A MULTIPLE SUBSYSTEM APPROACH TO PREDICTING SPEECH INTELLIGIBILITY DECLINES IN OLDER ADULTS

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

A MULTIPLE SUBSYSTEM APPROACH TO PREDICTING

SPEECH INTELLIGIBILITY DECLINES IN OLDER ADULTS

presented by Jacob McKinley,

a candidate for the degree of Master of Health Science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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ABSTRACT

Introduction: Given the significant impact of progressive dysarthrias on individuals' communication abilities and the increasing prevalence of progressive dysarthrias in the United States, it is becoming imperative to develop prediction models of speech intelligibility decline. As a first step, the present study focused on healthy older adults and specifically, on determining age-related effects on the respiratory, phonatory, and articulatory subsystems and their impact on speech intelligibility. For this purpose, we used a multiple subsystem approach similar to that used in the extant literature on cerebral palsy (Lee, Hustad, & Weismer, 2013) and amyotrophic lateral sclerosis (ALS; Rong et al., 2016). The aims of the present study were to (1) determine age-related changes to the respiratory, phonatory, and articulatory subsystems and (2) investigate whether speech intelligibility decline is observed in healthy older adults and if so, to determine which variables from each subsystem are predictive of intelligibility decline.

Method: Fifteen healthy, older adults and fifteen younger adults participated in instrument-based assessments of the phonatory, respiratory, and articulatory subsystems. Respiratory, acoustic, aerodynamic, and kinematic measures were obtained during syllable, sentence, word, and nonspeech tasks. Speech intelligibility for each speaker was determined by naïve listeners during multi-talker babble. Contributions of selected subsystem variables on speech intelligibility were determined using a multiple linear regression analysis.

Results: Age-related differences were detected across phonatory and articulatory subsystem measures including maximum phonation time and cepstral peak prominence (phonatory subsystem) and spatiotemporal variability index and maximum speed of tongue movements (articulatory subsystem). Selected variables in the phonatory and articulatory subsystem were significant predictors of speech intelligibility in older adults including laryngeal airway resistance (39%), airflow during voicing (35%), maximum phonation time (9%; phonatory subsystem) and duration (10%) and maximum speed (5%) of tongue movements (articulatory subsystem). Collectively, 98% of speech intelligibility variance in older adults could be explained by the phonatory (83%) and articulatory (15%) subsystem models.

Discussion: Significant subsystem differences between older and younger adults were found indicating age-related speech decline. Measures representing phonatory and articulatory subsystems predicted speech intelligibility differences in older adults suggesting that age-related speech declines such as breathy voice quality and age-related articulatory slowing contributed to intelligibility decline. Subsystem measures were more sensitive to age-related speech differences in older adults than intelligibility, which is a finding consistent in ALS literature (Ball, Willis, Beukelman, & Pattee, 2001; Green et al., 2013).

INTRODUCTION

Dysarthria

Many progressive neurologic conditions such as Parkinson's disease (PD) and Amyotrophic Lateral Sclerosis (ALS) will result in motor speech disorders (e.g., dysarthria) characterized by progressive loss of speech and eventual mutism. Dysarthria, specifically, is a collective name for several neurologic speech conditions that affect the strength, speed, range, steadiness, tone, or accuracy of one or more of the speech subsystems (e.g., phonatory, resonatory, respiratory, articulatory; Duffy, 2013). The impairments on these subsystems due to dysarthria often cause declines in speech intelligibility, that is, a listener's ability to understand the speaker (Kent et al., 1990; Kent, Weismer, Kent, & Rosenbek, 1989; Rong et al., 2016).

The epidemiology of progressive dysarthria in the United States is difficult to estimate due to the varying diseases which cause dysarthria and the various types of dysarthria that exist (e.g., flaccid, spastic, hypokinetic, hyperkinetic, unilateral upper motor neuron, mixed). One study analyzed a group of 14,235 people with acquired neurologic communication disorders at the Mayo Clinic and found that 53% of these patients had a primary diagnosis of dysarthria, inclusive of all dysarthria types (Duffy, 2013). Another study analyzed a group of adult patients with neuromuscular disorders and found that dysarthria affected the communication ability of 46-62% of those individuals (Knuijt et al., 2014). Overall, it is estimated that approximately 1.5 million Americans are diagnosed with progressive neurodegenerative conditions (ALS, PD, multiple sclerosis, and Huntington's) and that the majority of these individuals will develop progressive dysarthrias (Jones, 2016; Parkinsons's Disease Foundation, 2016; Schneider, 1999).

Despite the high incidence and prevalence, the diagnosis and tracking of progressive dysarthria remains challenging due to limitations of current measures such as speech intelligibility, which only provide a broad index of severity. Given the increasing prevalence of progressive dysarthrias due to the growth of the elderly population in the United States (American Medical Association, 2008) and the significant impact of progressive dysarthrias on individuals' communication abilities, it is becoming imperative to develop prediction models, that is, find a set of valid and reliable measures to better assess and predict declines in speech intelligibility in these individuals. As a first step, we will focus on determining whether and which speech subsystems contribute to the speech intelligibility decline in healthy older adults in the present study. This will be investigated through a multiple subsystem approach shown to predict intelligibility in individuals with cerebral palsy (Lee, Hustad, & Weismer, 2013) and ALS (Rong et al., 2016). By studying these effects in a healthy aging population we will be able to delineate healthy aging versus disordered processes, which will be used to inform future studies focused on predicting dysarthria progression. The following sections will give an overview of dysarthria types and normal aging processes and the impact of physiological changes due to these conditions on speech intelligibility.

Dysarthria Types and Their Impact on Speech Subsystems

Different types of dysarthria (e.g., flaccid, spastic, hypokinetic, hyperkinetic, unilateral upper motor neuron, mixed) impact the subsystems of speech (phonatory, resonatory, respiratory, and articulatory) in varying ways (Darley, Aronson, & Brown, 1975). For example, individuals with ALS most commonly present with either spastic or flaccid dysarthria, but eventually develop mixed spastic-flaccid dysarthria involving both upper motor neurons and lower motor neurons as the disease progresses. The deviant speech characteristics observed in talkers with spastic dysarthria include: slow, effortful, and imprecise speech as a result of phonatory (strained-strangled voice), resonatory (hypernasality), and articulatory (reduced range of movement, distorted consonants) deficits (Darley et al., 1975). Spastic dysarthria typically has the most significant effect on articulation, primarily resulting in imprecise consonant production. The predominant speech characteristics evident in flaccid dysarthria are: breathiness or aphonia (phonatory), nasal emission or hypernasality (resonatory), and imprecise or distorted consonants and vowels (articulatory; Darley et al., 1975). There are conflicting findings about the contribution of these speech subsystems to speech intelligibility decline in individuals with ALS. Some experts have suggested that resonatory impairments predominantly contribute to intelligibility decline (Duffy, 2013; Kent et al., 1990; Kent et al., 1992), whereas other findings suggest that declines in the articulatory subsystem contribute most significantly to intelligibility decline (Rong et al., 2016). Hypokinetic dysarthria is seen in individuals with PD and they primarily display phonatory characteristics such as monopitch and monoloudness, weak phonation, limited vocal endurance (Stemple, Roy, & Klaben, 2014), and decreased loudness (Ramig, 2004). The prosodic deficits seen in this patient population include variable rate and short rushes of speech (Darley et al., 1975).

Currently there are limitations that prevent the accurate prediction of speech decline in individuals with progressive dysarthria. Firstly, previous research has found that clinical measures for determining the presence and severity of dysarthria, such as speech intelligibility, are relatively insensitive at the mild-moderate stages of ALS (Ball, Willis, Beukelman, & Pattee, 2001). Another limitation is the current lack of knowledge about speech intelligibility decline as a result of physiologic changes in healthy older adults, which makes it challenging to determine whether intelligibility declines in older adults with progressive dysarthrias can solely be attributed to the disease process.

Impact of Normal Aging Process on Speech Subsystems

The normal aging process results in many physiologic changes in each speech subsystem, which start as early as 50 years (Hixon, Weismer, & Hoit, 2014). The physiologic changes in the healthy aging voice are referred to as presbyphonia or presbylaryngis (Kendall, 2007; Stemple et al., 2014). Presbylaryngis refers to inadequate glottic closure due to vocal fold atrophy (Gregory, Chandran, Lurie, & Sataloff, 2010). Changes in the phonatory subsystem can be perceptually detected as changes in pitch, reduced loudness, breathy and rough voice quality, and instability (Baker, Ramig, Sapir, Luschei, & Smith, 2001; Kendall, 2007). Respiratory subsystem differences typically present as declines in speech breathing patterns [e.g., higher lung volumes required for speech resulting in shorter speech phrases in the normal aging population (Hoit & Hixon, 1987; Huber & Spruill, 2008)]. Declines in tactile acuity, tongue and lip strength, and lip movement consistency observed in the aging population make it apparent that articulatory motor performance is altered in the normal aging process (Robbins, Levine, Wood, Roecker, & Luschei, 1995; Wohlert & Smith, 1998). Moreover, some studies have suggested that the structural and functional changes in the brain, such as slower neural firing, in the aging population manifest as a decline in motor function (de Miranda Marzullo et al., 2010; Sadagopan & Smith, 2014). Regardless of the cause, these changes related with the normal aging process have detrimental effects on speech production (Kent & Burkhard, 1981).

Neurologic changes due to diseases like ALS and PD are often overlaid on these aging subsystems, therefore, it is important to differentiate healthy aging versus disease processes (Dromey, Boyce, & Channell, 2014; Duffy, 2013). An improved understanding of the normal aging process and the impact that it has on speech subsystems is necessary to identify speech characteristics that are atypical and indicative of neurologic disease. While some speech changes in the normal aging process have been discovered including deterioration of vocal efficiency and quality (Baker et al., 2001; Gorman, Weinrich, Lee, & Stemple, 2008; Gregory et al., 2010; Kendall, 2007), declines in speech breathing (Hoit & Hixon, 1987; Huber & Spruill, 2008), and decreased articulator strength and acuity (Robbins et al., 1995; Wohlert & Smith, 1998), to the best of our knowledge, there is still a need to differentiate speech changes as a result of normal aging and motor speech disorders. Additionally, it will be important to discover whether these physiological differences in healthy older adults lead to speech intelligibility decline and if so, to what degree.

Speech Intelligibility

Currently, clinicians predict dysarthria progression through speech intelligibility testing. Speech intelligibility has been defined in various ways. In simple terms, intelligibility is the “degree to which a listener understands the acoustic signal produced by a speaker” (Duffy, 2013, p. 84). Speech intelligibility measures are easily obtained and communicated in clinical settings with patients and other professionals (Yorkston & Beukelman, 1981). Intelligibility testing has become a crucial aspect of assessment and treatment of dysarthria because of its capability to determine the overall degree of communication impairment and measure treatment progress over time.

The methods for measuring intelligibility currently used in clinical and research settings fall under two categories: transcription and scaling tasks. Both tasks may include the evaluation of speech at different levels including word, sentence, and conversation. Transcription involves having a listener orthographically transcribe the speaker’s message as they hear it and then compare it with the target production to calculate the percentage of intelligible words or words correctly understood. The Sentence Intelligibility Test (SIT; Yorkston, Beukelman, Hakel, & Dorsey, 2007) is an example of a transcription-style intelligibility measure and is the most commonly used intelligibility test (Duffy, 2013; Stipancic, Tjaden, & Wilding, 2016; Yorkston, Beukelman, Strand, & Hakel, 2010). Scaling tasks allow listeners to mark on a visual analogue where they perceive the person’s level of intelligibility. Stipancic et al. (2016) found a moderately strong relationship between the transcription and scaling tasks. The authors concluded that while orthographic transcription remains the gold standard for measuring intelligibility, less time-consuming methods such as scaling tasks can be considered as alternative intelligibility measures. Intelligibility testing has several advantages as an assessment for dysarthria progression including its quick and easy administration, non-invasive nature, and ease of use with patients with a range of speech and language skills.

Sentence intelligibility tests may be used if the individual has a mild to moderate dysarthria and is capable of completing the task, whereas a word intelligibility test is used with more severe speech impairments. Sentence tests are preferred when appropriate because they provide a realistic analysis of a persons' speech and serve as an overall index of severity (Weismer, 2009).

Despite their widespread clinical use, intelligibility tests have several limitations. One of these limitations is the subjective nature of intelligibility tests, regardless of whether transcription or scaling tasks are used, and the high inter-rater variability (Hustad & Beukelman, 2002). Secondly, speakers tend to put their best effort forward when they know that they are completing a speech assessment and lastly, listeners get contextual cues from the sentences, which may result in an overestimation of speech intelligibility (Hustad & Beukelman, 2002; Hustad & Garcia. 2002). As of now, intelligibility tests do not have the ability to accurately predict the rate at which intelligibility decline will progress; they only provide an overall index of severity or functional oral communication at the time of the test. Moreover, while we know that specific dysarthria types disproportionately affect one subsystem over others, it is difficult to delineate subsystem involvement using the intelligibility score (Hustad & Weismer, 2007). Therefore, there is a need to identify objective measures across speech subsystems that can accurately predict intelligibility decline.

Physiologic Changes to Each Speech Subsystem and Their Impact on Speech Intelligibility

As previously discussed, physiologic changes to the speech subsystems occur as a result of healthy aging and progressive diseases. There is emerging research on the relationship between these physiologic changes and speech intelligibility in different neurologic diseases, but to the best of our knowledge no studies to date have examined this relationship in a healthy aging population. The earliest studies focused on identifying subsystem contributions to intelligibility, were those of Kent and colleagues who identified phonetic features associated with speech intelligibility declines in men (Kent et al., 1990) and women (Kent et al., 1992) with ALS. They found that velopharyngeal features predominantly impacted speech intelligibility in both men and women with ALS, which provided valuable clinical insights for improving the assessment and treatment of dysarthria despite the reliance on perceptual measures.

Recent studies have used more comprehensive sets of physiologic measures for each subsystem to evaluate speech intelligibility in patient populations (de Bodt, Huici, & Van De Heyning, 2002; Lee et al., 2014, Rong et al., 2016). This work is particularly informative to linking what we know about subsystem decline as a result of specific diseases and consequential breakdowns in communication. De Bodt et al. (2002) used auditory-perceptual judgments for several dimensions (voice quality, prosody, nasality, and articulation), as well as intelligibility to determine the relationship between perceptually detectable speech subsystem differences and intelligibility decline in speakers with dysarthria. This study found that the judgements related to the articulatory subsystem had the strongest correlation with intelligibility. While auditory-perceptual measures may be easily transferred to a clinical setting, they are significantly limited by listener biases.

Lee et al. (2014) investigated the effect of different subsystems, measured specifically by acoustic features, on speech intelligibility in children with cerebral palsy. The authors selected particular acoustic variables to assess the different speech subsystems. Acoustic features used to characterize the articulatory subsystem like vowel space, vowel duration, and F2 slope were found to have the largest impact on intelligibility. Similarly, Kim, Kent, and Weismer (2011) investigated acoustic predictors of speech intelligibility decline at the word and sentence level in individuals with different types of dysarthria caused by PD, stroke, multiple system atrophy, and traumatic brain injury. They too found that F2 slope was the most sensitive acoustic measure for predicting speech intelligibility across dysarthria types. However, while acoustic features may provide an easy transfer to clinical application, they "do not unambiguously represent the status of individual speech subsystems" (Rong et al., 2016, p. 2). This is true especially for the articulatory subsystem because there may not be a one-to-one correspondence between articulatory adjustments and acoustic events (Mefferd & Green, 2010; Stevens, 1972, 1989).

The most recent study by Rong et al. (2016) used a longitudinal, subsystem approach to investigate the relationship between acoustic, aerodynamic, and kinematic measures and intelligibility of individuals with ALS. They found that the articulatory subsystem characterized by kinematic measures, such as articulator movement speed, showed the most substantial contribution to intelligibility decline over time, similar to the results of De Bodt et al. (2002) and Lee et al. (2014). The order of subsystem contribution to intelligibility observed in the Rong study started with the articulatory subsystem, followed by the resonatory, then the phonatory, and finally the respiratory subsystem. This study demonstrated that a multi-subsystem model, along with instrumentation-based subsystem measures accounts for individual and comprehensive subsystem contributions and effectively predicts intelligibility.

The present study intends to use similar multiple subsystem models of predicting intelligibility to that of Lee et al. (2014) and Rong et al. (2016). More specifically, we will use acoustic and aerodynamic measures that characterize the phonatory system in addition to aerodynamic and kinematic measures that assess the respiratory and articulatory subsystems, respectively. Further, the present study will utilize a sentence intelligibility test instead of a single word intelligibility measure (Yorkston, et al., 2007).

Purpose of the Present Study

While the long-term goal of the proposed research is to create prediction models of intelligibility for individuals with progressive dysarthrias, it is an important first step to establish whether declines in intelligibility are present in the typical aging population and to determine the relationship between specific subsystem measures and intelligibility decline. Progressive neurologic conditions which result in progressive dysarthrias, such as PD, are overlaid onto aging subsystems, so the impact of aging and dysarthria must also be differentiated. An intelligibility prediction model may then be established to improve the accuracy of speech assessments and to inform patients how fast their speech will deteriorate so that they are able to make personal, financial, and treatment decisions. From a clinician's perspective, developing a prediction model will not only allow them to present treatment options such as augmentative and alternative communication in a timely manner but will also allow them to set effective and appropriate therapy goals to best serve clients' present and future communication needs. The purpose of the present study is to address this gap in the literature by obtaining respiratory (aerodynamic), phonatory (acoustic, aerodynamic), and articulatory (kinematic) data as part of a comprehensive subsystem analysis to predict intelligibility in healthy older adults.

Aims and Hypotheses

1. To determine age-related changes to the respiratory, phonatory, and articulatory subsystems. We predict that:
    a. Vital capacity will be a respiratory measure demonstrating significant age-related differences based on normative data from Zraick, Smith-Olinde, and Shotts (2012).
    b. The Cepstral/Spectral Index of Dysphonia (CSID) will be a phonatory acoustic measure sensitive to age-related differences (Watts, Ronshaugen, & Saenz, 2015). In addition, maximum phonation time (MPT) will be a respiratory-laryngeal measure showing significant age-related differences based on an aging study from Awan (2006).
    c. Spatiotemporal movement variability will be an articulatory kinematic measure that demonstrates significant age-related differences (Wohlert & Smith, 1998)
2. To investigate whether speech intelligibility decline is observed in healthy older adults and if so, to determine which variables from each subsystem (respiratory, phonatory, articulatory) are predictive of intelligibility decline. Predictions for

subsystem contributions to intelligibility decline were difficult to make because so far, intelligibility models based on subsystem measures have only been developed for ALS (Rong et al., 2016; Kent et al., 1992; Kent et al., 1990) and CP (Lee et al., 2013). However, within each subsystem predictions about the independent contribution of each variable to the variance in intelligibility scores were made based on the extant aging literature.

a. We predict that among all phonatory measures, acoustic measures will correlate most with speech intelligibility changes, specifically measures contributing to the multivariate CSID, based on the findings from Watts and colleagues (2015) where CSID values were significantly higher in older compared with younger adult males. High CSID values correlate with higher auditory-perceptual ratings of dysphonia severity (Awan, Roy, Jette, Meltzner, & Hillman, 2010) and may impact intelligibility.

b. We predict that both spatiotemporal movement variability and movement speed will have strong associations with speech intelligibility based on the aging study by Wohlert and Smith (1998) and kinematic studies that suggest movement speed is an early indicator of speech decline (Green et al., 2013).

METHOD

Participants

Speakers

Fifteen healthy, older adults (50-90 years) and fifteen healthy, younger adults (20-35 years) were recruited to participate in the present study. All participants were native speakers of English and had no history of speech or language impairments; neurological disorders; stroke; head/neck/thoracic trauma, surgery, or cancer; diagnosed voice disorders or self-report of voice problems; pulmonary disorders; smoking in the past 5 years; or metal implants in the head and/or upper body. Participants with hearing loss affecting one-on-one conversation were excluded. Further, participants that had a score of <26 on the Montreal Cognitive Assessment were excluded (Nasreddine et al., 2005). All participants were provided written consent and were compensated for their participation.

Listeners

Five naïve listeners who were unfamiliar with the test materials as well as each participant listened to and transcribed the sentence intelligibility speech samples. The listeners were undergraduate students in communication science and disorders at the University of Missouri, Columbia. Only listeners who met the following criteria were included: (a) native speakers of American English; (b) pass a pure-tone hearing screening at 25 dB HL at 1, 2, and 4 kHz bilaterally; (c) between 18 and 40 years of age; (d) have no language, learning, or cognitive disabilities based on self-report; and (e) unfamiliar with the test materials.

Materials and Procedures

Each participant attended two sessions: the first session, focused on the respiratory-laryngeal subsystems, was used to capture acoustic and aerodynamic data, as well the Voice Handicap Index (VHI; Jacobson, Johnson, & Grywalski, 1997). The second session, focused on the articulatory subsystem, was used to track and record tongue kinematics, strength, and endurance data as well as speech intelligibility. Participants were required to attend the two sessions within one week of the other. The study was approved by the University of Missouri Institutional Review Board. All participants provided informed consent and were paid for their participation.

Stimuli

a) Stimuli used across subsystems

The majority of the connected speech and single word stimuli were used to assess all three subsystems. These speech stimuli were carefully selected due to their phonetic characteristics. More specifically, four target words comprised of alveolar (e.g., /t, d/) or velar sounds (e.g., /k, g/) that capture tongue movement along the vertical axis were selected from the Multiple-Word Intelligibility Test (Kent et al., 1989). These monosyllabic words were embedded into a short phrase (e.g., "Say _____ again") in order to ensure naturalness of production and minimalize variability associated with tongue position at word onset and offset. Each target word, along with two foil words, were repeated 10 times for acoustic, aerodynamic, and kinematic data collection (see Table 1 for details about the stimuli as well as the subsystem and measures each is associated with).

Similar to the word stimuli, three target sentences comprised predominantly of alveolar and velar consonants were selected from the Harvard sentences (Institute of Electrical and Electronics Engineers, 1969). Participants were asked to produce a total of 108 different sentences for each subsystem assessed. Among the 108 sentences, each target sentence was presented 10 times and each time the target sentence was presented along with two foil sentences. The same procedure and order was followed for acoustic, aerodynamic, and kinematic data collection (see Table 1).

b) Specific phonatory and respiratory measures

Participants produced sentences from the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V; Kempster, Gerratt, Abbott, Barkmeier-Kraemer, & Hillman, 2009) and the Rainbow Passage (Fairbanks, 1960) in the first session as part of standard clinical acoustic analysis of voice in speech. To assess respiratory-laryngeal voicing efficiency, participants produced the syllable “pi” five times in a row on one breath at 90 bpm and with comfortable pitch and loudness. The syllable string was repeated three separate times. In addition, participants phonated /a/ for as long as they can, three times. To assess respiratory function, participants exhaled maximally, after inhaling maximally, three times. Target words and sentences common across subsystems were collected after the CAPE-V sentences for acoustic measurements and again after vital capacity and maximum sustained phonation measurements for aerodynamic measurements. The voicing efficiency task was completed last.

c) Intelligibility

Speech intelligibility data were obtained using the sentence intelligibility test (SIT). Each participant produced 10 randomized five to 15 word sentences generated by the SIT program.

Data Acquisition

Phonatory and respiratory data acquisition

In the first session, each participant first completed the Voice Handicap Index (VHI; Jacobson et al., 1997). This 30-item questionnaire allowed each participant to self-report their voice complaints in regard to functional, physical, and emotional issues on a 5-point scale (Stemple et al., 2014). Then acoustic, respiratory-laryngeal, and respiratory data were collected during sentence and single word productions using the *Analysis of Dysphonia in Speech and Voice* (ADSV, Awan, 2011) program (Computerized Speech Lab [CSL] Model 4500, KayPentax, Lincoln Park, NJ) and during exhalation, sustained vowels, syllables, and sentence and single word productions using the *Phonatory Aerodynamic System* (PAS, Model 6600; KayPentax, Lincoln Park, NJ). A headset microphone (AKG C520, Vienna, Austria) was used for acoustic recordings and was distanced 4 cm from the participants' corner of the mouth. All data collection during the first session occurred in a soundproof acoustic booth (IAC Acoustics, North Aurora, IL) and participants were seated facing a computer screen, which displayed the stimuli. Participants also produced the syllable “pi” five times in a row at 90 bpm, and repeated that three separate times and then produced the sound /a/ for as long as they can, three times. Each participant was required to complete one respiratory task to assess vital capacity three separate times, which involved inhaling maximally and then exhaling maximally. The first session took approximately one hour to complete.

Kinematic data acquisition

In the second session, tongue kinematic data were collected during sentence and single word productions using an electromagnetic articulograph (Wave Speech Research System, NDI, Waterloo, ON, Canada). Participants were seated in a comfortable position approximately 10 cm from the transmitter that generates the electromagnetic field by which orofacial sensors are tracked in 3D space (see Figure 1a). Sensors were attached along the mid-sagittal plane to three locations on the tongue that corresponds to the tip, middle, and back. The first sensor on the tongue was placed 1 cm from the tongue tip, the second was placed 1.5 cm from the first sensor, and the third was placed 1.5 cm from the second sensor. Two sensors were also attached to the mandibular gingiva under the lateral incisors on each side and one sensor was affixed to the vermillion border of the lower lip (see Figures 1b & c). All of the sensors placed in and around the mouth were attached using a non-toxic dental adhesive (PeriAcryl®90, Glustitch Inc.). A 6DOF (degrees of freedom) head sensor served as the reference sensor to create a local coordinate system to express movement from each of the orofacial sensors in the x, y, and z axis (Green et al., 2013). The head sensor was attached to an adjustable headband to avoid skin motion artifacts (Green & Wilson, 2006). Another 6DOF sensor attached to a palate probe was used to capture each participant's palate geometry and help locate other articulators. Movement data was collected at a sampling rate of 400 Hz. Audio signals were recorded at a sampling rate of 22,000 Hz using a solid state recorder (Marantz, PMD670) and high quality condenser microphone (Shure, PG42) placed 20 cm from the participant’s mouth. The sentence and word stimuli were presented visually on a television screen (Samsung, BN68).

(a) (b) (c)

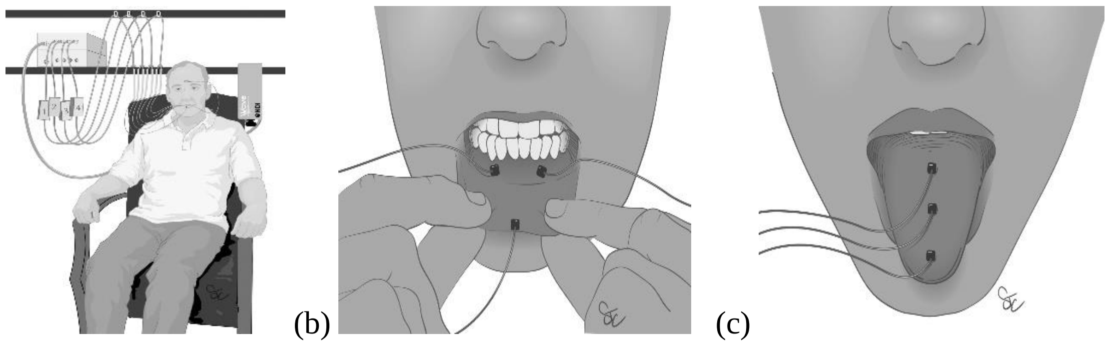

Figure 1. (a) Wave Speech Research System set-up; (b) placement of lower lip and jaw markers; (c) placement of tongue tip, mid, and back markers.

Tongue strength and endurance were measured using the Iowa Oral Performance Instrument (IOPI Medical, Redmond, WA). The IOPI measures tongue pressure using a small air-filled plastic tongue bulb which is connected through plastic tubing to a hand-held instrument (see Figure 2). For the strength task, participants inserted the tongue bulb against their hard palate and, using their tongue, pushed as hard as they can for two seconds. For the endurance task, the participants were instructed to press the tongue bulb against the hard palate at 50% of their average maximum pressure as determined from the strength task, for as long as they can. Both the tongue strength and endurance tasks were repeated three times. For the second session, the articulatory kinematic data were collected first followed by the IOPI and lastly the sentence intelligibility test. The second session took approximately one hour.

Table 1. Instruments, Protocols, and Measures Utilized to Collect Data from Each Stimuli Type and Which Subsystem They Represent.

Stimuli Type	Tasks	Speech Subsystem(s)	Instrument/ Protocol Used	Outcome Measures
Connected speech	Harvard sentences: - Cats and dogs each hate the other. - The grass curled around the fence post. - The cup cracked & spilled its contents. Repeated 10 times for each subsystem.	Respiratory-laryngeal (Session 1)	PAS, Running Speech	Intensity (dB), mean airflow during voicing (L/s)
		Respiratory-laryngeal (Session 1)	CSL/ADSV	CPP (*M*, *SD* in dB, L/H ratio (*M*, *SD* in dB), CSID, intensity (dB)
		Articulatory (Session 2)	EMA	STI
Single words	Multiple-word Intelligibility Test: - Ache, ate, cake, tell; inserted in phrase "Say _____ again" x 10	Respiratory-laryngeal (Session 1)	PAS, Running Speech	Intensity (dB), mean airflow during voicing (L/s)
		Respiratory-laryngeal (Session 1)	CSL/ADSV	CPP (*M*, *SD* in dB, L/H ratio (*M*, *SD* in dB), CSID, intensity (dB)
		Articulatory (Session 2)	EMA	Velocity (mm/s), distance (mm), duration (seconds)
Syllable production	/pi/ - 3 strings with 5 repetitions each at comfortable pitch and loudness at a rate of 90 bpm	Respiratory-laryngeal (Session 1)	PAS, Voicing Efficiency	Mean peak air pressure (P_{sub} cmH_2O), mean airflow during voicing (L/s), airway resistance (P_{sub}/airflow), intensity (dB)
Vowel production	Take a deep breath and sustain the sound /a/ for as long as possible x3	Respiratory-laryngeal (Session 1)	PAS, Maximum, Sustained Phonation	Duration (s), intensity (dB)
Nonspeech tasks	Inhale maximally, then exhale maximally x3	Respiratory (Session 1)	PAS, Vital Capacity	Expiratory volume (L)
	Press the tongue bulb as hard as possible for 2 secs x 3	Articulatory (Session 2)	IOPI	Maximum Pressure (kPa)
	Squeeze the tongue bulb at 50% max. pressure for as long as possible x 2	Articulatory (Session 2)	IOPI	Tongue Endurance (s)
Voice quality of life	30 questions on a 5-point scale	Respiratory-Laryngeal (Session 1)	VHI	Total score
Sentence Intelligibility Test	10 randomized 5-15 word sentences generated by the SIT	Sentence Intelligibility (Session 2)	SIT	Percentage correct in transcription

Note. Phonatory Aerodynamic System (PAS), Computerized Speech Lab (CSL), Analysis of Dysphonia in Speech and Voice (ADSV), Electromagnetic Articulography (EMA), Sentence Intelligibility Test (SIT), Iowa Oral Performance Instrument (IOPI); cepstral peak prominence (CPP), L/H spectral ratio (low to high spectral ratio), Cepstral/Spectral Index of Dysphonia (CSID), Spatiotemporal Index (STI), beats per minute (bpm), Voice Handicap Index (VHI).

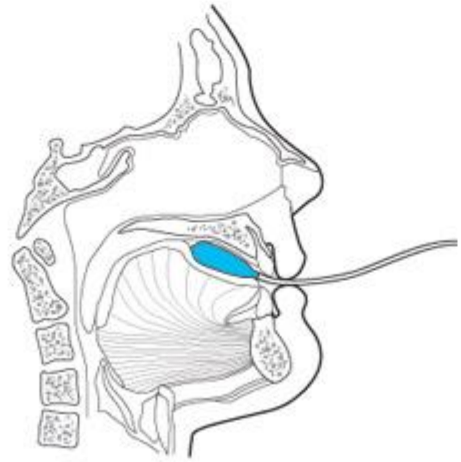

Figure 2. Placement of the Iowa Oral Performance Instrument tongue bulb (IOPI Medical, Redmond, WA).

Data Analysis

All of the measures were selected for the present study because prior research showed their ability to detect significant differences between older and younger adults that bear relevance for speech intelligibility or because they are state-of-the art sensitive measures of voice and speech function.

Respiratory data analysis

Respiratory data collected from the vital capacity task were analyzed using the PAS. Three repetitions of the vital capacity task were analyzed and averaged from the onset of exhalation until the end of exhalation.

Respiratory outcome measures

The primary measure to represent the respiratory subsystem was vital capacity (expiratory volume in L). Research has shown significantly smaller expiratory volume in older compared with younger adults (Zraick et al., 2012). Speech intelligibility has the potential to be impacted when older adults do not have the respiratory capability to support speech.

Phonatory data analysis

Acoustic data from connected speech and single word productions were analyzed using the ADSV program. The entirety of each production was selected and analyzed to obtain cepstral-spectral data and CSID values. Of note, currently the ADSV program does not automatically provide CSID values for the Rainbow Passage (second and third sentence) but a CSID formula for the Rainbow Passage was provided in Awan, Roy, and Dromey (2009), which was used to calculate those values. Values from the first three repetitions of Harvard sentences and single word productions were averaged. In some cases, the first three productions did not meet measurement criteria (i.e., were not able to be segmented from productions of other target words or sentences) and successive productions of that target, which met measurement criteria, were used instead.

Respiratory-laryngeal data were analyzed through the PAS programs. The length of duration for the maximum phonation time (MPT) task was analyzed and averaged from three productions. Analysis of voicing efficiency was based on the average of the middle three /pi/ productions from three sets or a minimum of six qualitatively acceptable /pi/ productions across sets following guidelines by Solomon (2011) and Solomon and Helou (2013).

Phonatory outcome measures

Several studies have shown significant differences in traditional time-based perturbation measures between older and younger adults, including jitter, shimmer, noise-to-harmonic ratio, and more (Awan, 2006; Xue & Deliyski, 2001). However, such traditional measures rely on sustained vowel productions and are not ecologically valid to make inferences about speech intelligibility. Cepstral/spectral acoustic analyses work for the analysis of voice in connected speech and provide a more defined display of acoustic signals and appear to be sensitive to potentially subtle differences in voice quality between older and younger adults (Awan, 2006; Watts et al., 2015;). The cepstral/spectral measurement that displayed sensitivity was the Cepstral/Spectral Index of Dysphonia (CSID) (Watts et al., 2015), which is a multivariate estimate of dysphonia severity. This index is made up of measures such as cepstral peak prominence (CPP in mean and *SD*), low/high spectral ratio (L/H ratio in mean and *SD*), of which in particular the mean CPP was sensitive to differences in older and younger adults (Awan, 2006). Age-related changes in voice quality as detected with these cepstral/spectral acoustic measures may cause distortion of the signal and therefore impact speech intelligibility.

Measures used to represent the phonatory subsystem will include acoustic (Cepstral/Spectral Index of Dysphonia; CSID) and respiratory-laryngeal measures (MPT in seconds and voicing efficiency [mean peak subglottal pressure in cm H_2O, mean airflow during voicing in L/s, airway resistance as the ratio of subglottal pressure and airflow]). Declines in MPT were present in an aged population compared with younger populations (Awan, 2006). While voicing efficiency was not significantly different among age groups (Zraick et al., 2012), studies have shown a trend for increased airflow during voicing with aging (Gorman et al., 2008; Zraick et al., 2012), which may result in breathiness and lack of projection. Intensity (dB) will be tracked across stimuli because of its possible impact on speech intelligibility; however it will not be a primary measure.

Age-related changes in respiratory-laryngeal function may impact older adults' ability to increase their vocal loudness to be understood by others and produce clear voice quality, which are both relevant for speech intelligibility.

A self-report measure of phonatory function was included as well. Previous research showed that voice-related quality of life in individuals with presbyphonia was often in the disordered range compared with vocally healthy young adults because of complaints about voice quality and difficulties being heard (Etter, Stemple, & Howell, 2013; Gregory et al., 2012). The participants' ratings of the 30 statements on the VHI were totaled. The VHI was not used as a primary outcome measure.

Kinematic data analysis

In order to calculate STI we first parsed each target word and sentence using SMASH (Green et al., 2013) which is a custom written Matlab tool (The MathWorks, Inc., 2012b). Word stimuli was segmented from the carrier phrase using the vertical displacement time histories corresponding to the primary place of articulation for consonants at the beginning and end of each word or sentence. For example, the target word '*cake*' the vocal tract constriction for the initial and final velar consonants which coincides with the peak displacement of the tongue back sensor was used as the word onset and offset, respectively. Sentence stimuli were segmented similarly, using the primary place of articulation for consonants at the beginning of the first word in the sentence and the end of the last word in the sentence. For example, the target sentence '*cats and dogs each hate the other*' was segmented using the vocal tract constriction for the initial velar consonant of '*cats*' which coincides with the peak displacement of the tongue back sensor and the final velar consonant of ‘*other*’ which coincides with the peak displacement of the tongue middle sensor (see Figure 3 for an example).

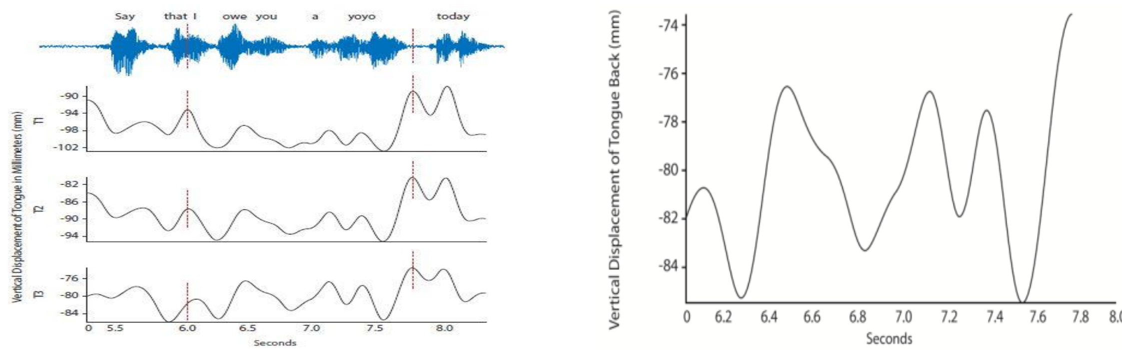

Figure 3. (a) Onset and offset points based on peak displacement of the T1 sensor that were used to segment the target sentence ‘I owe you a yoyo’ from the carrier phrase. (b) vertical displacement of the T3 (tongue back) sensor for *‘I owe you a yoyo’.*

Because the STI examines the spatiotemporal pattern consistency over several productions of an utterance, the time and amplitude of each vertical tongue displacement trajectory for each repetition of the target stimuli was normalized. To normalize amplitude, the mean of each displacement was subtracted and divided by the standard deviation. Once the movement data were amplitude normalized, a cubic spline procedure was used to adjust each movement trajectory onto a constant axis length of 1000 points to achieve time-normalization. Standard deviations (SD) of 10 normalized tongue displacement trajectories were then calculated at fixed 2% intervals in relative time. STI was then the sum of 50 SD (see Figure 4).

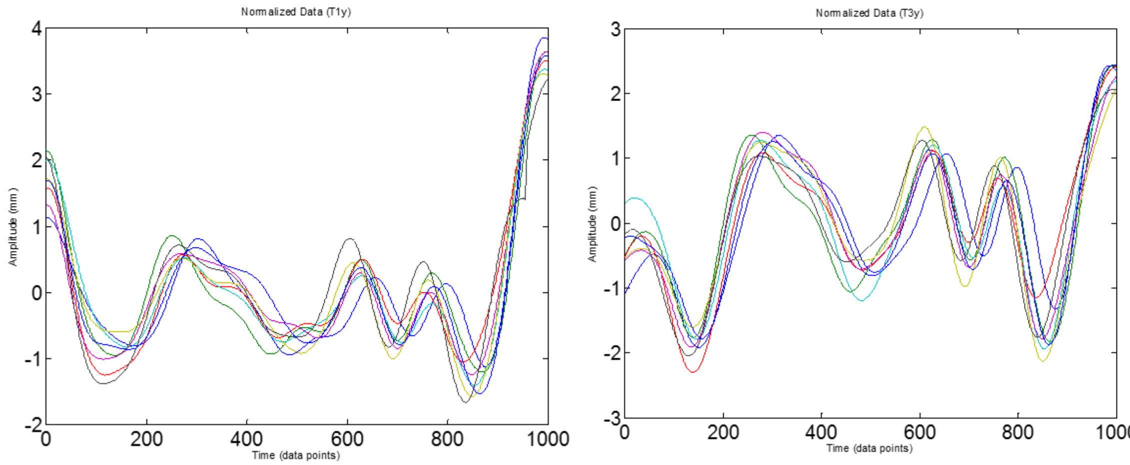

Figure 4. An example of amplitude and time-normalized vertical displacement trajectories of the tongue-tip (T1) and tongue-back (T3) for '*I owe you a yoyo*'.

Kinematic outcome measures

The STI (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995), tongue strength (maximum pressure in kPa), and endurance (duration in seconds) were selected as the primary measures to represent the articulatory subsystem. Wohlert and Smith (1998) found that older adults had increased lip movement variability (higher STI values) during speech as compared to younger adults. These authors also found that older adults demonstrated declines in lip strength, tactile acuity, and rate of speech. Much of the research analyzing articulator movement variability has focused on jaw and lip movements while tongue kinematic and strength data has been sparse (Chen et al., 2008; Green et al., 2013; Kuruvilla, Green, Yunusova, & Hanford, 2012; Kuruvilla-Dugdale, Isabelle, & Chuquilin, 2016; Kuruvilla-Dugdale & Mefferd, 2016; Mefferd, Green, & Pattee, 2014; Solomon, Robin, & Luschei, 2000). Previous research has found that auditory-perceptual (De Bodt et al., 2002), acoustic (Lee et al., 2013), and kinematic (Rong et al., 2016) measures that represent the articulatory subsystem are sensitive to differences in intelligibility in dysarthric speakers.

Tongue strength and endurance data analysis

Tongue strength indexed by maximum pressure (kPa) was averaged across the three trials of the task. For the endurance task, the pressure was set at 50% of the participants' average peak pressure during the tongue strength task. Their endurance to maintain this pressure was recorded in seconds and averaged over the three trials.

Speech intelligibility data analysis

A disadvantage of speech intelligibility tests is the potential for ceiling effects, especially when examining a healthy individual. Multi-talker babble has been used in intelligibility studies as a way of eliminating ceiling effects of non-disordered speakers (Tjaden, Sussman, & Wilding, 2014). This method interferes with the transmission system in order to generate a more challenging listening environment. This is an ecologically valid method and takes advantage of typical noise and frequencies of background speech present in most speaking environments. To avoid the possibility of ceiling effects in intelligibility tests with healthy adult participants, the present study utilized the multi-talker protocol proposed by Tjaden et al. (2014). This method allowed the researchers to determine whether intelligibility decline can be observed in the typical aging population in a functional listening environment.

Naïve listeners who are unfamiliar with the test materials listened to and transcribed the sentence intelligibility speech samples. The samples were mixed with multi-talker babble with a signal-to-noise ratio of -1 dB. Listeners will hear speech samples in a soundproof acoustic booth **(**IAC Acoustics, North Aurora, IL). The outcome measure for speech intelligibility was percentage correct in transcription of sentences from the SIT.

Statistical Analysis

To investigate age-related decline in respiratory, phonatory, and articulatory subsystems, both univariate and multivariate analysis of variance was used. All data were screened in order to determine if assumptions for each analysis of variance (ANOVA) were met. The Brown-Forsythe test (α=.05) was used to test the homogeneity of variance for between-subjects ANOVAs, and results had to be non-significant. In addition, for any proposed mixed ANOVA compound symmetry, i.e. homogeneity of variance and covariance was tested. For that purpose, both Box's *M* (α=.001) and Mauchly's test of sphericity (α=.05) was used and both results should be non-significant. If either test was significant, the Huynh-Feldt adjustment was used. The Shapiro-Wilk test was used to test for normality (α=.05) and results should be non-significant as well. However, ANOVA is known to be robust against violations of normality (Glass & Hopkins, 1996). Violations of normality were screened and reported, but no action was taken. Further, the independence of subjects was assumed. Finally, the data were examined for extreme outliers (> 3 *SD*), however, large variability in the dataset was expected and no outliers were excluded. To investigate the phonatory and kinematic predictors of speech intelligibility, a simultaneous method of multiple linear regression was used. First, multiple predictor variables from the phonatory and articulatory subsystems (e.g., four phonatory variables, five articulatory kinematic variables) were entered separately into a simultaneous multiple linear regression to determine the combined influence of all the variables within a subsystem on sentence intelligibility. Additionally, in order to examine the independent contribution of each subsystem variable to variance in intelligibility scores a hierarchical stepwise regression analysis was performed. Among the predictor variables, one variable was entered into the second block and all of the remaining variables from the same subsystem were entered into the first block. An incremental R^2 change for the first and second block were examined to determine the independent contribution of the variable entered in the second block relative to the model specified by the first block.

RESULTS

Age-related Subsystem Differences

Participant Characteristics

Mean and standard deviation of VHI scores were calculated for each group. The older group demonstrated a mean VHI score of 5.8 (*SD* = 5.69) and the younger group a mean score of 8.60 (*SD* = 13.56). One extreme outlier from the younger group significantly impacted the data and when removed from selection the younger adults demonstrated a mean VHI score of 5.50 (*SD* = 6.55). Thus, the groups were comparable on perceived voice quality of life. The low scores underscore the fact that these individuals were not seeking treatment for voice disorders.

Respiratory subsystem

A one-way between-subjects ANOVA was performed on expiratory airflow (L) as a function of age (older adults vs. younger adults). The mean for the younger group was 3.47 L (*SD* = 0.99, range 1.93-5.19) and the mean for the older group 2.96 L (*SD* = 0.96, range 1.55-4.93). There was not a significant difference on expiratory airflow as a function of age [$F(1,28) = 2.08$, $p = .161$].

Phonatory subsystem

A one-way between-subjects ANOVA was performed on MPT (s) as a function of age (older adults vs. younger adults). The mean for the younger group was 23.72 s (*SD* = 7.91, range 12.76-34.78) and the mean for the older group 16.45 s (*SD* = 7.16, range 9.02-35.68). The assumption of normality was violated in the older group but not corrected as ANOVA is robust against violations of normality. There was a significant difference on MPT as a function of age [$F(1,28) = 6.96$, $p = .013$]. The older adults had shorter MPTs than the younger adults.

A one-way between-subjects multivariate analysis of variance (MANOVA) was performed on mean peak air pressure (cmH_2O), mean airflow during voicing (L/s), and aerodynamic resistance (cmH_2O/[L/s]) as a function of age (older adults vs. younger adults). The descriptive data are presented in Table 2. Data from five participants in the older group were excluded because the voicing efficiency data did not meet quality criteria (Solomon, 2011). The assumption of normality was violated for aerodynamic resistance in both groups but not corrected as ANOVA is robust against violations of normality. There were no significant differences on voicing efficiency measures as a function of age [mean peak air pressure and mean airflow during voicing $F < 1$, airway resistance $F(1,23) = 1.41$, $p = .247$].

Table 2. Descriptive Statistics for Voicing Efficiency Data (Mean Peak Air Pressure, Mean Airflow During Voicing, Airway Resistance) as a Function of Age (Younger vs. Older Adults).

	Younger (*n* = 15)		**Older (*n* = 10)**	
	M	***SD* (range)**	***M***	***SD* (range)**
Mean Peak Air Pressure (cmH_2O)	7.88	1.82 (4.63-10.75)	7.44	1.4 (5.35-10.44)
Mean Airflow During Voicing (L/s)	0.144	0.06 (0.03-0.24)	0.160	0.06 (0.10-0.26)
Airway Resistance (cmH_2O/[L/s])	63.86	38.14 (23.48-185.08)	48.98	11.88 (37.04-76.42)

A 3x2 two-way mixed model ANOVA was performed on mean airflow during voicing (L/s) as a function of the between-subjects factor age (older adults vs. younger adults) and the within-subjects factor stimuli (Harvard sentences: Cats and dogs each hate the other; The grass curled around the fence post; The cup cracked and spilled its contents). Descriptive results are presented in Table 3. Assumptions were tested and because Mauchly's test of sphericity was significant, the Huynh-Feldt adjustment was used. The pattern of airflow among stimuli was not significantly different between groups [$F(1.82,50.90) = 1.73$, $p = .190$]. There was no significant difference on airflow between groups averaged across stimuli [$F(1,28) = 4.08$, $p = .053$]. There was a significant difference on airflow among stimuli averaged across group [$F(1.82,50.90) = 37.45$, $p < .001$]. Pairwise comparisons were computed using the Bonferroni correction. Airflows for sentences *'cats'* and *'grass'* were significantly smaller than airflow for sentence *'cup'* (all $p < .001$).

Table 3. Descriptive Statistics for Mean Airflow During Voicing Data as a Function of Age (Younger vs. Older Adults) and Stimuli (Harvard Sentences).

	Younger (*n* = 15)		**Older (*n* = 15)**	
	M	***SD* (range)**	***M***	***SD* (range)**
Cats and dogs each hate the other.	0.13	0.05 (0.03-.22)	0.17	0.06 (0.06-0.29)
The grass curled around the fence post.	0.14	0.06 (0.04-.25)	0.17	0.06 (0.07-0.28)
The cup cracked and spilled its contents.	0.16	0.07 (0.04-.31)	0.21	0.06 (0.08-0.32)

A 5x2 two-way mixed model MANOVA was performed on the acoustic measures CPP (*M*, *SD*), L/H spectral ratio (*M*, *SD*), and CSID as a function of the between-subjects factor age (older adults vs. younger adults) and the within-subjects factor stimuli (CAPE-V sentences: How hard did he hit him, We were away a year ago, We eat eggs every Easter, Peter will keep at the peak, second and third sentences of Rainbow passage). Descriptive data are presented in Table 4. The assumption of normality was violated for CPP for both groups but not corrected as ANOVA is robust against violations of normality. The pattern of acoustic measures among CAPE-V sentences was not significantly different between groups regardless of outcome measure [CPP mean $F(4,136) = 1.12$, $p = .351$; CPP *SD*, L/H ratio mean, and *SD*, and CSID, $F < 1$]. There was a significant difference on acoustic measures between groups averaged across stimuli for CPP (*M*, *SD*) but not for L/H ratio (*M*, *SD*) and CSID [CPP mean $F(1,136) = 8.08$, $p = .005$; CPP *SD* $F(1,136) = 6.48$, $p = .012$; L/H ratio mean $F < 1$; L/H ratio *SD* $F(1,136) = 2.41$, $p = .123$; CSID $F(1,136) = 3.52$, $p = .063$]. The main effect of group showed that the older adults had lower CPP values than the younger adults. There were significant differences for all acoustic measures among stimuli averaged across groups [CPP mean $F(4,136) = 64.43$, $p < .001$; CPP *SD* $F(4,136) = 10.64$, $p < .001$; L/H ratio mean $F(4,136) = 58.02$, $p < .001$; L/H ratio *SD* $F(4,136) = 104.01$, $p < .001$; CSID $F(4,136) = 68.15$, $p < .001$]. Although a significant interaction was not observed for group by stimuli, multiple pairwise comparisons were carried out, adjusting the family-wise Type I error rate to .05 using the Sidak correction. Mean CPP was significantly lower in the group with older adults for the all-voiced sentence than for the group with younger adults ($p = .008$).

A 4x2 two-way mixed model MANOVA was performed on the acoustic measures CPP (*M*, *SD*) and L/H spectral ratio (*M*, *SD*) as a function of the between-subjects factor age (older adults vs. younger adults) and the within-subjects factor stimuli (words: ache, ate, cake, tell). Descriptive data are presented in Table 5. The assumption of normality was violated for CPP and L/H ratio *SD* for both groups and L/H for the older group but not corrected as ANOVA is robust against violations of normality. The pattern of acoustic measures among stimuli was not significantly different between groups regardless of outcome measure [$F < 1$]. There were no significant differences on acoustic measures between groups averaged across stimuli [CPP mean $F(1,112) = 1.72$, $p = .192$; CPP *SD*, L/H ratio mean and *SD*, $F < 1$]. There were significant differences for acoustic measures among stimuli averaged across groups except for CPP *SD* [CPP mean $F(3,112) = 25.97$, $p < .001$; CPP *SD* $F < 1$; L/H ratio mean $F(3,112) = 38.40$, $p < .001$; L/H ratio *SD* $F(3,112) = 7.32$, $p < .001$]. Multiple pairwise comparisons were carried out for the interaction effect of stimuli by group, adjusting the family-wise Type I error rate to .05 using the Sidak correction. No pairwise comparisons were significant.

Table 4. Means and Standard Deviations for Acoustic Measures as a Function of Age (Younger vs. Older Adults) and Stimuli (CAPE-V Sentences).

	Younger (n = 15)[1]					**Older (n = 15)[1]**				
	CPP (dB)	**CPP *SD* (dB)**	**L/H ratio (dB)**	**L/H ratio *SD* (dB)**	**CSID**	**CPP (dB)**	**CPP *SD* (dB)**	**L/H ratio (dB)**	**L/H ratio *SD* (dB)**	**CSID**
Easy onset	7.72 (0.75)	3.45 (0.53)	38.77 (2.39)	6.64 (0.93)	-6.82 (9.63)	6.71 (1.33)	3.09 (0.55)	39.51 (2.90)	7.76 (2.02)	-1.26 (13.54)
All-voiced	5.14 (1.15)	3.68 (0.69)	34.30 (1.74)	9.26 (1.30)	3.66 (12.51)	4.59 (0.88)	3.31 (0.66)	35.60 (3.21)	9.61 (2.22)	8.24 (12.93)
Hard glottal attack	4.28 (0.94)	3.18 (0.53)	29.56 (3.03)	13.68 (1.84)	6.86 (14.52)	4.06 (0.86)	2.93 (0.53)	29.12 (2.50)	14.01 (1.19)	10.51 (8.84)
Voiceless plosives	3.42 (0.85)	2.97 (0.42)	31.15 (2.50)	10.66 (0.96)	2.55 (10.59)	3.42 (0.85)	2.97 (0.42)	31.15 (2.50)	10.66 (0.96)	21.55 (10.59)
Rainbow	5.72 (0.91)	3. 78 (0.41)	32.22 (2.67)	13.59 (1.53)	39.69 (10.93)	5.27 (0.87)	3.66 (0.37)	32.79 (2.52)	13.69 (1.18)	43.70 (9.20)

Note. CAPE-V = Consensus Auditory Perceptual Evaluation of Voice, CPP = cepstral peak prominence, L/H ratio = low to high spectral ratio, CSID = Cepstral/Spectral Index of Dysphonia.

[1]For the all-voiced sentence, the sample size was n = 14 for the younger group and n = 12 for the older group in order to analyze only all-voiced productions.

Table 5. Descriptive Statistics for Acoustic Measures as a Function of Age (Younger vs. Older Adults) and Stimuli (Words).

	Younger (*n* = 15)				**Older (*n* = 15)**			
	CPP (dB)	**CPP *SD* (dB)**	**L/H ratio (dB)**	**L/H ratio *SD* (dB)**	**CPP (dB)**	**CPP *SD* (dB)**	**L/H ratio (dB)**	**L/H ratio *SD* (dB)**
Ache	5.15 (1.80)	2.92 (0.86)	2.56 (2.56)	8.02 (1.60)	4.54 (1.49)	2.78 (0.63)	2.33 (2.33)	7.96 (1.22)
Ate	4.45 (1.45)	2.70 (0.75)	4.03 (4.03)	10.71 (3.32)	4.45 (1.45)	2.70 (0.75)	4.03 (4.03)	10.71 (3.32)
Cake	4.34 (1.32)	2.73 (0.93)	2.12 (2.12)	8.62 (1.50)	4.34 (1.32)	2.73 (0.93)	2.12 (2.12)	8.62 (1.50)
Tell	7.88 (1.75)	3.12 (0.67)	3.28 (3.28)	9.22 (2.65)	6.99 (1.87)	2.74 (0.61)	3.13 (3.13)	9.38 (2.62)

Note. CPP = cepstral peak prominence, L/H ratio = low to high spectral ratio.

Articulatory subsystem

The effects of age (older and younger adults), stimuli (words: ache, ate, cake, tell), and articulator (tongue tip, tongue mid, tongue back, jaw, and lip) on articulatory kinematics (maximum speed, average speed, distance, duration) were analyzed using multivariate analyses of variance. Pairwise comparisons were carried out for the simple effects of various interactions, adjusting the family-wise Type I error rate to .05 using the Sidak correction.

(i) Maximum speed

Findings revealed a significant interaction effect for marker x stimuli [$F(15,652) = 5.06$, $p < .01$] with the interaction of group x stimuli approaching significance [$F(3,652) = 2.48$, $p = .060$]. Pairwise comparisons of group x stimuli revealed significant differences in maximum movement speed between the older and younger adults for the word ‘*tell*’ ($p = .000$). Although a significant interaction was not observed for group x stimuli x marker [$F < 1$, $p = 1.00$], pairwise comparisons showed significant differences in maximum speed of tongue tip (p = .013) and tongue back (p = .028) movements between the older and younger adults for word ‘*tell*’ (see Figure 5). Significant main effects were observed for group [F(1,652) = 13.21, p < .01], marker [F(5,652) = 29.47, p < .001], and stimuli [F(3,652) = 60.87, p < .01].

(ii) Average speed

For average speed, a significant interaction effect was observed only for group x stimuli [F(3,652) = 3.89, p < .01] and marker x stimuli [F(15,652) = 7.56, p < .001] but not group x marker [F < 1, p = .978] or group x stimuli x marker [F < 1, p = 1.00]. Pairwise comparisons of group x stimuli revealed significant differences in average speed between the older and younger adults for the word ‘*tell*’ (p = .000). Although a significant interaction was not observed for group x stimuli x marker, pairwise comparisons showed significant differences in average speed of tongue tip (p = .037) and back (p = .043) movements between the older and younger adults for word ‘*tell*’ (see Figure 6). Significant main effects were observed for group [F(1,652) = 7.64, p < .01], marker [F(5,652) = 48.64, p < .001], and stimuli [F(3,652) = 85.36, p < .001].

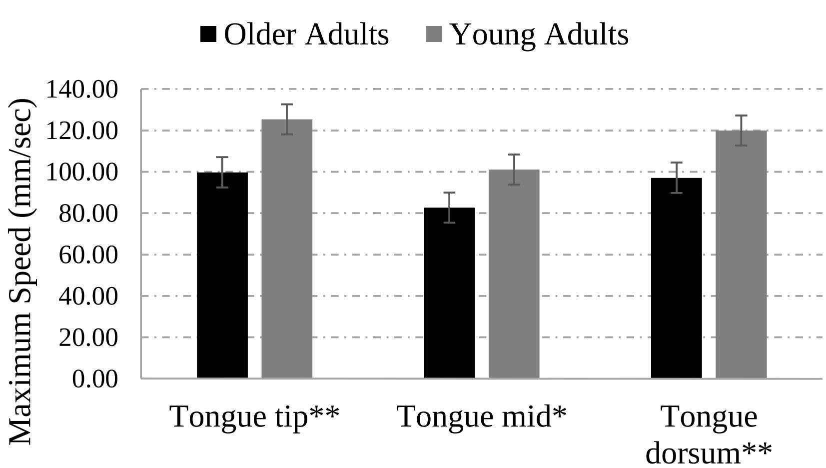

Figure 5. Mean (+/- *SE*)) of maximum tongue speed for the word ‘tell’ from older and younger adults. ** p < .05, * p = .08 (approaching significance)

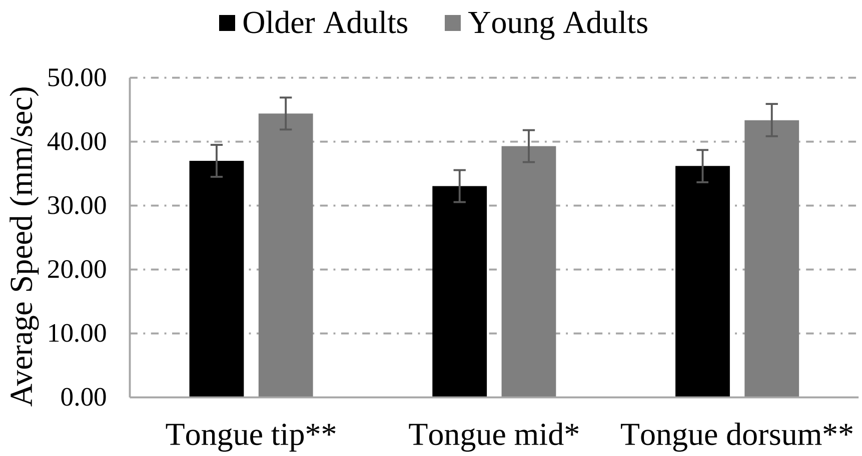

Figure 6. Mean (+/- *SE*) of average tongue speed for the word 'tell' from older and younger adults. ** $p < .05$, * $p = .08$ (approaching significance)

(iii) Distance

Findings revealed no significant interaction effects for group x stimuli [$F(3,652) = 0.63$, $p = .598$], group x marker [$F < 1$, $p = .993$], and group x marker x stimuli [$F < 1$, $p = 1.000$]. Significant main effects were observed for group [$F(1,652) = 7.98$, $p < .01$], marker [$F(5,652) = 12.01$, $p < .001$], and stimuli [$F(3,652) = 17.80$, $p < .001$].

(iv) Duration

For duration, no significant interaction effects were observed for group x stimuli [$F < 1$, $p = .967$], group x marker [$F < 1$, $p = 1.000$], and group x marker x stimuli [$F < 1$, $p = 1.00$]. Significant main effects were only observed for stimuli [$F(3,652) = 3.23$, $p < .05$] but not for group [$F(1,652) = 2.63$, $p = .105$] and marker [$F < 1$, $p = .997$].

Age Effects on Articulatory Movement Variability

The effects of age (older and younger adults), stimuli (words: ache, ate, cake, tell), and articulator (tongue tip, tongue mid, tongue back, jaw, and lip) on movement variability was analyzed using univariate analyses of variance. Pairwise comparisons were carried out for the simple effects of various interactions, adjusting the family-wise Type I error rate to .05 using the Sidak correction.

Findings revealed a significant interaction effect for marker x stimuli [$F(15,648) = 9.90$, $p < .001$] but no significant interaction effects were observed for group x stimuli [$F(3,648) = 1.82$, $p = .142$], group x marker [$F < 1$, $p = .931$], or group x stimuli x marker [$F < 1$, $p = .949$]. Although a significant interaction was not observed for group x stimuli x marker, pairwise comparisons showed significant differences in spatiotemporal variability of the tongue dorsum movements ($p = .003$) for the word 'ache' with variability of the tongue mid ($p = .075$) and jaw ($p = .082$) approaching significance for the word '*ache*' (see Figure 7).

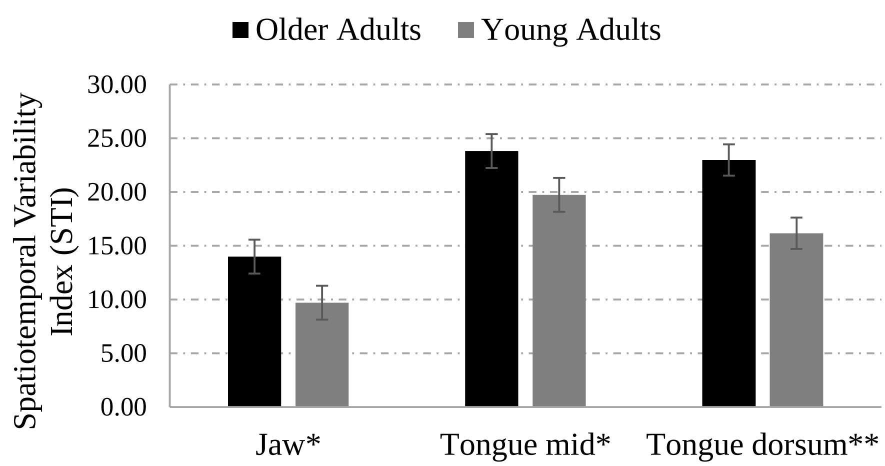

Figure 7. Mean STI scores (+/- *SE*) for the words 'ache' from older and younger adults. ** $p < .05$, * $p = .08$ (approaching significance)

Age Effects on Tongue Strength and Endurance

Age effects on tongue strength and endurance analyzed using multivariate analysis of variance revealed significant group differences in tongue strength [$F(1,28) =$

17.32, $p < .001$] with group differences in endurance approaching significance [$F(1,28) = 4.22$, $p = .049$]. For both strength and endurance, the older adults had lower values than the younger adults.

Age Effects on Speech Intelligibility and Speaking Rate

The effect of age on speech intelligibility and speaking rate were analyzed using two separate one-way ANOVAs. Findings revealed that between-group differences in intelligibility were approaching significance [$F(1,28) = 3.61$, $p = .068$]. In contrast, significant between-group differences were observed for speaking rate [$F(1,29) = 6.05$, $p < .05$] with the younger talkers displaying significantly faster speaking rates compared to the older adults.

Inter- and Intra-rater Reliability for Respiratory, Aerodynamic ,Acoustic, Kinematic, Intelligibility, and Rate Analyses

Interrater reliability was determined using Pearson's product-moment correlation from 100% of the samples subjected to the respiratory, aerodynamic (voicing efficiency, MPT), and acoustic analyses (CSID, all-voiced sentence). There were strong agreements between raters for analyses of expiratory airflow ($r = 1$, p < .001), MPT ($r =.996$, $p < .001$), mean peak air pressure ($r =.856$, $p < .001$), mean airflow during voicing ($r =.906$, $p < .001$), laryngeal airway resistance ($r =.947$, $p < .001$), and CSID (all voiced sentence) ($r =.910$, $p < .001$), Further, inter- and intra-rater reliability was determined using Pearson's product-moment correlation from 20% of the samples subjected to the articulatory kinematic, intelligibility, and rate analyses. There was a strong agreement both within ($r_s = .99$, $p = .00$) and between raters ($r_s = .77$, $p = .00$) for the articulatory kinematic analyses. A strong agreement was also observed for inter-rater judgments of sentence intelligibility and speaking rate (r_s = .73, p = .01).

Contribution of Selected Variables to Speech Intelligibility in Healthy Older Adults

Two approaches to multiple linear regression modeling were completed to determine predictors of speech intelligibility for older adults. First, all predictor variables from a single subsystem were treated as a single block using a simultaneous method of multiple linear regression for prediction of intelligibility. Second, hierarchical stepwise regression was completed where each variable was entered in the second block and the remaining variables from the same subsystem were entered in the first block. Separate linear regression models were obtained for the three subsystems. Change in R^2 between the first and second blocks showed the independent contribution of the variable entered in the second block relative to the model specified by the first block. The sum of the R^2 with the variable in the second block and the R^2 with the other four variables in the first block yields the total R^2 of the model.

Contribution of Respiratory Variables to Speech Intelligibility

A linear regression for the respiratory variable expiratory airflow revealed a non-significant model for the older adults [$F(1, 13) = 1.08$, p = .319], adjusted R^2 = .005.

Contribution of Phonatory Variables to Speech Intelligibility

The measures selected from the older group included acoustic measures (CPP [*M, SD*], L/H spectral ratio [*M, SD*], and CSID) from production of CAPE-V sentences and words (ache, ate, cake, tell), aerodynamic measures (mean peak air pressure, mean airflow during voicing, airway resistance) from syllable production of /pi/, and MPT from production of the vowel /a/. As shown in Table 6, significant correlations were observed among the nine selected variables and the variance inflation factor did not exceed 10 indicating the multiple regression assumption regarding multicollinearity was not violated.

Table 6. Correlation Coefficient Matrix of the Nine Selected Phonatory Variables for Older Adults (n = 12)[1].

Variable	1	2	3	4	5	6	7	8	9
1. CPP	-	.544**	.547**	-.256*	-.449*	-.138	-.073	-.029	.233
2. CPP *SD*		-	.091	.103	-.138	.043	-.039	.208	.114
3. L/H Ratio			-	-.710**	-.304*	.028	.091	-.087	.096
4. L/H Ratio *SD*				-	.311*	.101	-.066	.172	.031
5. CSID					-	.025	.070	-.093	-.204
6. P_{sub}						-	.661**	.385*	-.002
7. Airflow							-	-.360*	.187
8. R_{law}								-	-.226
9. MPT									-

Note. CPP = cepstral peak prominence, L/H ratio = low to high spectral ratio, CSID = Cepstral/Spectral Index of Dysphonia, P_{sub} = subglottic pressure, R_{law} = laryngeal airway resistance, MPT = maximum phonation time
[1]n = 12 for all-voiced sentence and n = 10 for aerodynamic measures.
* p <.05. ** p < .01.

(i) All variables

The simultaneous method of linear regression for the acoustic measures revealed a significant model for the older adults [F(9,38) = 26.24, p < .001], adjusted R^2 = .829 (see Table 7). Mean L/H spectral ratio, airflow, airway resistance, and MPT were significant predictors of speech intelligibility based on the beta coefficients in this model. The variance inflation factor values were below 10 for the phonatory measures and indicate that the multiple regression assumption regarding multicollinearity was not violated even with the observed intercorrelations among the variables described above (Cohen, Cohen, West, & Aiken, 2003).

Table 7. Beta Coefficients of Phonatory Variables of the Simultaneous Multiple Linear Regression Model Against Speech Intelligibility for Older Adults (*n* = 15)[1].

Predictor Variables	Unstandardized Coefficients (*B*)	Standardized Coefficients (β)	t	Sig.	Variance Inflation Factor (VIF)
CPP	.003	.055	.530	.599	2.926
CPP *SD*	.013	.086	1.068	.292	1.791
L/H Ratio	-.005	-.239	-2.191	.035	3.258
L/H Ratio *SD*	-.005	-.188	-1.923	.062	2.607
CSID	.000	.026	.349	.729	1.470
P_{sub}	.021	.326	1.739	.090	9.623
Airflow	-1.621	-.868	-4.747	.000	9.176
R_{law}	-.008	-1.144	-7.571	.000	6.262
MPT	-.003	-.301	-4.527	.000	1.211

Note. CPP = cepstral peak prominence, L/H ratio = low to high spectral ratio, CSID = Cepstral/Spectral Index of Dysphonia, P_{sub} = subglottic pressure, R_{law} = laryngeal airway resistance, MPT = maximum phonation time

[1]*n* = 12 for all-voiced sentence and *n* = 10 for aerodynamic measures.

(ii) Single variables

The independent contribution of each variable in this model is reported in Table 8. The sum of the R^2 with the variable in the second block and the R^2 with the other three variables in the first block yields the total R^2 of the model described above. As seen in Table 8, 39% of the variance in intelligibility can be explained by airway resistance, 35% by airflow during voicing and 9% by MPT.

Table 8. Incremental R^2 Change Results of the Multiple Linear Regression Model Examining Each Phonatory Measure's Independent Contribution to Speech Intelligibility in Older Adults (n = 15)[1].

Rank	**Variable**	***R*² change with the fourth variable in the second block**	***R*² change with the remaining three variables in the first block**
1	R_{law}	.394	.442
2	Airflow	.351	.485
3	MPT	.089	.747
4	P_{sub}	.002	.834

Note. R_{law} = laryngeal airway resistance, MPT = maximum phonation time, P_{sub} = subglottic pressure
[1]n = 12 for all-voiced sentence and n = 10 for aerodynamic measures.

Contribution of Articulatory Kinematic Variables to Speech Intelligibility

The measures selected for the multiple linear regression from the older group included maximum speed, average speed, distance, duration, and STI of tongue tip, mid, and back movements for the four target words. As shown in Table 9, significant correlations were observed among the five selected variables but the variance inflation factor was taken into consideration for the regression analysis to ensure that the multiple regression assumption regarding multicollinearity was not violated.

Table 9. Correlation Coefficient Matrix of the Five Selected Articulatory Kinematic Variables for Older Adults (n = 15).

Variable	**1**	**2**	**3**	**4**	**5**
1. Maximum Speed	-	0.886**	0.855**	0.149*	-0.407**
2. Average Speed		-	0.806**	-0.084	-0.502**
3. Distance			-	0.478**	-0.519**
4. Duration				-	-0.150*
5. STI					-

Note. STI = spatiotemporal variability index. ** $p < .001$. * $p < .05$.

(i) All variables

The simultaneous method of liner regression revealed a significant model for the older adults [$F(5, 179) = 7.05$, $p < .001$], adjusted $R^2 = .145$ (see Table 10). Maximum speed and duration were significant predictors of speech intelligibility based on the beta coefficients in this model. The variance inflation factor values were below 10 for maximum speed, duration, and STI and indicate that the multiple regression assumption regarding multicollinearity was not violated even with the observed intercorrelations among these variables described above (Cohen, Cohen, West, & Aiken, 2003, p. 423). For average speed and distance, the variance inflation factor was above 10 making it difficult to interpret the regression coefficients.

Table 10. Beta Coefficients of the Simultaneous Multiple Linear Regression Model Against Speech Intelligibility for Older Adults (*n* = 15).

Predictor Variables	**Unstandardized Coefficients (*B*)**	**Standardized Coefficients (β)**	**t**	**Sig.**	**Variance Inflation Factor (VIF)**
Maximum Speed	-.145	-.611	-3.402	.001	6.753
Average Speed	.258	.453	1.534	.127	18.257
Distance	.432	.309	.988	.324	20.466
Duration	22.444	.319	1.755	.081	6.919
STI	.119	.128	1.514	.132	1.504

Note. STI = spatiotemporal variability index.

(ii) Single variables

The independent contribution of each variable in this model is reported in Table 8. As seen in Table 11, 10% of the variance in intelligibility can be explained by duration and 5% of the variance in intelligibility can be explained by maximum speed.

Table 11. Incremental R^2 Change Results of the Multiple Linear Regression Model Examining Each Articulatory Kinematic Measure's Independent Contribution to Speech Intelligibility in Older Adults (*n* = 15).

Rank	**Variable**	**R^2 change with the fifth variable in the second block**	**R^2 change with the remaining four variables in the first block**
1	Duration	0.096	0.049
2	Maximum Speed	0.052	0.093
3	Average Speed	0.008	0.137
4	Distance	.000	0.145
5	STI	.005	0.140

Note. STI = spatiotemporal variability index.

DISCUSSION

The first aim of the present study was to determine age-related changes to the respiratory, phonatory, and articulatory subsystems. As predicted, significant differences were observed between older and younger adults on MPT (phonatory subsystem), CPP (phonatory subsystem), and STI (articulatory subsystem). These results suggest that older adults have shorter phonation times, lower harmonic energy during sentence production, and slower as well as more variable tongue movements during word production. Contrary to our predictions, no significant differences were observed between older and younger adults in respiratory function indexed by vital capacity. Overall, the results suggest significant age-related changes to the phonatory, and articulatory subsystems that likely contribute to the reduced speech intelligibility observed in the older adults relative to the younger adults.

The second aim of the study was to investigate whether speech intelligibility decline is observed in healthy older adults and if so, to determine which variables from each subsystem (respiratory, phonatory, articulatory) are predictive of intelligibility decline. As predicted, we observed reduced speech intelligibility scores in healthy older adults compared to younger adults; however, these differences were only approaching significance. Results of the regression analyses confirmed that phonatory subsystem measures contributed to intelligibility in healthy older individuals to a greater extent than articulatory subsystem measures. While the exact prevalence of voice disorders in the healthy aging population is currently unknown, a study by Roy, Stemple, Merrill, and Thomas (2007) found that 29% of non-treatment seeking adults over the age of 65 reported current voice disorders (defined in the study as “any time the voice did not work, perform, or sound as it normally should so that it interfered with communication” [p. 629]) based on responses elicited from the participants. Common symptoms reported by participants in that study included hoarseness, difficulty with projecting voice, and vocal fatigue or voice quality changes; all of which may contribute to intelligibility declines. The fact that voice complaints are observed in the aging population while articulatory problems are rarely reported may suggest that voice problems are more prevalent in older adults and therefore, it is not surprising that phonatory subsystem measures were better predictors of intelligibility differences in older adults over articulatory subsystem measures.

Regarding the predictive value of individual subsystem measures, hypothesized variables from the phonatory subsystem were confirmed as predictive of intelligibility decline including laryngeal airway resistance, airflow during voicing, and MPT. Similarly, for the articulatory subsystem, maximum speed and duration emerged as the best predictors of intelligibility changes in older adults in support of our hypothesis. Some findings within this aim are discussed using relevant research on disordered populations due to lack of research on an aging population.

Age-related Subsystem Differences

Respiratory subsystem

Previous research has found that older adults had significantly lower expiratory volume (Awan, 2006; Zraick et al., 2012) as compared to younger adults. While the hypothesis suggesting that expiratory airflow (vital capacity) would demonstrate significant differences between older and younger adults was not confirmed, the related phonatory measure MPT detected differences, which has a respiratory component (Solomon, Garlitz, & Milbrath, 2000) and for which age-related differences in female older adults have been found in a study by Awan (2006). The findings from the present study and Awan (2006) suggest that older adults have worse laryngeal valving activity than younger adults with potential contribution of declined respiratory support and efficiency for speech (Solomon et al., 2000).

Phonatory subsystem

Watts and colleagues (2015) suggested that older adult males display significantly reduced phonation periodicity and significantly reduced concentrations of harmonic energy in lower frequencies compared to a younger group reflected through higher CSID values in connected speech. CPP, the measure that primarily contributes to CSID (Awan, 2011), during production of the all-voiced CAPE-V sentence was found to be significantly lower in older adults in the present study with no significant difference in the broader CSID measure. The finding that older adults had significantly different CPP values compared with younger adults, but not significantly different CSID values, is consistent with one recent aging voice study by Awan and colleagues (Awan, Acompanado, Connors, & Fanelli, 2015). CPP is regarded specifically as a measure that represents the degree of periodicity in the voice signal from productions of sustained vowel or connected speech. Dysphonic voices will have lower CPP and demonstrate disturbed periodicity and lower harmonic energy (Watts, Awan, & Maryn, 2015). Perceptually, lower CPP values are associated with more breathiness in voice (Awan et al., 2009; Hillenbrand & Houde, 1996). The finding in the present study that older adults have significantly lower CPP than younger adults suggests that older adults have voices with lower harmonic energy, which are breathier and do not carry as well.

Articulatory subsystem

Our results show an age-related slowing of tongue movements indexed by lower maximum speed and slower average speed in the older compared to younger talkers and may contribute significantly to slower speaking rates and reduced intelligibility in the older group. These findings are in line with previous research by Wohlert and Smith (1998) who also reported aslower speaking rate among older adults relative to younger adults during habitual, fast, and slow speech. The authors attributed this age-related slowing to the loss of peripheral sensorimotor function due to the loss of fast twitch muscles and declining physical status (Doherty, Vandervoort, & Brown, 1993; Ramig, 1983) but also suggested that slow speech may be a compensatory strategy which allows for more accurate speech movements and consequently, intelligibility (Wohlert & Smith, 1998). In fact, several other researchers have suggested slow rate as a compensatory strategy to improve intelligibility because it allows talkers more time to make precise articulatory contacts, improve coordination, and facilitate speech motor control (McHenry, 2003; Weismer Laures, Jeng, Kent, & Kent, 2000; Yorkston, Hakel, Beukelman, & Fager, 2007). In contrast, however, speech motor control studies show significantly greater articulatory movement variability indicative of poorer motor control during slow speech in both healthy and disordered speakers (Kleinow, Smith, & Ramig, 2001; Mefferd, Pattee, & Green, 2014; Smith et al., 1995; Wohlert & Smith, 1998). Our finding of increased tongue movement variability support the prior literature on aging speech (Wohlert & Smith, 1998) and suggests that a slower speaking rate may be detrimental to speech motor control in older talkers.

Although the tongue was not decoupled from the jaw in this study, our findings suggest that the tongue may be affected before the lower lip and jaw in older individuals. Similar findings are reported in ALS where the lingual motor neurons are considered to be disproportionately affected compared to the trigeminal and facial motor neurons that innervate the jaw and lips, respectively (DePaul & Brooks, 1993; DePaul, Abbs, Caligiuri, Gracco, & Brooks, 1988). Researchers have also shown differential impairment within the tongue where the mid-posterior region displayed altered speech motor control before the anterior tongue in talkers with ALS (Kuruvilla et al., 2012). In contrast, a histopathologic study of the tongue musculature in ALS reported greater degenerative changes to muscle fiber type, muscle fiber group, and connective tissue to the anterior tongue regions compared to the posterior regions (DePaul et al., 1998). Our results show that tongue tip, mid, and back movements were equally affected in older individuals.

Significant age-related declines in maximum tongue strength were observed in the current study during non-speech tasks, supplementing the findings in existing literature on tongue strength and aging (Clark & Solomon, 2012; Youmans, Youmans, & Stierwalt, 2009). While informative to age-related physiologic differences of the tongue, Neel and Palmer (2011) found that tongue strength and endurance were poor predictors of healthy adults' speaking rate in diadochokinetic and reading tasks. Recent work from Neel and colleagues (2014) demonstrated that although individuals with oculopharyngeal muscular dystrophy have significantly impaired tongue strength, this did not impact their speech and voice measures or speech intelligibility. Maximum performance tasks including tongue strength and their impact on speech performance during the evaluation and treatment of communication disorders remains controversial (Kent, 2015) because speaking uses only a fraction (20% or less) of the force capability of the musculature (Amerman, 1993; Barlow & Rath, 1985; Hinton & Arokiasamy, 1997; Kent, Kent, & Rosenbek, 1987). While maximum strength tasks can serve as an indicator for motor impairment before speech differences are detectable in ALS (Weikamp, Schelhaas, Hendrinks, de Swart, & Geurts, 2012), the measures do not appear to directly impact speaking tasks in healthy older adults (Neel et al., 2011) and therefore, tongue strength was not included in intelligibility prediction in the current study.

Age Effects on Speech Intelligibility and Speaking Rate

Differences in speech intelligibility between older and younger adults were approaching significance and suggest that an everyday communication context high in background noise like multi-talker babble, can interfere with a listener’s ability to understand aging speech. This notion is consistent with subjective complaints of older adults suggesting that their voices are hoarse, they have difficulty projecting or being understood in background noise, and their voices tire or change quality (Etter et al., 2013; Roy et al., 2007), which can be perceptually detected as changes in pitch, reduced loudness, breathy and rough voice quality, and instability (Baker et al., 2001; Kendall, 2007).

It is not surprising that a system-level measure like speech intelligibility was relatively insensitive to age-related declines in speech performance while subsystem-level measures were able to detect age-related differences in speech function. Similar findings have been reported in talkers with ALS. Green and colleagues (2013) found significant, large effects for tongue speed between healthy older adults and ALS individuals with unimpaired intelligibility, suggesting that differences in articulator speed are detected before speech intelligibility. One potential reason that speech intelligibility remains relatively insensitive during early disease stages is the compensatory inter- or intra-articulator adjustments that individuals use in an attempt to improve their intelligibility (DePaul & Brooks, 1993; Green et al., 2013; Yunusova et al., 2010). For example, Green and colleagues (2013) reported an unexpected increase in lip and jaw speed along with the expected disease-related slowing of tongue movements, indicating lip and jaw compensation for a slowing tongue in individuals with ALS. As a result of this type of compensation, intelligibility may be inflated in the early stages of ALS making it difficult as a clinical measure to detect speech decline.

Significant age-related differences in speaking rate were found in the present study, which suggest that speaking rate declines are observed in the healthy aging population before speech intelligibility differences. This finding has also been reported in talkers with ALS where speaking rate was found to be more sensitive to changes in speech performance than intelligibility measures (Ball et al., 2001; Green et al., 2013).

Contribution of Selected Variables to Speech Intelligibility in Older Healthy Adults

Phonatory subsystem

Our hypothesis that phonatory measures would contribute more to intelligibility differences in older adults than articulatory measures was confirmed, as the phonatory subsystem model can explain 83% of the variance in intelligibility in healthy older adults.

However, the contributions by the voicing efficiency measures were more significant than those by acoustic measures, which contributed to a smaller degree. Voicing efficiency captures respiratory-laryngeal interactions for voice production, specifically the relationship between subglottal pressure and airflow during voice production (Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989), whose ratio can be expressed as laryngeal airway resistance (R_{law}). The fact that airflow but not subglottal pressure was a significant predictor of intelligibility besides $R_{law,}$ shows that airflow was the driving factor in the R_{law} equation. R_{law} and airflow during voicing can explain 39% and 35% of the variance in intelligibility in older adults, respectively. While voicing efficiency did not demonstrate significant age-related differences in our study, there appeared to be a trend that older adults displayed more airflow and less subglottal pressure during syllable production and more airflow during sentence production, resulting in lower R_{law} (see Tables 2 and 3) indicating incomplete vocal fold closure (Hillman et al., 1989). A lower R_{law} with increased airflow during voicing would correlate with a breathy and more asthenic voice quality, which would make it more difficult to be heard in noise.

Gorman and colleagues (2008) demonstrated that through vocal function exercises (Stemple, 2000) older men who were referred for voice evaluation were able to improve laryngeal pressure values resulting in improved vocal fold closure. Given that vocal fold atrophy and bowing occur in the aging population (Gregory et al., 2010), there was a possibility of bowing and glottal insufficiency in our participants indicated by findings of decreased subglottal pressure and increased airflow although we did not directly visualize participants’ vocal folds. These findings provide evidence that the hypofunctional voice associated with glottal insufficency that is often present in older adults' voices contributed to intelligibility differences.

Articulatory subsystem

Previous studies analyzing multiple subsystem measures and their impact on intelligibility in dysarthria populations (CP in children: Lee et al., 2013; ALS in adults: Rong et al., 2016; de Bodt et al., 2002) have found that measures representing the articulatory subsystem contribute most significantly to intelligibility. One explanation for phonatory measures contributing more to intelligibility than articulatory measures in the healthy aging population can be explained from a perceptual standpoint. Perceived articulation differences are rarely observed in healthy older adults, but voice differences are often perceived easily (Gregory et al., 2012).

Articulatory subsystem measures that emerged as the best predictors of intelligibility changes in older adults (i.e., maximum speed, duration) were also reported to predict intelligibility decline in the ALS population (Rong et al., 2016). Duration and maximum speed explained 10% and 5% of the variance in intelligibility of older adults, respectively. Specifically, slowing of articulatory movements, specifically lip and jaw movements, was shown to result in impaired intelligibility in ALS (Ball et al., 2001; Rong et al., 2016; Yunusova, Green, Greenwood, Wang, Pattee, & Zinman, 2012). Although tongue data was not included in their study, Rong and colleagues (2016) concluded that including the tongue in future studies may strengthen the relationship between articulatory function and intelligibility because lingual function is more impacted by motor neuron degeneration than jaw or lip function in ALS. Measures representing articulatory speed have also been found to predict intelligibility decline in children with CP. Lee and colleagues (2014) found that acoustic measures that generally reflect articulatory slowness (average F2 slope) contributed primarily to speech intelligibility variability in children with CP. These results along with findings from the present study suggest that movement speed and duration measures are sensitive to speech declines in individuals with dysarthria and healthy older adults.

CONCLUSION

Age-related differences were detected across phonatory and articulatory subsystem measures including MPT (phonatory subsystem), CPP (phonatory subsystem), and STI and movement speed (articulatory subsystem) demonstrating age-related speech subsystem declines. Of all the subsystem variables, the significant predictors of speech intelligibility variance in older adults were: laryngeal airway resistance (39%), airflow during voicing (35%), and MPT (9%; all phonatory subsystem), and duration (10%) and maximum speed (5%) of tongue movements (articulatory subsystem) suggesting that age-related subsystem changes (i.e., breathy voice, articulatory slowing) contributed to intelligibility decline. Collectively, 98% of speech intelligibility variance in older adults can be explained by the phonatory (83%) and articulatory (15%) subsystem models. In our study, subsystem and speaking rate measures were more sensitive to age-related speech differences in older adults than intelligibility measures. Similar findings have been reported previously in the ALS literature where declines in speaking rate (Ball et al., 2001) and tongue movement speed (Green et al., 2013) were observed earlier than intelligibility declines. Our study provides an index of sensitive subsystem measures that will be clinically relevant for detecting differences in healthy older and younger adults' speech with potential to expand to individuals with progressive dysarthrias.

Limitations and Future Directions

Certain limitations that need to be considered when interpreting the results from the present study include the small sample size and disproportionate age range in the older adult group. Ideally, the older group should have proportionate amount of participants from each decade so that speech changes present in each decade are represented. Secondly, the use of multi-talker babble during the rating of speech intelligibility may be considered a shortcoming due to its ability to interfere with the signal; however this method is commonly used with non-disordered populations in order to eliminate ceiling effects. Another limitation is the absence of measures representing the resonance subsystem. Resonatory subsystem measures were not included because of the lack of appropriate instrumentation to study this subsystem and the authors did not feel that acoustic measures would be adequate to represent the resonatory subsystem. Lastly, the present study did not separate the results of male and female participants; however, the groups were nearly gender balanced. Sex differences have been reported for respiratory and selected voicing efficiency measures (Zraick et al., 2012) as well as acoustic measures (Awan, 2011).

Because different disease populations present with differently impacted speech subsystems, it is imperative to develop disease specific models of intelligibility decline. That is, it will be necessary to investigate subsystem measures that contribute significantly to intelligibility decline in different diseases to create a prediction model for intelligibility decline specific to that population. Rong and colleagues (2016) have begun work into developing intelligibility prediction models for ALS and Lee and colleagues (2014) for CP. This work is critical for improving early detection of speech decline particularly, for progressive conditions like ALS. Developing a prediction model of speech intelligibility decline will improve accuracy of speech assessments and inform patients on how fast their speech will deteriorate in progressive dysarthrias seen in individuals with PD and ALS. This will allow patients to make personal, financial, and treatment decisions sooner and allow clinicians to present treatment options in a timely manner and set appropriate therapy goals for these individuals. Subsystem prediction models of intelligibility will also be important for non-progressive dysarthrias (e.g., CP) in order to focus on the treatment of a certain subsystem when the goal of therapy is to improve intelligibility (Lee et al., 2014).

In addition, the present study has provided evidence of speech subsystem and intelligibility differences in the healthy aging population. Given that many neurological disorders are overlaid onto aging subsystems (Dromey et al., 2014; Duffy, 2013), it was crucial to delineate speech changes as a result of the aging process. The results of the present study can be expanded into future studies analyzing speech subsystem impacts on intelligibility in different types of dysarthria and disease populations.

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