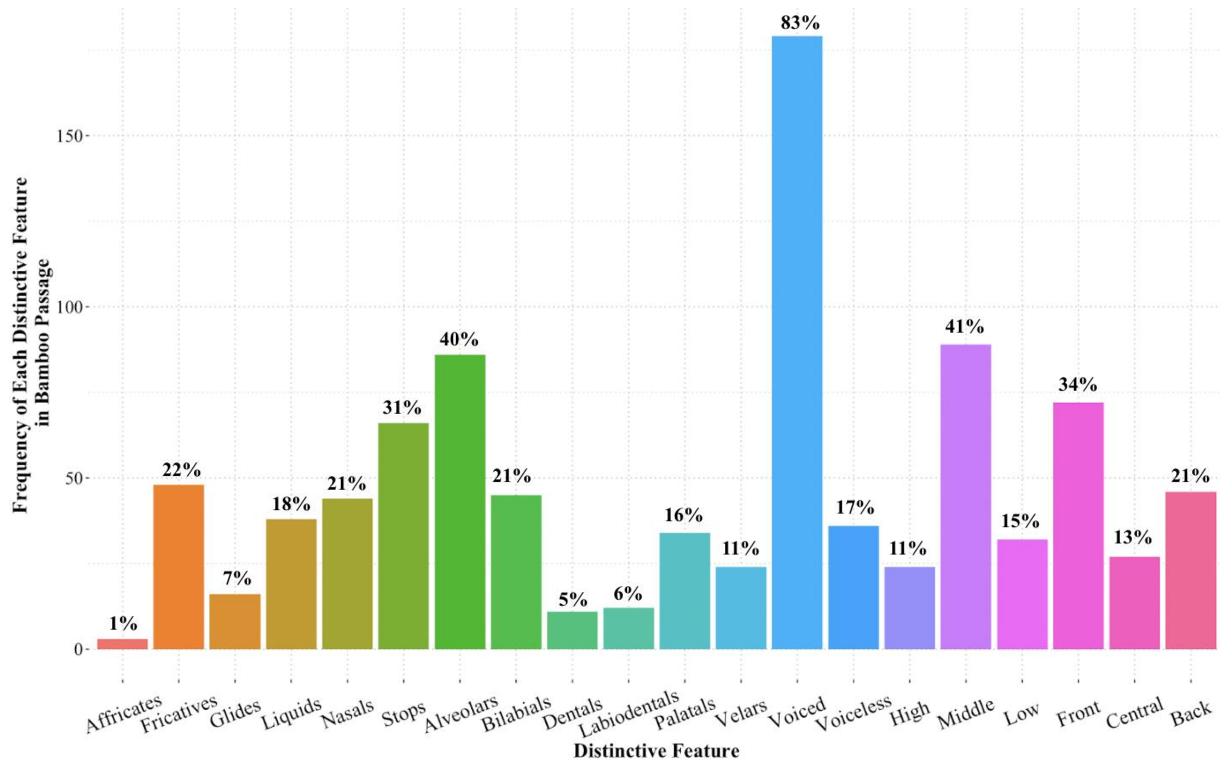
Procedures

Data collection

Participants came to the clinic at the respective institution (UTD, MGH IHP, or UNL) for multiple data collection sessions, separated by three months on average. The study protocol was approved by the institutional review boards of all institutions involved in the study, and written informed consent was obtained from all participants. The number of days between the first and last sessions varied from 81 to 591 days (M = 330.33, SD = 163.97). See Table 1 for the number of sessions and days between the first and last session for each subject. Data from all sessions were of interest for Research Questions 1 and 2, but only data from the first and last sessions were of interest for Research Question 3 (more detail is provided below). As part of a larger experimental testing protocol, participants read the Bamboo Passage (Green et al., 2004) (see Appendix) at each session, which included eight sentences and 97 words (215 total phonemes). Participants were instructed to read the passage at a comfortable speaking rate and loudness. See Appendix for the complete Bamboo Passage and a bar chart illustrating the frequency (and percentage of total phonemes in the passage) of each distinctive feature in the passage.

Appendix

Bamboo walls are getting to be very popular. They are strong, easy to use, and good-looking. They provide a good background and can create a look of a Japanese garden. Bamboo is one of the largest and most rapidly growing grasses all over the world. Many varieties of bamboo are grown in Asia, although it is also grown in America. Last year we bought a new home and have been working on the flower garden. In a few more days, we will be done with the bamboo wall in our garden. We have really enjoyed the project.



Bar chart illustrating the frequency (and percentage of total phonemes in the passage) of each distinctive feature in the Bamboo Passage.

Recording and phonemic transcription

Speech samples were recorded using a high-quality Shure Microflex microphone (at 22 kHz sampling rate) placed approximately 15 mm from the participant’s mouth. One research assistant, who had completed graduate-level coursework and advanced training in phonemic transcription, identified and phonemically transcribed each word produced by participants using the transcription consensus procedures described by Shriberg and colleagues (Shriberg et al., 1984). The research assistant spoke English as their native language and had normal hearing. The phonemic transcriptions were then entered into the open-source software Programs to Examine Phonetic and Phonological Evaluation Records (PEPPER) (Shriberg et al., 2000). To assess interrater reliability for the phonemic transcriptions, a second research assistant with the same qualifications as the first transcribed a randomly selected 10% of the Bamboo Passage samples. The intraclass correlation coefficient for absolute agreement (i.e., ICC[2,1]) was used to calculate reliability between the two raters and demonstrated strong phoneme-by-phoneme agreement between the two transcribers ($ICC = .91$, $p < .001$).

Speech intelligibility ratings

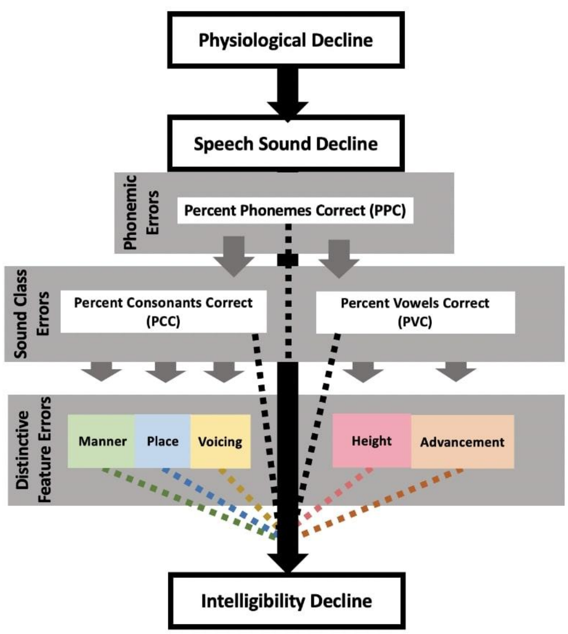
Undergraduate and graduate students at UTD were recruited through advertisements via flyers, emails, and verbal announcements to participate as listeners for the study. There was one listener per each unique participant-timepoint pair. Thus, each listener transcribed only one Bamboo passage read by a participant with ALS to remove the effect of familiarity (Beukelman & Yorkston, 1980). All listeners spoke English as their native language, passed hearing screenings, and were not familiar with the Bamboo Passage nor with the goals of the study. Each listener listened to the Bamboo passage produced by one speaker with ALS and was instructed to orthographically transcribe each word across the eight sentences. Each passage was presented to the listeners using professional-grade headphones. The following instructions were given to each listener: *You will hear a speaker reading a short passage. We would like you to type each word the speaker produces in the order that you hear them. If a word is unintelligible (can't be* *understood as a real word), please type an 'X' where the word is in the sentence. You are allowed to go back and re-listen to any portion of the audio that you feel is necessary.* Intelligibility for each speaker was determined by calculating the percentage of words correctly transcribed by the listener. To calculate interrater reliability for the intelligibility transcriptions, 10% of all Bamboo samples recorded were randomly selected, transcribed independently by a second blinded naive listener, and intelligibility was calculated. ICC(2,1) was again used to calculate reliability between the two intelligibility scores obtained from the two raters and demonstrated strong agreement ($ICC = .92$, $p < .001$).

Phoneme, sound class, and distinctive feature analysis

The PEPPER software was used to assess the speech production of individual speakers. The phonemic transcriptions provided by the research assistants and the target sentences (i.e., the eight sentences as written in the Bamboo Passage) were entered into PEPPER, which provided target phonemic transcriptions of each sentence. PEPPER then completed the following three analyses by comparing the phonemic transcriptions (i.e., those provided by the research assistants and the target transcriptions provided by the software program): (1) *phoneme*-level analysis (Phonemic Errors in Figure 1), which consisted of percent phonemes correct (PPC); (2) *sound class*-level analysis (Sound Class Errors in Figure 1), which consisted of percent consonants correct (PCC) and percent vowels correct (PVC); and (3) *distinctive feature*-level analysis (Distinctive Feature Errors in Figure 1), which consisted of the percent accuracy of features involved in Manner of Articulation (affricates, fricatives, glides, liquids, nasals, stops), Place of Articulation (alveolar, bilabial, dentals, labiodental, palatal, velar), Laryngeal Voicing (voiced consonants and voiceless consonants), Tongue Height (high, middle, low), and Tongue

Advancement (front, central, back). For example, a /p/ that was produced as an /f/ would count as an incorrect phoneme at the Phonemic Error level, incorrect consonant at the Sound Class Error level, and incorrect Manner (stop -> fricative) and Place (bilabial -> labiodental) but not Voicing (i.e., it was correctly produced as a voiceless consonant) at the Distinctive Feature Error level. Figure 1 illustrates the connections between the three levels and their position in the causal pathway from physiological decline to intelligibility decline.

Figure 1. Flow chart illustrating the connection between physiological decline, speech sound decline, and intelligibility decline. Neurologic abnormalities due to neurodegenerative diseases, such as amyotrophic lateral sclerosis (ALS), lead to Physiological Decline, including that of the speech subsystems. Physiological Decline of speech subsystem function leads to Speech Sound Decline, or the inability to produce correct speech sounds, which then results in Intelligibility Decline. The dotted lines indicate the relationships we examined in this study between each level of analysis and intelligibility.



Statistical analysis

Effect of phoneme accuracy on intelligibility (Research Question 1). For the first research question, we sought to determine the relationship between PPC and intelligibility. Because we used data from all sessions and each participant had multiple sessions, a linear mixed effects (LME) model was conducted by regressing intelligibility on PPC with subject as a random intercept.

Sound class and distinctive feature errors with the greatest impact on intelligibility (Research Question 2). For the second research question, we examined the effects of sound class accuracy (i.e., accuracy of consonants [PCC] and vowels [PVC]) and distinctive feature accuracy (i.e., accuracy of Manner features, Place features, Voicing features, Height features, and Advancement features) on intelligibility. Again, because we used data from all sessions and each participant had multiple sessions, LME models were conducted by regressing intelligibility on sound class (i.e., consonants and vowels) or distinctive features (e.g., affricates) with subject as a random intercept.

Extent of decline over time for each sound class and distinctive feature (Research Question 3). For the third research question, we examined change over time for the accuracy of each sound class and distinctive feature. In contrast to Research Questions 1 and 2, we only used data from the first and last sessions. The data were thus stratified into two timepoints: 'Timepoint 1', which was the first session, and 'Timepoint 2', which was the last session. We then created a new variable (i.e., 'Difference'), which consisted of the difference in accuracy for each sound class or distinctive feature from Timepoint 1 to Timepoint 2 (e.g., accuracy of Fricatives at Timepoint 1 minus accuracy of Fricatives at Timepoint 2). Importantly, because the date of disease onset was not available for all participants, we were unable to determine the extent of decline *from initial diagnosis*. Instead, we captured the extent of decline from each participant's initial session. LME models were conducted by regressing the difference in accuracy on sound class or distinctive feature with subject as a random intercept. The contrasts were then assessed for each model.

For the analyses for Research Questions 2 and 3, six separate LME were conducted (i.e., sound classes, Manner features, Place features, Voicing features, Height features, and Advancement features). We conducted individual models because the small sample size reduced the power necessary to combine all predictors into one model. Additionally, conducting individual models allowed us to include only between-group predictors (and no within-group predictors) in a single model. For example, because Manner and Place features overlap with Voicing features (e.g., a fricative or an alveolar can be voiced or voiceless), it was advantageous to examine Manner and Place separately from Voicing.

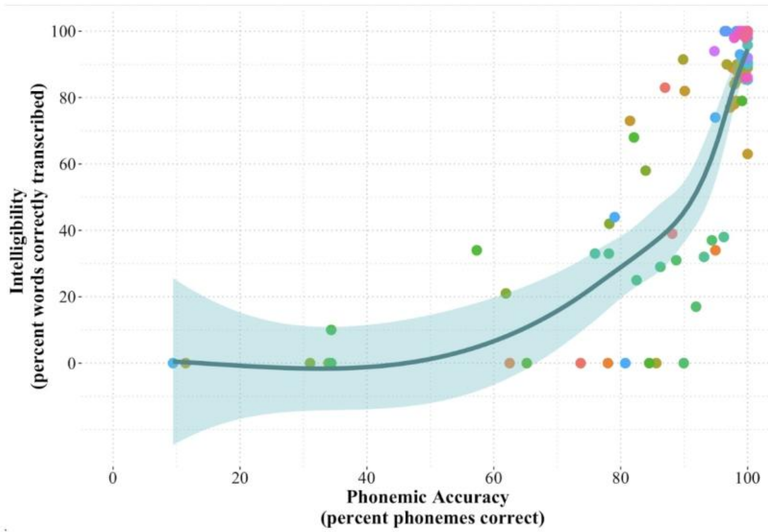
Results

Effect of phoneme accuracy on intelligibility (Research Question 1)

Average intelligibility across all participants was 84.14% words correct (SD = 18.54) in the first session and 48.99% words correct (SD = 47.40) in the last session. The overall LME analysis revealed a significant effect of PPC on intelligibility (b = 1.39, SE = .11, $t(88.86)$ = 12.27, p < .001). The strength of the association between the two variables was also examined using the standardized beta coefficient, which indicated a strong association (B = .77). This relationship was determined to be non-linear, as small declines in PPC initially corresponded with large declines in intelligibility, but once PPC was lower than 75%, even large declines in PPC did not result in noticeable declines in intelligibility (see Figure 2).

Figure 2. Scatterplot illustrating the relationship between percent phonemes correct [PPC] and intelligibility. The colored dots represent each participant, with multiple sessions per participant (and therefore multiple dots of the same color). Although an arcsine transformation was performed on the two variables for the statistical analyses, no transformation was performed on

the data for this visualization to ease interpretability. A lowess (locally weighted scatterplot smoothing) regression line was also used to illustrate the relationship between the two variables.



Sound class and distinctive feature errors with the greatest impact on intelligibility (Research Question 2)

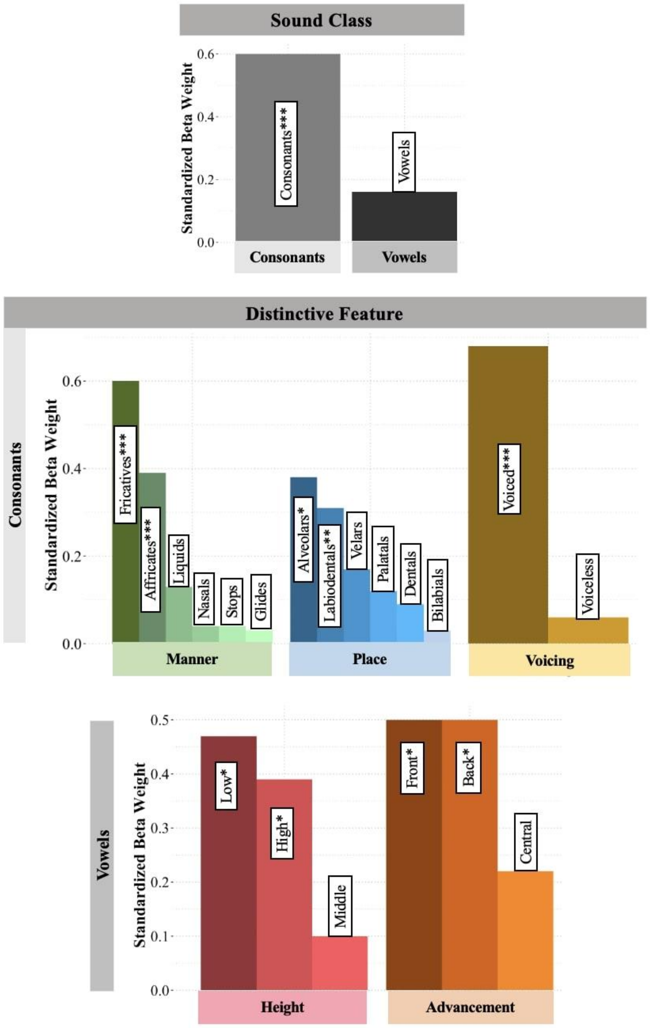
The results of the LME analyses examining the effects of sound class accuracy (i.e., accuracy of consonants [PCC] and vowels [PVC]) and distinctive feature accuracy (i.e., accuracy of all Manner features, Place features, Voicing features, Height features, and Advancement features) on intelligibility are summarized in Table 2 and Figure 3. Most notably, for the sound class model, consonants were significantly associated with intelligibility, whereas vowels were not. For the distinctive feature models, the following features were significantly associated with intelligibility: fricatives and affricates in the Manner model, alveolars and labiodentals in the Place model, voiced consonants in the Voicing model, low and high vowels in the Height model, and front and back vowels in the Advancement model.

Table 2. Linear mixed effects (LME) models examining the association between intelligibility and each sound class and each distinctive feature.

LME Model	Fixed Effects	Estimate	*SE*	*df*	*t*	*p*
Consonants versus Vowels						
	PCC	**1.17**	**.26**	**86.67**	**4.49**	**< .001*****
	PVC	0.24	.22	87.57	1.13	.26
Manner						
	Affricates	**0.42**	**0.10**	**72.50**	**4.00**	**< .001*****
	Fricatives	**0.89**	**0.26**	**82.75**	**3.48**	**< .001*****
	Glides	0.07	0.23	75.35	0.29	.77
	Liquids	-0.25	0.24	70.94	-1.06	.29
	Nasals	-0.13	0.33	77.94	-0.41	.69
	Stops	-0.06	0.28	75.58	-0.22	.83
Place						
	Alveolars	**0.68**	**0.27**	**79.96**	**2.51**	**.01***
	Bilabials	-0.06	0.30	76.67	-0.21	.84
	Dentals	0.14	0.23	73.98	0.64	.53
	Labiodentals	**0.35**	**0.13**	**73.96**	**2.67**	**< .01****
	Palatals	-0.22	0.26	75.99	-0.87	.39
	Velars	0.27	0.23	83.99	1.21	.23
Voicing						
	Voiced	**1.40**	**0.32**	**87.93**	**4.42**	**< .001*****
	Voiceless	0.08	0.20	87.57	0.41	.69
Height						
	Low	**0.64**	**0.29**	**84.91**	**2.19**	**.03***
	Middle	-0.15	0.33	72.80	-0.45	.65
	High	**0.52**	**0.25**	**83.04**	**2.05**	**.04***
Advancement						
	Front	**0.71**	**0.28**	**85.77**	**2.53**	**.01***
	Central	-0.32	0.28	81.24	-1.16	.25
	Back	**0.70**	**0.30**	**86.90**	**2.37**	**.02***

Note. SE = standard error; PCC = percent consonants correct; PVC = percent vowels correct; * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Figure 3. Bar charts of the standardized beta coefficients illustrating the impact of each sound class and distinctive feature on intelligibility (* = $p < .05$, ** = $p < .01$, *** = $p < .001$).



Extent of decline over time for each sound class and distinctive feature (Research Question 3)

The results of the LME analyses examining the differences in extent of decline between sound classes and between distinctive features within each group (i.e., Manner, Place, Voicing, Height, and Advancement) are summarized in Table 3 and Figure 4. Most notably, for the sound class model, consonants and vowels did not significantly differ in their extents of decline. For the distinctive feature models, fricatives, affricates, and stops declined to a significantly greater extent than nasals in the Manner model; labiodentals declined to a significantly greater extent than bilabials and palatals in the Place model; voiceless consonants declined to a significantly greater extent than voiced consonants in the Voicing model; and vowels in both Height and Advancement models did not significantly differ in their extents of decline.

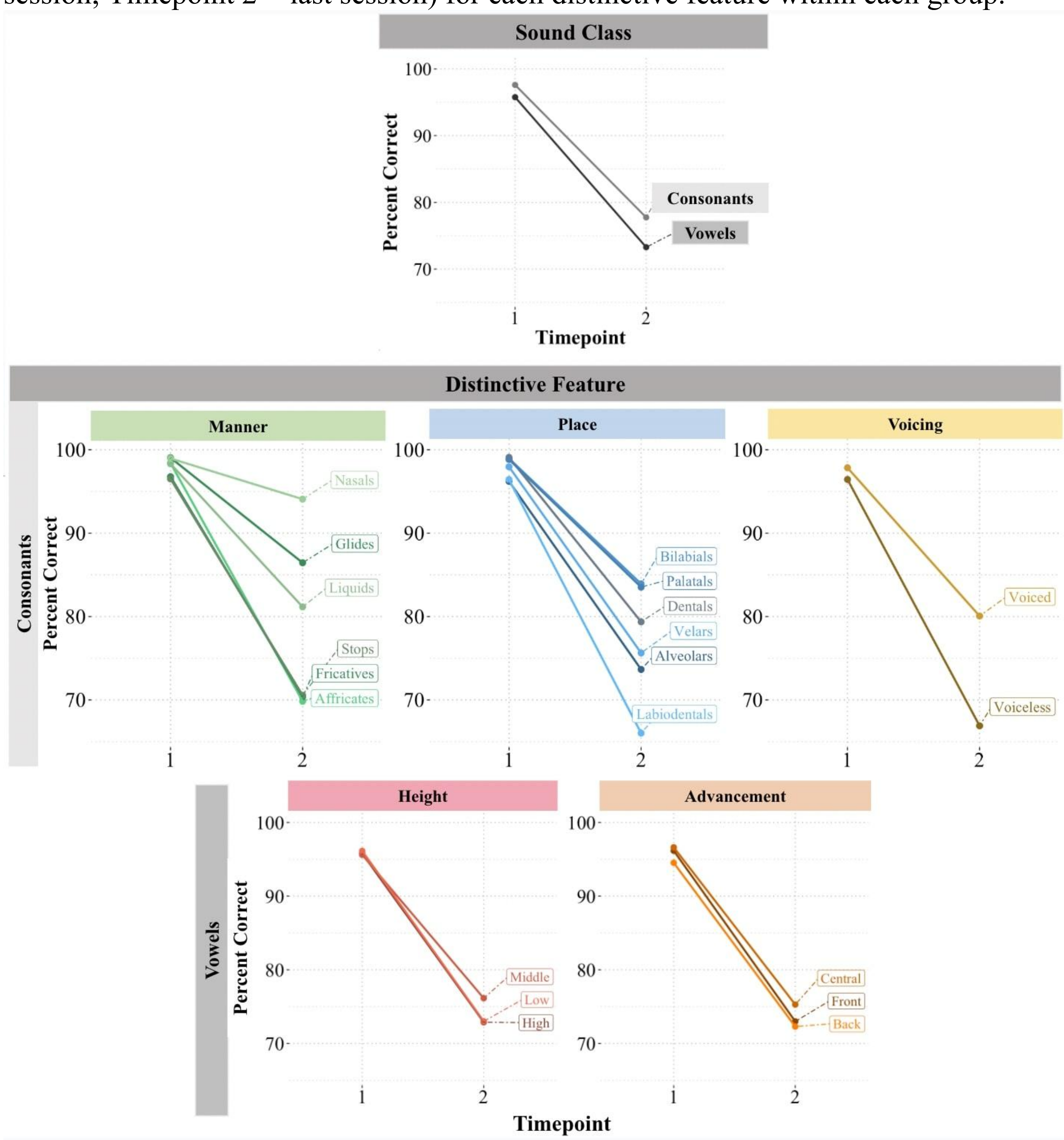
Table 3. Contrasts from linear mixed effects (LME) models examining differences in the extent of decline across sessions for each sound class and distinctive feature.

LME Model	Contrast	Estimate	*SE*	*df*	*t*	*p*
Consonants versus Vowels						
	PCC - PVC	0.02	0.05	20	0.35	.73
Manner						
	Affricates - Fricatives	-0.05	0.08	100	-0.56	.99
	Affricates - Glides	**-0.24**	**0.08**	**100**	**-2.96**	**< .05***
	Affricates - Liquids	-0.15	0.08	100	-1.90	.40
	Affricates - Nasals	**-0.35**	**0.08**	**100**	**-4.33**	**< .001*****
	Affricates - Stops	-0.05	0.08	100	-0.66	.99
	Fricatives - Glides	-0.20	0.08	100	-2.40	.17
	Fricatives - Liquids	-0.11	0.08	100	-1.34	.76
	Fricatives - Nasals	**-0.31**	**0.08**	**100**	**-3.76**	**< .01****
	Fricatives - Stops	-0.01	0.08	100	-0.09	1.00
	Glides - Liquids	0.09	0.08	100	1.06	.90
	Glides - Nasals	-0.11	0.08	100	-1.36	.75
	Glides - Stops	0.19	0.08	100	2.30	.20
	Liquids - Nasals	-0.20	0.08	100	-2.42	.16
	Liquids - Stops	0.10	0.08	100	1.23	.81
	Nasals - Stops	**0.30**	**0.08**	**100**	**3.67**	**< .01****
Place						
	Alveolars - Bilabials	-0.06	0.06	100	-0.91	.94
	Alveolars - Dentals	-0.02	0.06	100	-0.39	1.00
	Alveolars - Labiodentals	0.13	0.06	100	2.23	.24
	Alveolars - Palatals	-0.07	0.06	100	-1.22	.83
	Alveolars - Velars	-0.01	0.06	100	-0.11	1.00
	Bilabials - Dentals	0.03	0.06	100	0.52	1.00
	Bilabials - Labiodentals	**0.19**	**0.06**	**100**	**3.14**	**.03***
	Bilabials - Palatals	-0.02	0.06	100	-0.31	1.00
	Bilabials - Velars	0.05	0.06	100	0.80	.97
	Dentals - Labiodentals	0.16	0.06	100	2.62	.10
	Dentals - Palatals	-0.05	0.06	100	-0.83	.96
	Dentals - Velars	0.02	0.06	100	0.28	1.00
	Labiodentals - Palatals	**-0.21**	**0.06**	**100**	**-3.44**	**.01***
	Labiodentals - Velars	-0.14	0.06	100	-2.34	.19
	Palatals - Velars	0.07	0.06	100	1.11	.88
Voicing						
	Voiced - Voiceless	**.18**	**0.05**	**20**	**3.62**	**< .01****

Height						
	High - Middle	-0.09	0.04	40	-2.17	.09
	High - Low	0.01	0.04	40	0.18	.98
	Middle - Low	0.09	0.04	40	2.34	.06
Advancement						
	Front - Central	-0.03	0.04	40	-0.72	.75
	Front - Back	0.01	0.04	40	0.15	.99
	Central - Back	0.04	0.04	40	0.87	.66

Note. SE = standard error; * = *p* < .05, ** = *p* < .01, *** = *p* < .001.

Figure 4. Spaghetti plots illustrating the average extent of decline over time (Timepoint 1 = first session; Timepoint 2 = last session) for each distinctive feature within each group.



Discussion

This work aimed to examine the impact of progressive dysarthria on speech sound accuracy and how speech errors affect speech intelligibility. The results can be summarized in three primary findings. First, the impact of phonemic errors on intelligibility was strong but non-linear. Second, intelligibility was dependent more on the accuracy of consonants than vowels and on the accuracy of a relatively small number of distinctive features (nine out of 20). Third, the majority of the consonant types that were most important for intelligibility (i.e., fricatives, affricates, and labiodentals, which putatively require precise lingual and/or labial constriction) also declined the most over time. These findings have the potential to (1) strengthen mechanistic understanding of the physiological constraints imposed by neuronal degeneration in ALS and (2) inform the timing and selection of treatment and assessment targets for individuals with progressive dysarthria secondary to ALS.

The impact of phonemic errors on intelligibility is strong but non-linear

The strong association between PPC and intelligibility was expected and consistent with findings reported in children and individuals with non-progressive dysarthria (Bunton et al., 2007; Hodge et al., 2013; McLeod et al., 2012). The curvilinear association between these variables (see Figure 2) suggests that when at least 75% of phonemes were produced correctly, small declines in PPC resulted in large declines in intelligibility. However, once more than 75% of phonemes were produced incorrectly, the association between PPC and intelligibility weakened (i.e., decreases in PPC were not associated with clear decreases in intelligibility). These findings raise the possibility that the benefits of improving PPC as an intelligibility-enhancing strategy may be limited for speakers with low PPCs (i.e., lesser than 75%).

The sharp decline in intelligibility based on a small decrease in the upper range of PPC (i.e., 75% and greater) suggests that the phonemes produced incorrectly were important for intelligibility. This interpretation is supported by our finding that most of the consonant types that significantly degraded intelligibility (i.e., fricatives, affricates, and labiodentals) also declined the most over time. The dissociation between PPC and intelligibility in the lower range of PPC (i.e., 75% and lower) and especially for a subset of individuals with high PPCs was unexpected. For the individuals in the lower range of PPC, the lack of association with intelligibility was less surprising, as it is reasonable that without at least 75% of sounds produced correctly, listeners are very poor at deciphering speech. For the individuals with high PPCs but low intelligibility, one potential explanation for the lower intelligibility may be that the speakers had deficits in subsystems other than articulation (i.e., phonation) that impaired their ability to be understood.

The impact of fricatives, affricates, alveolars, labiodentals, and non-centralized vowels on intelligibility

To determine the relative impact of different errors on intelligibility, we examined the association between intelligibility and specific sound classes (i.e., consonants versus vowels) and distinctive features (e.g., fricatives versus stops). Consistent with prior work, we found a stronger association between consonant errors (i.e., PCC) and intelligibility than between vowel errors (i.e., PVC) and intelligibility (Hodge et al., 2013; McLeod et al., 2012). This finding is also consistent with the hearing-impaired literature, which found that consonants were more important than vowels for discerning word meaning (Owren & Cardillo, 2006).

Furthermore, across all consonants, we found that fricatives, affricates, alveolars, and labiodentals were most strongly associated with intelligibility. These findings align with prior work in adults with non-progressive dysarthria, all of which found the strongest associations between intelligibility and fricatives and affricates compared to other types of speech sounds (Ansel & Kent, 1992; Kim et al., 2010; Platt et al., 1980). Additionally, previous research has demonstrated strong associations between acoustic measures of affricate or fricative production and perceptual impressions of speech, such as intelligibility and articulatory imprecision (Liu et al., 2016; Maniwa et al., 2008; Tjaden & Turner, 1997). The current findings are inconsistent with those of Kent and colleagues (1989 and 1991), who observed a high proportion of stop-nasal contrast errors in speakers with ALS (Kent et al., 1989, 1991). However, stop-nasal contrasts were most notably impaired for speakers with poor intelligibility (i.e., < 65%), whereas the current study included speakers with intelligibility across the continuum (i.e., both speakers with low and high intelligibility), which may have contributed to our discrepant findings. For example, the types of errors made by speakers with low intelligibility may be distinct from errors made by more intelligible speakers. We also used different stimuli (i.e., paragraphs versus single words) and outcome measures (i.e., all possible error types versus certain contrasts) from the ones used by Kent and colleagues (1989 and 1991), which may be a potential cause of disparate results.

When PCC was included in the model, the relationship between PVC and intelligibility was not statistically significant; however, when vowels were examined in isolation, corner vowels (i.e., front, back, high, and low) were more significantly associated with intelligibility as compared to non-corner vowels. This result corroborates prior acoustic evidence that vowel space area, calculated from corner vowels, is an important component of intelligibility in speakers with ALS (Turner et al., 1995; Weismer et al., 2001).

Declines were greatest for distinctive features that may require the greatest articulatory precision

In addition to investigating their associations with intelligibility, we compared the extents of decline for each sound class and distinctive feature over time. Consonants and vowels exhibited similar extents of decline across sessions, as did different vowels. For consonants, we found that fricatives, affricates, and stops declined to a significantly greater extent than nasals, while labiodentals declined to a significantly greater extent than did bilabials and palatals.

These findings can be interpreted within the context of a framework proposed by Kent (1992), which characterizes different phonemes based on their presumed production complexity (see Table 4). This framework posits that sounds acquired later in life (e.g., affricates) are more motorically challenging or phonetically complex than sounds acquired earlier in life (e.g., bilabials) (Kent, 1992). Although Kent's framework was intended to explain the acquisition of speech, the same principals have been applied to patterns of speech loss in adults with neurodegenerative diseases (van der Merwe, 2009; Wertz et al., 1991). Prior research has suggested that individuals with dysarthria tend to have difficulty producing sounds with higher levels of phonetic complexity (Allison & Hustad, 2014; Kim et al., 2010; Kuruvilla-Dugdale et al., 2018). Speakers with ALS, in particular, are known to have deficits in controlling lingual and labial movement (Langmore & Lehman, 1994; Perry et al., 2018; Yunusova et al., 2010). These deficits may underlie the sharp declines in the accuracy of fricatives, affricates, stops, and labiodentals. Indeed, Manner and Place features that presumably require increased fine motor control and regulated, low velocity vocal tract constrictions (e.g., control of fine force for fricatives) declined to a greater extent than those that require less graded, ballistic movements (e.g., velopharyngeal port opening for nasals).

Table 4. An adapted version of Kent's (1992) framework including only sounds relevant to the current study.

Complexity Level (1 = least complex, 6 = most complex)	**Distinctive Features**		
	Height	**Advancement**	**Example**
Vowels			
1	Low	Back	/ɑ/
	Mid	Central	/ə/
2	High	Back	/u/
	High	Front	/i/
	Mid-high	Back	/o/
3	Mid-low	Front	/ɛ/
	Mid-low	Back	/ɔ/
4	Mid-high	Front	/ɪ/, /e/
	Mid-low	Front	/æ/
	Mid-high	Back	/ʊ/

	Voicing	**Place**	**Manner**	**Example**
Consonants				
3	Voiceless	Bilabial	Stop	/p/
	Voiced	Bilabial	Nasal	/m/
	Voiced	*Alveolar*	Nasal	/n/
	Voiced	Bilabial	Glide	/w/
	Voiceless	Glottal	*Fricative*	/h/
4	*Voiced*	Bilabial	Stop	/b/
	Voiced	*Alveolar*	Stop	/d/
	Voiceless	Velar	Stop	/k/
	Voiced	Velar	Stop	/g/
	Voiced	Palatal	Glide	/j/
	Voiceless	*Labiodental*	*Fricative*	/f/
5	Voiceless	*Alveolar*	Stop	/t/
	Voiced	Velar	Nasal	/ŋ/
	Voiced	*Alveolar*	Liquid	/ɹ/, /l/
6	Voiceless	*Alveolar*	*Fricative*	/s/
	Voiced	*Alveolar*	*Fricative*	/z/
	Voiceless	Palatal	*Fricative*	/ʃ/
	Voiced	*Labiodental*	*Fricative*	/v/
	Voiceless	Dental	*Fricative*	/θ/
	Voiced	Dental	*Fricative*	/ð/

	Voiceless	Palatal	*Affricate*	/tʃ/
	Voiced	Palatal	*Affricate*	/dʒ/

Note: Italicized = significant association with intelligibility; underlined = declined to a significantly greater extent than other distinctive features in its group for the current study.

Prior work has suggested that the time course of degeneration may vary among the cranial nerves that innervate the speech musculature (DePaul et al., 1988). Specifically, DePaul and colleagues (1988) found that hypoglossal motor neurons, which innervate tongue muscles, were affected to a greater extent than trigeminal motor neurons, which innervate jaw muscles (DePaul et al., 1988). While many studies in dysarthria secondary to other disorders have not supported a relationship between tongue weakness and impaired speech (McHenry et al., 1994; Neel et al., 2015; Solomon et al., 1995; Solomon et al., 2000; Theodoros et al., 1995), two recent studies, one of which focused on ALS, reported strong correlations between tongue weakness and intelligibility (Searl et al., 2017) or speech impairment (Jones et al., 2015). Based on these latter studies, we might have expected to find significantly more impaired alveolars (which involve precise tongue placement) than bilabials (which can be achieved with compensatory jaw movement even for more severe speakers). Yet, we found that only *labiodentals* declined to a significantly greater extent than bilabials. This finding should be considered with the knowledge that all labiodentals are fricatives, which might have driven its significant differences in accuracy compared to the other Place features. Nevertheless, it is possible that the difference in accuracy for labiodentals and bilabials may also reflect differential impairment of the lips and jaw, as labiodentals require the precise regulation of lower lip and jaw muscles to achieve the appropriate constriction between teeth and lower lip, whereas bilabials can be produced using more coarsely controlled movements of the lips and/or jaw.

Kent’s framework also discusses the level of complexity of vowel sounds. Low back vowels (e.g., /ɑ/) are posited as being the least complex because they involve only slight lingual elevation, while mid-high back vowels are considered the most complex given the need for lingual-jaw coordination (Kent, 1992). In contrast to this theory, low vowels have been found to be *more* impaired than high vowels in speakers with ALS due to the reliance of low vowels on larger and faster movements (Kent et al., 1990; Kuruvilla et al., 2012; Yunusova et al., 2008). While our study revealed similar extents of decline across *all* vowels, regardless of their hypothesized complexity, most of the prior work examined the reduction of tongue movements rather than phoneme accuracy, which precludes a direct comparison of findings.

Voiced versus voiceless sounds in the Bamboo Passage

One final notable result was that voiceless sounds declined to a greater extent than voiced sounds, but errors on voiced sounds were more strongly associated with reduced intelligibility. The former finding is consistent with prior work demonstrating a higher error rate for voiceless sounds than for voiced sounds in speakers with ALS (Antolik & Fougeron, 2013; Caruso & Burton, 1987; Kent et al., 1990; Riddel et al., 1995). While voiceless sounds were disproportionately impacted compared to voiced sounds, we found that voiced sound accuracy was more strongly associated with intelligibility than was voiceless sound accuracy. These findings may be related to phonemic inventory biases in the Bamboo Passage, which was intentionally loaded with voiced sounds to enhance the automatic detection of word boundaries in connected speech (Green et al., 2004; Yunusova et al., 2005). The Bamboo Passage may, therefore, not be the most effective task for comparing the impact of voiced versus voiceless sounds on intelligibility. Additional research on the impact of speech stimuli is needed.

Clinical implications

Overall, the findings from this study have two central clinical implications for speakers with ALS: (1) They may help identify potential candidate treatment targets for speakers with reduced intelligibility; and (2) They may help guide stimuli selection for global measures of intelligibility or speech severity.

First, the strong association between features such as affricates and fricatives and intelligibility, and the large extents of decline for these same features, suggests that targeting specific sounds in therapy early on, either directly or indirectly, could benefit speakers with ALS. This proposal is consistent with recommendations in recent work, which have suggested that complementing traditional therapy approaches with more specific speech targets (Ansel & Kent, 1992; Icht, 2021; Kent et al., 1991; Kuruvilla-Dugdale et al., 2018; Platt et al., 1980; Turner & Tjaden, 2000) or more direct instructions regarding articulatory movements (Mefferd & Dietrich, 2019) could lead to improved acoustic and perceptual outcomes.

Knowledge of which sounds are most impacted by physiologic constraints of ALS over time may also offer an alternative means of conceptualizing therapy for speakers with lower intelligibility. The nonlinear relationship between PPC and intelligibility demonstrates that for speakers who produce less than 75% of all phonemes correctly, increases in PPC (e.g., from 65% to 70%) have little influence on intelligibility. This finding suggests that targeting specific sounds in therapy may not be terribly beneficial for this subset of speakers. Thus, to maximize the functional impact of treatment for these speakers, clinicians could select a list of functional words for the speaker to use that include less impaired distinctive features (e.g., bilabials, glides, or nasals).

Lastly, our findings may offer further guidance for stimuli selection for assessing intelligibility. Given the relationships between each impaired distinctive features and intelligibility, intelligibility ratings may be inflated if the stimuli do not include sounds most likely to be impacted by ALS. For example, if the stimuli primarily included bilabials and glides, the speaker may be rated as highly intelligible since those sounds tend to be less affected by disease progression. Similarly, Kuruvilla and colleagues (2018 and 2020) found that more phonetically complex stimuli were better able to detect subtle disease-related speech changes in speakers with ALS. However, the discrepancies between our findings and those of prior work using single word stimuli suggest that measures of intelligibility may differ depending on the task. Aside from allowing for more time to achieve appropriate articulatory placement, single words allow more opportunities to precisely coordinate the speech subsystems (e.g., increase breath support), which further influences intelligibility (Yunusova et al., 2005). Therefore, the findings from this study, based on a longer connected speech task, may provide important knowledge about more functional/ecologically valid impacts of phonemic accuracy on intelligibility.

Limitations and future work

There were several limitations in this study. First, although the Bamboo Passage is a more functional speech task than single words, an even more ecologically valid task would be spontaneous speech. Indeed, in this study, the same passage was read multiple times by each participant, which may have led to practice effects. In addition, the wide variation of time between data collection points may have further influenced our results. Moreover, a potential reason why we might have found high PPCs for some individuals with low intelligibility is that the phonemic transcribers, too, were familiar with the passage, which could have resulted in slightly inflated PPC values. Moreover, as noted earlier, the passage is not phonetically balanced but rather was designed to include more voiced consonants at word boundaries to ease the identification of pauses (Green et al., 2004; Yunusova et al., 2016). Thus, the unequal frequency of voiced versus voiceless sounds, in addition to other distinctive features (e.g., fricatives versus affricates), may have further influenced our findings.

Second, while our dataset was, to our knowledge, the largest used to examine longitudinal changes in speech sound accuracy in ALS, the dataset was still limited by its small size and unknown timing of disease onset. Additional work is needed to examine the decline of speech performance from disease onset and whether the same results can be replicated with a larger sample size.

Third, we did not conduct analyses on error types (e.g., distortions, substitutions, deletions), which may provide useful information about the speaker's physiological constraints. Future work should examine not only specific error types, but combinations of distinctive features (e.g., alveolar fricatives) as opposed to in isolation (e.g., alveolars and fricatives). Such analyses would allow for a more precise examination of the underlying physiology of speech error patterns.

Furthermore, we did not examine the effect of word position (i.e., initial, medial, or final) on intelligibility or decline over time. Prior work has demonstrated that the highest number of errors occur in word-final positions (Blaney & Hewlett, 2007). Therefore, our phonemic accuracy values may have been inflated or deflated if, for example, palatals occurred most frequently in the word-initial position and alveolar occurred most frequently in the word-final position, respectively. Moreover, a recent study found that position of a sentence within a longer paragraph influences intelligibility (van Brenk et al., 2022). Given the potential for fatigue across a lengthy speaking task, further research should investigate the impact of sentence position / stimuli length on phoneme production. Lastly, future work should consider other features, such as voice quality and prosody, for a more comprehensive understanding of the different subsystems' roles in intelligibility.

Conclusions

In sum, when examining speech production during a paragraph-reading task over time, we found a nonlinear relationship between PPC and intelligibility. This relationship suggests that PPC may have a limited working range and that focusing on increasing phonemic accuracy in therapy may not be universally helpful for all speakers. We also found that features highly dependent on precise lingual and labial constriction (i.e., fricatives, affricates, and labiodentals) and greater lingual and labial movement (i.e., non-centralized vowels) were most important for intelligibility *and* declined to a greater extent over time. Overall, examining the patterns of phonemic errors in ALS is integral for better understanding the impacts of physiologic constraints on functional communication and could, in turn, ultimately inform the selection of the most effective treatment targets and stimuli for assessing intelligibility.

Acknowledgments

The authors would like to thank Dr. Jun Wang, Jenny McGlothlin, Chris Johnson, Daniel Roniger, and Jana Mueller for their support during data collection and data analysis. Special thanks is also extended to Dr. Daragh Heitzman for his help in evaluating and referring individuals with ALS to the study.

Funding

This work was supported by the following grants awarded by the NIDCD, part of the NIH: R01DC013547, R01DC017291, K24DC016312, STTR-R42DC019877, and F31DC019556.

Declaration of interest

The authors report no declarations of interest.

References

Allison, K. M., & Hustad, K. C. (2014). Impact of sentence length and phonetic complexity on intelligibility of 5-year-old children with cerebral palsy. *International Journal of Speech-Language Pathology*, *16*(4), 396–407.

Allison, K. M., Yunusova, Y., & Green, J. R. (2019). Shorter sentence length maximizes intelligibility and speech motor performance in persons with dysarthria due to amyotrophic lateral sclerosis. *American Journal of Speech-Language Pathology*, *28*(1), 96–107.

Ansel, B. M., & Kent, R. D. (1992). Acoustic-phonetic contrasts and intelligibility in the dysarthria associated with mixed cerebral palsy. *Journal of Speech, Language, and Hearing Research*, *35*(2), 296–308.

Antolik, T., & Fougeron, C. (2013). Consonant distortions in dysarthria due to Parkinson's disease, amyotrophic lateral sclerosis and cerebellar ataxia. *Interspeech*, 2152–2156.

Beukelman, D. R., & Yorkston, K. M. (1980). Influence of passage familiarity on intelligibility estimates of dysarthric speech. *Journal of Communication Disorders*, *13*, 33–41.

Blaney, B., & Hewlett, N. (2007). Dysarthria and Friedreich's ataxia: What can intelligibility assessment tell us? *International Journal of Language and Communication Disorders*, *42*(1), 19–37.

Brooks, B., Miller, R., Swash, M., & Munsat, T. (2000). El Escorial revisited: Revised criteria for the diagnosis of amyotrophic lateral sclerosis. *Amyotrophic Lateral Sclerosis and Other Motor*

Neuron Disorders, *1*, 293–299.

Brownlee, A., & Bruening, L. M. (2012). Methods of communication at end of life for the person with amyotrophic lateral sclerosis. *Topics in Language Disorders*, *32*(2), 168–185.

Bunton, K., Leddy, M., & Miller, J. (2007). Phonetic intelligibility testing in adults with Down syndrome. *Down Syndrome Research and Practice*, *12*(1), 1–4.

Bunton, K., & Weismer, G. (2001). The relationship between perception and acoustics for a high-low vowel contrast produced by speakers with dysarthria. *Journal of Speech, Language, and Hearing Research*, *44*(6), 1215–1228.

Carpenter, R. J., McDonald, T. J., & Howard, F. M. (1978). The otolaryngologic presentation of amyotrophic lateral sclerosis. *Otolaryngology*, *86*(3), 479–484.

Caruso, A. J., & Burton, E. K. (1987). Temporal acoustic measures of dysarthria associated with amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *30*(1), 80–87.

De Bodt, M. S., Hernández-Díaz Huici, M. E., & Van De Heyning, P. H. (2002). Intelligibility as a linear combination of dimensions in dysarthric speech. *Journal of Communication Disorders*, *35*(3), 283–292.

DePaul, R., Abbs, J. H., Caligiuri, M., Gracco, V. L., & Brooks, B. R. (1988). Hypoglossal, trigeminal, and facial motoneuron involvement in amyotrophic lateral sclerosis. *Neurology*, *38*, 281–283.

DePaul, R., & Brooks, B. R. (1993). Multiple orofacial indices in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *36*(6), 1158–1167. https://doi.org/10.1044/jshr.3606.1158

DePaul, R., & Kent, R. (2000). A longitudinal case study of ALS: Effects of listener familiarity and proficiency on intelligibility judgments. *American Journal of Speech-Language Pathology*, *9*, 230–240.

Green, J. R., Beukelman, D. R., & Ball, L. J. (2004). Algorithmic estimation of pauses in extended speech samples of dysarthric and typical speech. *Journal of Medical Speech Language Pathology*, *12*(4), 149–154.

Hodge, M. M., Brown, C., & Kuzyk, T. (2013). Predicting intelligibility scores of children with dysarthria and cerebral palsy from phonetic measures of speech accuracy. *Journal of Medical Speech Language Pathology*, *20*(4), 41–47.

Icht, M. (2021). Improving speech characteristics of young adults with congenital dysarthria: An exploratory study comparing articulation training and the Beatalk method. *Journal of Communication Disorders*, *93*, 106147.

Jones, H. N., Crisp, K. D., Asrani, P., Sloane, R., & Kishnani, P. S. (2015). Quantitative assessment of lingual strength in late-onset Pompe disease. *Muscle & Nerve*, *51*(5), 731–735.

Kent, R. D. (1992). The biology of phonological development. In C. A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, implications* (pp. 65–90). York Press.

Kent, R. D., Kent, J. F., Weismer, G., Sufit, R. L., Rosenbek, J. C., Martin, R. E., & Brooks, B. R. (1990). Impairment of speech intelligibility in men with amyotrophic lateral sclerosis. *Journal of Speech and Hearing Disorders*, *55*(4), 721–728.

Kent, R. D., Sufit, R. L., Rosenbek, J. C., Kent, J. F., Weismer, G., Martin, R. E., & Brooks, B. R. (1991). Speech deterioration in amyotrophic lateral sclerosis: A case study. *Journal of Speech, Language, and Hearing Research*, *34*(6), 1269–1275.

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.

Kim, H., Martin, K., Hasegawa-Johnson, M., & Perlman, A. (2010). Frequency of consonant articulation errors in dysarthric speech. *Clinical Linguistics and Phonetics*, *24*(10), 759–770.

Kuruvilla, M. S., Green, J. R., Yunusova, Y., & Hanford, K. (2012). Spatiotemporal coupling of the tongue in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *55*(6), 1897–1909.

Kuruvilla-Dugdale, M., Custer, C., Heidrick, L., Barohn, R., & Govindarajan, R. (2018). A phonetic complexity-based approach for intelligibility and articulatory precision testing: A preliminary study on talkers with amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *61*(9), 2205–2214.

Langmore, S. E., & Lehman, M. E. (1994). Physiologic deficits in the orofacial system underlying dysarthria in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *37*(1), 28–37.

Lawyer, T., & Netsky, M. G. (1953). Amyotrophic lateral sclerosis: A clinicoanatomic study of fifty-three cases. *Archives of Neurology and Psychiatry*, *69*(2), 171–192.

Lee, J., Hustad, K. C., & Weismer, G. (2014). Predicting speech intelligibility with a multiple speech subsystems approach in children with cerebral palsy. *Journal of Speech, Language, and Hearing Research*, *57*(5), 1666–1678.

Liu, C.-T., Chen, L., Lin, Y.-C., Cheng, C.-F., & Chang, H. (2016). Speech intelligibility and the production of fricative and affricate among Mandarin-speaking children with cerebral palsy. *28th Conference on Computational Linguistics and Speech Processing*, 153–163.

Maniwa, K., Jongman, A., & Wade, T. (2008). Perception of clear fricatives by normal-hearing and simulated hearing-impaired listeners. *The Journal of the Acoustical Society of America*, *123*(2), 1114–1125.

McHenry, M., Minton, J., Wilson, R., & Post, Y. (1994). Intelligibility and nonspeech orofacial strength and force control following traumatic brain injury. *Journal of Speech, Language, and Hearing Research*, *37*, 1271–1283.

McLeod, S., Harrison, L. J., & McCormack, J. (2012). The intelligibility in context scale: Validity and reliability of a subjective rating measure. *Journal of Speech, Language, and Hearing Research*, *55*(2), 648–656.

Mefferd, A. S., & Dietrich, M. S. (2019). Tongue- and jaw-specific articulatory underpinnings of reduced and enhanced acoustic vowel contrast in talkers with Parkinson's disease. *Journal of Speech, Language, and Hearing Research*, *62*(7), 2118–2132.

Neel, A. T., Palmer, P. M., Sprouls, G., & Morrison, L. (2015). Muscle weakness and speech in oculopharyngeal muscular dystrophy. *Journal of Speech, Language, and Hearing Research*, *58*(1), 1–12.

Owren, M. J., & Cardillo, G. C. (2006). The relative roles of vowels and consonants in discriminating talker identity versus word meaning. *The Journal of the Acoustical Society of America*, *119*(3), 1727–1739.

Perry, B. J., Martino, R., Yunusova, Y., Plowman, E. K., & Green, J. R. (2018). Lingual and jaw kinematic abnormalities precede speech and swallowing impairments in ALS. *Dysphagia*, *33*(6), 840–847.

Platt, L. J., Andrews, G., Young, M., & Quinn, P. T. (1980). Dysarthria of adult cerebral palsy. *Journal of Speech and Hearing Research*, *23*, 28–40.

Riddel, J., McCauley, R. J., Mulligan, M., & Tandan, R. (1995). Intelligibility and phonetic contrast errors in highly intelligible speakers with amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *38*(2), 304–314.

Rong, P., & Green, J. R. (2019). Predicting speech intelligibility based on spatial tongue-jaw coupling in persons with amyotrophic lateral sclerosis: The impact of tongue weakness and jaw adaptation. *Journal of Speech, Language, and Hearing Research*, *62*(8S), 3085–3103.

Rong, P., Yunusova, Y., Wang, J., & Green, J. R. (2015). Predicting early bulbar decline in amyotrophic lateral sclerosis: A speech subsystem approach. *Behavioural Neurology*, *2015*, 1–11.

Searl, J., Knollhoff, S., & Barohn, R. J. (2017). Lingual–alveolar contact pressure during speech in amyotrophic lateral sclerosis: Preliminary findings. *Journal of Speech, Language, and Hearing Research*, *60*(4), 810–825.

Shriberg, L. D., Allen, C., McSweeny, J., & Wilson, D. (2000). *PEPPER: Programs to examine phonetic and phonological evaluation records [Computer software]*. The Phonology Project.

Shriberg, L. D., Kwiatkowski, J., & Hoffmann, K. (1984). A procedure for phonetic transcription by consensus. *Journal of Speech, Language, and Hearing Research*, *27*(3), 456–465.

Sidtis, J. J., Ahn, J. S., Gomez, C., & Sidtis, D. (2011). Speech characteristics associated with three genotypes of ataxia. *Journal of Communication Disorders*, *44*(4), 478–492.

Solomon, N., Lorell, D. M., Robin, D., Rodnitzky, R., & Luschei, E. S. (1995). Tongue strength and endurance in mild to moderate Parkinson's disease. *Journal of Medical Speech-Language Pathology*, *3*, 15–26.

Solomon, N. P., Makashay, M. J., Helou, L. B., & Clark, H. M. (2017). Neurogenic orofacial weakness and speech in adults with dysarthria. *American Journal of Speech-Language Pathology*, *26*(3), 951–960.

Solomon, N. P., Robin, D. A., & Luschei, E. S. (2000). Strength, endurance, and stability of the tongue and hand in Parkinson disease. *Journal of Speech, Language, and Hearing Research*, *43*(1), 256–267.

Stipancic, K. L., Yunusova, Y., Campbell, T. F., Wang, J., Berry, J. D., & Green, J. R. (2021). Two distinct clinical phenotypes of bulbar motor impairment in amyotrophic lateral sclerosis. *Frontiers in Neurology*, *12*, 1–9.

Strong, M. J., Abrahams, S., Goldstein, L. H., Woolley, S., Mclaughlin, P., Snowden, J., Mioshi, E., Roberts-South, A., Benatar, M., Hortobágyi, T., Rosenfeld, J., Silani, V., Ince, P. G., & Turner, M. R. (2017). Amyotrophic lateral sclerosis—Frontotemporal spectrum disorder (ALS-FTSD): Revised diagnostic criteria. *Amyotrophic Lateral Sclerosis and Frontotemporal Degeneration*, *18*(3–4), 153–174.

Theodoros, D. G., Murdoch, B. E., & Stokes, P. (1995). A physiological analysis of articulatory dysfunction in dysarthric speakers following severe closed-head injury. *Brain Injury*, *9*, 237–254.

Tjaden, K., & Turner, G. S. (1997). Spectral properties of fricatives in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *40*(6), 1358–1372.

Turner, G. S., & Tjaden, K. (2000). Acoustic differences between content and function words in amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *43*(3), 769–781.

Turner, G. S., Tjaden, K., & Weismer, G. (1995). The influence of speaking rate on vowel space and speech intelligibility for individuals with amyotrophic lateral sclerosis. *Journal of Speech, Language, and Hearing Research*, *38*(5), 1001–1013.

van Brenk, F., Stipancic, K., Kain, A., & Tjaden, K. (2022). Intelligibility across a reading passage: The effect of dysarthria and cued speaking styles. *American Journal of Speech-Language Pathology*, *31*(1), 390–408.

van der Merwe, A. (2009). A theoretical framework for the characterization of pathological speech sensorimotor control. In M. R. McNeil (Ed.), *Clinical management of sensorimotor speech disorders* (2nd ed., pp. 3–18). Thieme Medical Publishers.

Wang, J., Kothalkar, P. V., Kim, M., Bandini, A., Cao, B., Yunusova, Y., Campbell, T. F., Heitzman, D., & Green, J. R. (2018). Automatic prediction of intelligible speaking rate for individuals with ALS from speech acoustic and articulatory samples. *International Journal of Speech-Language Pathology*, *20*(6), 669–679.

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.

Wertz, R., LaPointe, L., & Rosenbek, J. (1991). *Apraxia of speech in adults: The disorder and its management*. Single Publishing Group.

Wood, L. M., Hughes, J., Hayes, K. C., & Wolfe, D. L. (1992). Reliability of labial closure force measurements in normal subjects and patients with CNS disorders. *Journal of Speech, Language, and Hearing Research*, *35*(2), 252–258.

Yorkston, K., & Beukelman, D. (1991). Staging interventions in progressive dysarthria. *Perspectives on Neurophysiology and Neurogenic Speech and Language Disorders*, *9*(4), 7–12.

Yunusova, Y., Graham, N. L., Shellikeri, S., Phuong, K., Kulkarni, M., Rochon, E., Tang-Wai, D. F., Chow, T. W., Black, S. E., Zinman, L. H., & Green, J. R. (2016). Profiling speech and pausing in amyotrophic lateral sclerosis (ALS) and frontotemporal dementia (FTD). *PLOS ONE*, *11*(1), e0147573.

Yunusova, Y., Green, J. R., Greenwood, L., Wang, J., Pattee, G. L., & Zinman, L. (2012). Tongue movements and their acoustic consequences in amyotrophic lateral sclerosis. *Folia Phoniatrica et Logopaedica*, *64*(2), 94–102.

Yunusova, Y., Green, J. R., Lindstrom, M. J., Ball, L. J., Pattee, G. L., & Zinman, L. (2010). Kinematics of disease progression in bulbar ALS. *Journal of Communication Disorders*, *43*(1), 6–20.

Yunusova, Y., Weismer, G., Kent, R., & Rusche, N. (2005). Breath-group intelligibility in dysarthria characteristics and underlying correlates. *Journal of Speech, Language, and Hearing Research*, *48*, 1294–1310.

Yunusova, Y., Weismer, G., Westbury, J., & Lindstrom, M. (2008). Articulatory movements during vowels in speakers with dysarthria and healthy controls. *Journal of Speech, Language, and Hearing Research*, *51*, 596–611.