Acoustic Measures of Voice and Physiologic Measures of Autonomic Arousal During Speech as a Function of Cognitive Load in Older Adults

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Summary: Objectives/Hypothesis. The purpose of this study was to determine the relationships among cognitive loading, autonomic arousal, and acoustic measures of voice in healthy older adults.

Study Design. Prospective and observational.

Methods. Twelve healthy older adults (six females) produced a sentence containing an embedded Stroop task in each of two cognitive load conditions: congruent and incongruent. Three physiologic measures of autonomic arousal (pulse volume amplitude, pulse period, and skin conductance response amplitude) and four acoustic measures of voice (cepstral peak prominence, low-to-high spectral energy ratio, fundamental frequency, and sound pressure level) were analyzed in each cognitive load condition.

Results. A logistic regression model was used to predict the cognitive load condition using participant as a categorical predictor and the four acoustic measures and three autonomic measures as continuous predictors. Skin conductance response amplitude and pulse volume amplitude were both predictive of cognitive load; however, no acoustic measures of voice were statistically significant predictors of cognitive load for older adults.

Conclusions. These findings support the idea that increased cognitive load is associated with increased autonomic nervous system activity in older adults. The lack of changes in acoustic measures of voice with increased cognitive load may result from age-related changes in vocal quality and speech subsystems.

Key Words: Cepstral−Spectral−Voice−Pulse volume amplitude−Pulse period−Skin conductance response amplitude−Autonomic arousal− Autonomic nervous system−Stroop task−Psychophysiology.

INTRODUCTION

Hyperfunctional voice disorders account for up to 40% of referrals and the majority of caseloads in multidisciplinary voice clinics[1,2] and are the most frequently diagnosed voice disorder in the United States population.[3] However, there is a lack of consensus regarding pathophysiology likely due to their heterogeneous clinical presentations and variability in physiological vocal fold changes (eg, they can present with or without physiological changes to the vocal folds). Many factors have been suggested as contributors to hyperfunctional voice disorders, such as high voice use,[4] poor vocal hygiene,[5,6] and personality traits.[7−13] Although there are a variety of proposed causes of hyperfunctional voice disorders, the core feature of the disorder is widely agreed upon as increased tension observed in the laryngeal muscles.[2,14] Some authors have proposed that the observed increases in muscle tension may be a physiological response to psychological stress loading (mediated by the autonomic nervous system), based on the documented co-occurrence of psychosocial symptoms and hyperfunctional voice symptoms.[5,15−20]

Dysfunction in autonomic nervous system activity has been documented subjectively via patient questionnaires in speakers with hyperfunctional voice disorders,[12,21−23] which supports the premise that autonomic nervous system activity is linked to changes in voice. The autonomic nervous system has a sympathetic branch, responsible for processing responses to stress (eg, increased cognitive demand), and a parasympathetic branch, responsible for rest and repair.[24,25] These two branches of the autonomic nervous system function in tandem to mediate bodily reactions.[24,26] When the sympathetic branch of the autonomic nervous system is more active relative to the parasympathetic branch (eg, responding to increased cognitive demand), this is termed autonomic arousal. A disruption to the autonomic nervous system's regulation of sympathetic and parasympathetic activity reactions is termed autonomic nervous system dysfunction.

Increased cognitive demand (a mental stressor that elicits physiological changes) is also associated with changes in acoustic measures of voice in young adults with typical voices, but the literature reports conflicting findings. Voice fundamental frequency (f_o) and sound pressure level have both shown increases as well as decreases with increased cognitive load.[27−34] Similarly, studies have found both increases and decreases for nonharmonic noise with increased cognitive load.[31, 32] However, the variable vocal acoustic results in these studies may stem from the lack of including an objective quantification of autonomic arousal.

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Studies that have included objectives measures of autonomic arousal during physiological stressors in healthy young adults demonstrate changes to voice and laryngeal level physiology consistent with hyperfunctional voice symptoms. One study found increased measures of autonomic arousal and increased cepstral peak prominence (CPP) paired with reduced low-to-high (L/H) ratio (the ratio of spectral energy below and above 4000 Hz) with cognitive loading in healthy young speakers.[35] Another study reported increased intrinsic laryngeal muscle tension with increased measures of autonomic arousal due to physiological stressors[36] in healthy young adults. Hence, these combined findings imply that vocal acoustics during cognitive loading in young adults have shared features with hyperfunctional voice symptoms, reinforcing a possible association between the autonomic nervous system and voice. However, in older adults, who are still prone to developing voice disorders,[37] there may be age-related differences in these associations.

In older adults, the relationship between physiological stressors, autonomic arousal, and vocalization may differ due to changes in laryngeal physiology.[38,39] Physiological changes to the laryngeal structures in older adults can include increased vocal fold bowing, changes to elasticity,[40,41] increased glottal gap,[42] and greater prominence of the vocal process.[41,43] Further, a greater degree of vocal fold atrophy is found in older adults[20,44] as well as changes to the lamina propria of the vocal folds.[45] Age-related changes to laryngeal function have also been observed, such as increased phase and amplitude asymmetry of vocal fold vibration.[41]

In line with the physiological changes at the laryngeal level, acoustic measures of voice also demonstrate changes with typical aging. Greater variability has been reported for voice f_o[46−48] and sound pressure level[47] in older compared to younger adults. A study by Stathopoulos et al[47] found increased variability in signal-to-noise ratio in adults above 50 years of age, but other work found no differences as a function of age.[49] Additionally, one study found no age-related differences in L/H ratio, which is affected by high frequency noise.[50] Similarly, measures of CPP and smoothed CPP show both decreases (aged 20 - 30 years compared to 40 - 50 years[50];) or no age-related changes (17 - 87 years old[46];), respectively. The differing findings in these works may result from full body physiological factors, which interact with voice production[51] and were not controlled for in these studies.

Aging also affects autonomic nervous system activity and autonomic arousal. Prior findings indicate a reduction in parasympathetic nervous system activity and an increase in basal sympathetic nervous system activity with typical aging.[52,53] Additionally, in response to cognitive loading, studies show greater autonomic arousal (ie, increased sympathetic nervous system reactivity) in older adults compared to younger adults.[54−58] Although it is evident that older adults have different physiological responses to cognitive loading and show greater variability in measures of voice, the combined effects of age and cognitive load on autonomic arousal and vocal acoustics have not been directly investigated. Increased understanding of the relationship between cognitive load, aging, autonomic arousal, and measures of voice would have clinical implications for treatment of voice disorders.

Thus, the objective of the current work was to evaluate the effects of cognitive load on the degree of autonomic arousal and vocal acoustics in a cohort of healthy older adults. The current work employed the same experimental paradigm as MacPherson et al[35] using a sentence-level modification of Stroop's naming of color words task,[59] which has been widely used to examine cognitive loading and autonomic arousal.[60−64] The specific research aims of this study were to (1) determine the effect of cognitive load during a Stroop task on autonomic arousal as measured by pulse volume amplitude, pulse period, and skin conductance response amplitude in older adults, (2) determine the effect of cognitive load during a Stroop task on acoustic measures (CPP, L/H ratio, voice f_o, and sound pressure level) of the voices of older adults, and (3) discuss the current findings with respect to previously reported results in younger adults.

During cognitive loading, we hypothesized that autonomic measures would strongly predict cognitive loading (via odds ratios) considering the prior findings in the younger cohort[35] and given that older adults have heightened autonomic responses to stressors. For measures of voice, we expected that CPP and L/H ratio would be predictors of cognitive loading in older adults, since these measures may not be affected by age[46,50] and were predictors of cognitive loading in young adults.[35] However, we hypothesized that CPP and L/H ratio would be weak predictors of cognitive loading compared to autonomic measures (quantified with odds ratios) due to the decline in voice quality and laryngeal function with increased age.[41] We did not expect voice f_o or sound pressure level to be predictors of cognitive load in older adults since they were not predictors in young adults[35] and show greater variability with aging.[46−48]

METHOD

Participants

Twelve healthy older participants (6 males, 6 females) between 68 and 78 years of age (M = 73 years; 3 months, SD = 4 months) participated in the study. All participants were recruited from the greater West Lafayette, IN area and were screened for aural, visual, cognitive, and linguistic factors that could confound study outcomes, using the following screening procedures: (1) a 40 dB HL pure tone hearing screening at 1000, 2000, 4000, and 6000 Hz,[65] (2) the Oral Speech Mechanism Screening Examination-third Edition OSMSE-3 [66]; (3) the Ishihara Color Blindness Test[67], (4) the Cognitive Linguistic Quick Test CLQT [68]; (5) the Word Identification and Passage Comprehension subtests of the Woodcock Reading Mastery Tests-Revised WRMT-R[69]; and (6) the Sentence Reading subtest of the Psycholinguistic

Assessment of Language Processing in Aphasia PALPA; [70] at 80% accuracy. In addition to passing the requirements of these screening measures, all participants were native speakers of North American English and demonstrated reading abilities at an eighth-grade level or higher, based on the Word Identification and Passage Comprehension subtests of the Woodcock Reading Mastery Tests-Revised WRMT-R.[69]

No participant reported any of the following conditions: a diagnosis of mood or psychological disorders (eg, clinical depression or generalized anxiety disorder), sleep apnea, or other associated sleep disorders, dermatological conditions such as psoriasis, or sensorimotor dysfunction of the upper extremities. Participants had not smoked in the past five years and did not have abnormally high or low blood pressure.[71−73] These criteria were determined using a questionnaire. Participants were instructed to abstain from alcohol, caffeine, large meals, and physical activity for at least three hours prior to participating in the study, as these factors could impact autonomic arousal.

Procedure

Participants were seated in a cushioned chair in front of a computer monitor. Prior to study procedures, participants washed their hands with water and soap to clean the surface of the fingers. To measure skin conductance, each participant was first fitted with two disposable EDA surface electrodes (EL507), attached to the palmer surface of the medial phalanges of the first/index and second/middle finger of the right hand.[74] A photoplethysmogram transducer was then placed on the third/ring finger of the right hand and stabilized with a Velcro strap to acquire pulse data. A Countryman E6i omnidirectional ear-set microphone was also placed on each participant at a microphone-to-mouth distance of 6 cm and positioned at 90 degrees from the corner of the mouth for collection of acoustic signals.

Once all the equipment had been placed, participants were instructed to read sentences with a modified Stroop paradigm on the computer monitor in front them. The sentence task involved two cognitive load conditions − congruent (low cognitive load) and incongruent (high cognitive load) − using different colored words in various font colors. Participants were asked to read twelve versions of the following target sentence on a computer screen: "Pammy and Bobby picked blue, pink, red, and brown poppies for their mommy" while autonomic and acoustic signals of voice were collected over repeated sentence productions. The text of each of the four colored words (blue, pink, red, and brown) in the sentence varied in font color across the twelve "Pammy and Bobby" sentence trials. The text of the other words in the sentences (Pammy and Bobby picked ...and ... poppies for their mommy) were shown in black font.

In reading the sentences, participants were instructed to say the font color of the color words in the sentence out loud, regardless of what the written word semantically represented. In six of the trials, the text's font color matched the semantic meaning of the text (eg, the word "blue" written in blue font). In the other six trials, the font color of each word's text differed from the semantic representation of that word (eg, the word "pink" written in blue font). Sentences in the former condition were used to assess acoustic and autonomic parameters under relatively lower cognitive load (congruent condition); sentences in the latter condition were used to evaluate the effects of higher cognitive load on those same parameters (incongruent condition). Different combinations of color of font and semantic text were pseudorandomized in the incongruent condition to prevent any learning effects to the condition. The exceptions were that the word "pink" was never represented in red font and the word "red" was never represented in pink font; the text of a color word was never written in matching font in the incongruent condition.

To further minimize learning effects and to prevent autonomic habituation, four foil sentences with different combinations of the order of the color word text were also included, with two of the foil sentences occurring in the congruent condition and the other two sentences occurring in the incongruent condition. Acoustic and autonomic parameters acquired during the foil sentences were not included in the statistical analysis.

Prior to starting the formal experimental protocol with the two cognitive load conditions (congruent and incongruent), participants were asked to read three practice sentences on the computer screen to ensure they could accurately read the sentences and identify the font colors. Participants first read sentences all in black font, followed by two sentences with the color words in different combinations of font colors. Once accuracy was confirmed and participants were familiar with the task, they were asked to read the sentences out loud in their habitual pitch and comfortable loudness. Both target and foil sentences were presented in four blocks, with four sentences within each block, for a total of 16 sentences. A 30-second rest period prior to the start of each sentence block was recorded in order to acquire baseline autonomic parameters. An additional 8-second period followed each sentence block was also recorded to allow for autonomic recovery.

During these pre- and post-block rest periods, participants were asked to sit still and to focus their visual attention on a fixation cross on the computer screen. Participants could request short (eg, 1-3 minute) breaks after each segmented block, during which they could move around and ask questions. Participants were also asked to complete a brief picture description task at this time. The task was brief, so as not to induce fatigue, and helped to decrease the monotony of the Stroop sentences.

Instrumentation and signal processing

Autonomic and acoustic signals were simultaneously collected throughout the experimental procedure. Autonomic data were collected with the Biopac MPI150 Data Acquisition System, amplifiers, and the AcqKnowledge 382 program (Biopac Systems, Inc.). All signals were synchronized through the data acquisition unit (ODAU II) of the 3D Investigator Motion Capture System (Northern Digital, Inc.). Acoustic signals were acquired using an E6i omnidirectional earset microphone (Countryman Associates, Inc. Menlo Park, California) and a Marantz PMD670 solid state recorder (D&M Professional, Itasca, Illinois) at a sampling rate of 44.1 kHz.

Autonomic signal processing

Peripheral pulse signals were collected with the Biopac Pulse Plethysmogram Amplifier (PPG100C) and Photo Plethysmogram Transducer (TSD200), previously attached to the participant's third/ring finger with a Velcro strap. The position of the transducer and the tension of the Velcro strap remained constant throughout the experimental task so that the deformation of the underlying capillary bed did not change during the experiment. The transducer measures the amount of signal reflectance after emission of an infrared signal, which increases with increased blood volume in the capillaries[75]. The pulse signal was recorded with a gain of 100 V and a sampling rate of 14925 samples per second. The pulse volume amplitude and pulse period measures were determined using the recorded pulse signal.

The skin conductance signal was collected with the constant voltage (0.5 V) Biopac GSR EDA Galvanic Skin Response Amplifier (GSR100C) and the two disposable EDA electrodes (EL507), previously described. Skin conductance response amplitude reflecting phasic electrodermal activity, was examined. The skin conductance response amplitude was obtained through processing of the tonic skin conductance level signal, which was recorded with a gain of 10 μS/V and a sampling rate of 14925 samples per second.

Acoustic signal processing

The acoustic data for each of the twelve target sentences in the congruent and incongruent conditions were cropped using Praat software.[76] In order to examine only speech segments in the acoustic analysis, all pauses were removed from the cropped signals for each sentence using customized MATLAB[77] scripts. Each sentence was first low-pass filtered (Butterworth filter with a 400 Hz cutoff) and then the envelope of the filtered signal was plotted to determine a cutoff value for silent periods in the sentence. The determined cutoff value was used to trim the original, unfiltered, acoustic signal and remove pauses from the sentence. The processed twelve acoustic samples for each participant were visually and aurally inspected to determine all instances of speech had been maintained and that only voice segments were contained within each sample, prior to conducting acoustic analyses.

Autonomic data analysis

Custom MATLAB[77] scripts were used to extract and analyze the following physiological measures of autonomic arousal: (1) pulse volume amplitude, (2) pulse period, and (3) skin conductance response amplitude. The three physiological autonomic measures were each identified, starting at the time point the sentence was presented on the computer screen, and ending three seconds after the acoustic signal had come to completion, to capture autonomic arousal associated with task planning, preparation, and performance. The first time point captured the pre-motor planning period, while the latter time point was at termination of speech production, to account for lag in autonomic response.[78,79] Two 5-second segments within the 30-second rest period that preceded each sentence block were also identified. The two segments reflecting when the autonomic nervous system was most relaxed (ie, the relative lowest level of arousal) were selected and used as baseline anchors to which autonomic measures during sentence production were referenced.

Pulse volume amplitude and pulse period were extracted from the pulse signal using MATLAB. First, the pulse signal was bandpass filtered from $0.5 - 3$ Hz with a 100-order FIR filter and downsampled to 250 samples per second. Second, pulse volume amplitude during sentenced production, as a percent of baseline, was determined by measuring the amplitude (in V) of each pulse cycle. The amplitude of each pulse cycle was determined via a peak-finding algorithm that identified the minima and maxima of each pulse signal and compared them to the adjacent maximum and minimum amplitudes. The resultant number, representing the difference in amplitude between peaks, was then divided by the baseline pulse volume amplitude found within each corresponding 5-second rest period for that block. Third, the pulse period as a percentage of baseline was calculated by determining the mean time (in seconds) between adjacent pulse peaks in the signal for each sentence production and referencing it to the same measure in the baseline signals. When autonomic arousal increases, sympathetic activity is expected to induce vasoconstriction and result in decreases in both pulse volume amplitude and pulse period (reflecting an increase in heart rate) as a percentage of baseline.

Peak skin conductance response amplitude (in μS) for each sentence production was determined using the difference between the amplitude at skin response onset and the maximum amplitude skin response,[78] using an automated MATLAB script. Prior to amplitude calculations, the tonic skin conductance level signal was low-pass filtered at 1 Hz and downsampled to 250 samples per second. The skin conductance response amplitude was then derived using a direct-form II, second-order section Chebyshev high pass filter with a cut-off frequency of 0.07 Hz. Activity in the eccrine sweat glands in specific areas of the body (eg, surfaces of the hands) increases with sympathetic nervous system arousal, and greater sweat gland activity results in greater electrical conductance between electrodes on these surfaces e.g. fingers of the hand. [78,79,80] Thus, skin conductance response amplitude was examined in the current study as a measure of electrodermal sympathetic nervous system activity. Since these sweat gland responses are not expected during the rest periods used for baseline referencing, measures of skin conductance response were only captured and analyzed during sentence production (ie, the congruent and incongruent cognitive load tasks).

Acoustic analysis

Four acoustic measures were calculated from the processed voice samples using the KayPENTAX Computerized Speech Lab 4500 Multidimensional voice program (MDVP; Kay Elemetric Corp., Lincoln Park, New Jersey) and the Analysis of Dysphonia in Speech and Voice ADSV; [81] add-on program: (1) cepstral peak prominence (CPP); (2) low-to-high spectral energy decibel ratios (L/H ratio); (3) fundamental frequency (f_o); and (4) sound pressure level. These four measures were chosen because they are frequency-based, rather than time-based (eg, such as jitter, shimmer, harmonics-to-noise ratio). Time-based measures rely on estimation of periodic content in the voice signal, whereas frequency-based measures do not. Thus, frequency-based measures can be used to examine running speech and robustly represent aberrant (more aperiodic) vocal quality.[82,83] Additionally, these measures could be discussed directly in relation to previous work with younger adults who participated in the same experimental task.[35]

CPP was calculated at a threshold value of 1 dB using a Fourier transform of the power spectrum, smoothing, and regressing the expected value. L/H ratios were calculated as a discrete Fourier transform and the low-frequency energy regions divided by the high-frequency energy regions at a 4000 Hz cutoff. The raw f_o values (Hz) were converted to semitones (ST) for each sentence to be able to directly compare values across all male and female participants. Conversion to ST was achieved using each participant's average fundamental frequency values in the congruent condition as the reference frequency ($f_{o\ ref}$) in Eq. 1 shown below:

$$\mathrm{ST} = 39.86\mathrm{x}\log_{10}\left(\frac{f_o}{f_{oref}}\right) \qquad (1)$$

Custom MATLAB scripts were used to calculate (4) sound pressure level as the relative root-mean-square (RMS) value in dB. The RMS was calculated for all sentences in the congruent and incongruent conditions. To extract relative RMS, the RMS values extracted from the congruent condition were used as a reference for the RMS values from the incongruent condition for each speaker.

Statistical analysis

A binary logistic regression model was constructed to predict cognitive loading (comparing the congruent to the incongruent Stroop condition) in Minitab (Version 17; Minitab Inc., State College, Pennsylvania). Prior to model fitting, the distributions of all autonomic and acoustic parameters were examined. The skin conductance response amplitude distribution was found to have left skewness, thus a cube-root transform was administered to the data to reduce skewness. The model was fit using participant as a categorical predictor with the four acoustic parameters (CPP, L/H ratio, f_o, RMS) and three autonomic parameters (pulse volume amplitude, pulse period, cube-root transform of skin conductance response amplitude) as continuous predictors. The alpha level was set *a priori* at $P < 0.05$.

RESULTS

Descriptive differences between the congruent and incongruent conditions were seen in two out of the three autonomic parameters (Figure 1). Specifically, skin conductance response amplitude was, on average, higher in the incongruent condition (M = 0.19 μS, SD = 0.21 μS) as compared to the congruent condition (M = 0.13 μS, SD = 0.17 μS). The pulse volume amplitude was lower in the incongruent condition (M = 66.2%, SD = 21.8%), as compared to the congruent condition (M = 74.1%, SD = 25.6%). No descriptive differences were found in pulse period between congruent (M = 95.7%, SD = 5.4%) and incongruent conditions (M = 95.3%, SD = 5.1%).

In general, the acoustic parameters did not show descriptive differences as a function of cognitive load condition (Figure 2). CPP values remained consistent, on average, across the incongruent (M = 6.33 dB, SD = 1.08 dB) and congruent (M = 6.25 dB, SD = 1.04 dB) cognitive load conditions. L/H ratio measures were comparable in the incongruent cognitive load condition (M = 38.4 dB, SD = 2.17

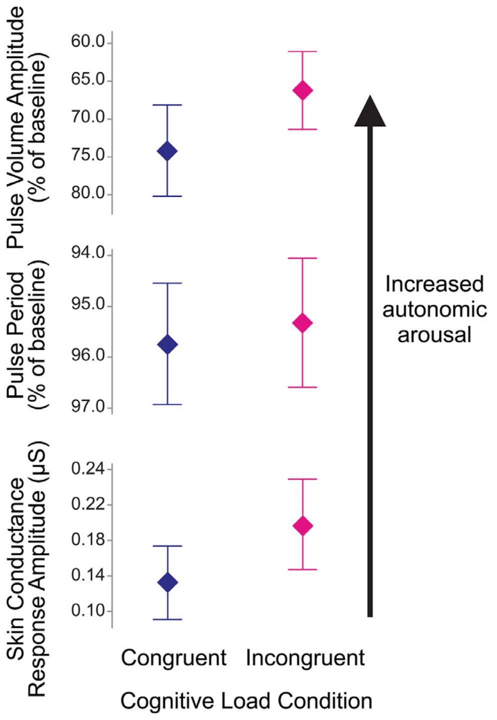

FIGURE 1. Autonomic measures as a function of cognitive load condition (congruent on the left, incongruent on the right). Symbols represent group means and error bars show 95% confidence intervals. Note the reversed y-axes on the upper two panels such that higher values on the y-axes reflect greater autonomic arousal.

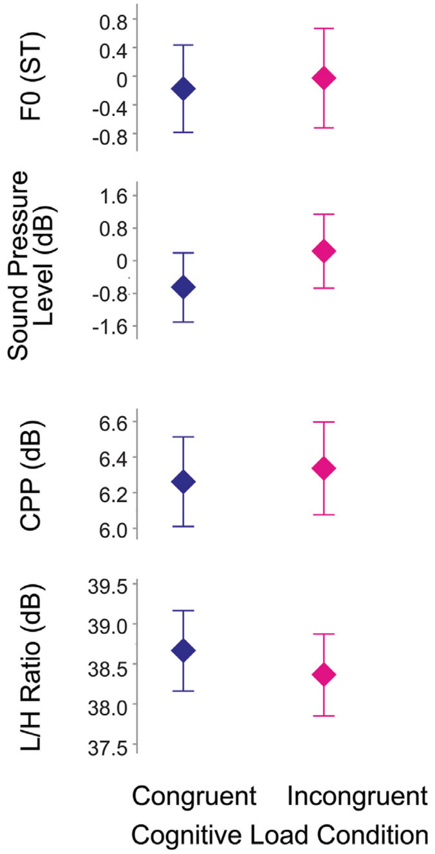

FIGURE 2. Acoustic measures as a function of cognitive load condition (congruent on the left, incongruent on the right). Symbols represent group means and error bars show 95% confidence intervals.

dB) and congruent cognitive load (*M* = 38.7 dB, *SD* = 2.12 dB). Similarly, voice f_o showed minimal change between the incongruent (*M* = –0.03 ST, *SD* = 2.91 ST) and congruent (*M* = –0.17 ST, *SD* = 2.12 ST) cognitive load conditions. There were also no substantial differences between the incongruent (*M* = 0.21 dB, *SD* = 3.81 dB) and congruent (*M* = –0.66 dB, *SD* = 3.56 dB) cognitive load conditions in sound pressure level.

The results of the logistic regression model paralleled the descriptive findings for the autonomic and acoustic measures in the current work (Table 1). When examining all three autonomic measures and four acoustic measures as predictor variables of cognitive load condition (Table 1), two variables were statistically significant predictors of cognitive load: pulse volume amplitude (chi-square [χ^2] = 5.05, *P* = 0.03) and skin conductance response amplitude ($\chi^2 = 11.47$, $P < 0.01$).

Regression model validation suggested that the model had a poor fit ($R^2 = 0.022$). A Pearson's chi-squared goodness-of-fit test was used to assess whether the experimental findings matched the theoretical distribution of the data; the results were not statistically significant (χ^2 = 147.86, *P* = 0.08). Thus, the poor model fit was likely due to the empirical nature of the data and not because of an inadequate model choice.

DISCUSSION

The objectives of the study were to assess the effects of cognitive load on autonomic arousal and vocal acoustics in a cohort of healthy older adults (aged 68 – 78 years old). Findings are discussed in relation to data from similar tasks in young adults, but no statistical comparisons were performed between young and older adults.

Autonomic findings

In agreement with our first study hypothesis, that autonomic measures would predict cognitive loading in older adults, two of the three autonomic measures were predictive of Stroop task condition. Pulse volume amplitude decreased and skin conductance response amplitude increased during the incongruent (high cognitive load) condition, which reflects increased sympathetic nervous system arousal that occurs in response to stressors.[24]

These findings of increased autonomic arousal during cognitive loading of a speech task are in alignment with the same experimental paradigm in younger adults.[35] However, in younger adults, only skin conductance amplitude was a statistically significant predictor of cognitive loading.[35] In older adults, both pulse volume amplitude and skin conductance amplitude were statistically significant predictors of cognitive load condition. Further, when comparing the odds ratio for skin conductance between the two cohorts, the older adults demonstrated a greater effect (odds

TABLE 1.
Results of the Logistic Regression Predicting Cognitive Load Condition (Congruent or Incongruent)

Predictor Variables	DF	χ^2	*p*	Odds Ratio
Pulse volume amplitude (% of baseline)	1	5.05	*0.025	0.986
Pulse period (% of baseline)	1	0.17	0.679	1.011
Skin conductance response amplitude ($\sqrt[3]{\mu S}$)	1	11.47	*0.001	21.563
Fundamental frequency (ST)	1	0.25	0.618	1.024
Sound pressure level (dB)	1	0.31	0.575	1.0186
CPP (dB)	1	1.00	0.318	1.2275
L/H ratio (dB)	1	3.13	0.077	0.8244
Participant	11	9.73	0.555	

ratio = 21.6; Table 1) compared to the younger adults (odds ratio = 13.3) for skin conductance amplitude. Thus, these results imply a greater effect of cognitive loading on electrodermal autonomic arousal in older adults, which is in agreement with other work.[54–58]

Voice findings

We hypothesized that CPP and L/H ratio would predict cognitive loading, but these two measures of voice quality were not statistically significant predictors of cognitive load condition. The descriptive trends suggest the possibility of a more pressed voice under cognitive loading (due to the decrease in L/H ratio that occurred concurrently with an increase in overall periodic energy, represented by higher CPP values), which aligns with results in younger adults reported by MacPherson et al[35] However, more direct physiological measures are necessary to determine whether these changes in CPP and L/H ratio are indicative of a more pressed voice. Previous studies support the lack of statistical findings for CPP and L/H ratio with cognitive loading. For example, a study by Yap et al (2011) demonstrated that CPP may be beneficial in determining level of cognitive loading, but with only 63% accuracy.[84] During cognitive loading, prior work has also reported conflicting changes in spectral information, which would be reflected in the L/H ratio values in the current work. One study found decreased spectral tilt[31] with cognitive load increases, consistent with a reduced L/H ratio, whereas another study reports reduced spectral noise,[32] which would result in a greater L/H ratio. These conflicting findings suggest there are other variables affecting measures of voice quality during cognitive loading and/or that CPP and L/H ratio measures are insensitive to the changes that occur.

The lack of differences found in acoustic measures of voice quality (CPP and L/H ratio) as a function of cognitive load in the current work could result from heterogeneous physiological changes to the respiratory, laryngeal, and articulatory subsystems of speech in older adults.[41,85–88] In alignment with the expected changes to the laryngeal system of older adults, the current work demonstrated lower average CPP values (reflecting reduced periodic energy and voice quality) across both conditions (congruent: M = 6.25 ST, SD = 0.25 ST and incongruent: M = 6.33 ST, SD = 0.26 ST), compared to the findings in younger adults (congruent: M = 7.00 dB, SD = 1.12 dB and incongruent: M = 7.11 dB, SD = 1.11 dB[35]). However, L/H values were comparable for the older cohort (congruent: M = 38.4 dB, SD = 2.17 dB and incongruent: M = 38.7 dB, SD = 2.12 dB) and younger cohort (congruent: M = 37.8 dB, SD = 2.78 dB and incongruent: M = 38.1 dB, SD = 2.80 dB[35]).

In agreement with our study hypotheses, voice f_o and sound pressure level were not statistically significant predictors of the presence of increased cognitive load. These results, which replicate those in younger adults,[35] support that cognitive loading does not have a large effect on voice f_o or sound pressure level. Regarding the lack of differences in sound pressure level, specifically, one prior study similarly showed a very small difference (1 dB sound pressure level) in acoustic samples of aviation pilots under stress-induced cognitive loads with flight simulation.[89]

There is also evidence that age-related changes to the speech system can differ by sex. When examining the respiratory system, older males have been found to produce speech at higher lung volumes compared to younger males, but this age-related difference was not found for females.[85] Similarly, sex differences have been observed in age-related changes to the laryngeal system (specifically, for voice f_o and noise content in the voice signal.[47,90] The current work did not examine effects of sex due to the sample size, but this should be explored in future work.

Additionally, there is evidence that age-related changes to the speech system interact with cognitive loading. For example, prior work found greater variability in articulatory coordination and movement duration with increased cognitive load during a Stroop task that was more pronounced for older compared to young adults.[91,92] A similar interaction may be true for respiratory or laryngeal changes to the speech system. Future work should incorporate measures of respiration, laryngeal physiology, and articulatory kinematics to fully characterize how cognitive loading affects acoustic measures of speech in older and younger adults.

Limitations and future work

The current work has several limitations. The first limitation is the relatively small sample size. The combination of small sample size and large variability in acoustic parameters could explain some of the null findings in acoustic outcomes. The second limitation is the lack of measures of respiratory patterns and laryngeal physiology, both of which directly influence vocal productions. Therefore, the relative contributions across the speech subsystems with increased cognitive demands cannot be determined. Future work should incorporate methods such as electroglottagraphy and high speed videoendoscopy in order to clarify contributions from the laryngeal system, whereas body plethysmography measures could also be included to determine respiratory system contributions. The third limitation is the lack of self-perceptual measures of cognitive load and self-reported arousal. Although participant-reported measures are subjective, they allow consideration of differences across speakers in the perception of physiological reactivity.

CONCLUSION

The current work extends prior findings in young adults by investigating both autonomic arousal and voice parameters in response to cognitive loading in an older adult cohort. The results of this study indicate that higher cognitive demands correspond to increases in autonomic arousal (via pulse volume amplitude and skin conductance response amplitude), but acoustic measures of voice (CPP, L/H ratio, voice f_o, and sound pressure level) do not clearly align with increases in cognitive demands and autonomic arousal in older adults.

Taken together, MacPherson et al[35] and the current study support that: (1) autonomic arousal is associated with increased cognitive loading during a speech task, regardless of age, (2) older adults demonstrate a greater autonomic arousal response compared to young adults during cognitive loading, and (3) acoustic measures of voice are associated with increased cognitive loading in younger, but not older adults. Given the concurrence of autonomic dysfunction in speakers with specific voice disorders via self-report,[21–23] the findings of MacPherson et al[35] provide support that autonomic arousal in speakers with voice disorders could be related to the observed voice changes. However, the current work suggests that this same relationship may not present in older adults and more work is needed to clarify age-related interactions between cognitive loading, autonomic arousal, and acoustic measures of voice.

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