ASHA American Speech-Language-Hearing Association

JSLHR

Research Article

Autonomic Arousal During Speech Production and Sensorimotor Adaptation

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ARTICLE INFO

Article History:
Received March 11, 2025
Revision received July 1, 2025
Accepted August 27, 2025

Editor-in-Chief: Jessica E. Huber
Editor: Emily Beth Myers

https://doi.org/10.1044/2025_JSLHR-25-00171

ABSTRACT

Purpose: Autonomic arousal impacts speech; however, it is unclear how it affects speech motor control mechanisms. The purpose of this study was to delineate the role of autonomic arousal during typical lower order speech output and higher order sensorimotor adaptation.
Method: Cognitive load was modulated to induce autonomic arousal in two experiments in a group of adults with typical speech (N = 30). Experiment 1 involved producing sentences with embedded Stroop stimuli. Experiment 2 consisted of an altered auditory feedback paradigm in which participants received predictable changes of F_1 of single Stroop words. Autonomic activity (cardiovascular and electrodermal) was collected in both experiments. Acoustic measures of articulation (F_2 slope, vowel articulatory index, and percent pause time) were collected from Experiment 1, and adaptive responses (% change in F_1) to manipulations of feedback were collected from Experiment 2. Mixed linear effect models were used to assess cognitive load and autonomic arousal on acoustic responses from both experiments.
Results: Increased autonomic arousal was related to decreased F_2 slope in Experiment 1. Increased autonomic arousal was related to greater adaptation in Experiment 2. Cognitive load did not significantly affect acoustic metrics in Experiment 1 or adaptation in Experiment 2.
Conclusion: These findings suggest that the physiological state of the body not only plays a role in typical speech production but could also be important for sensorimotor adaptation.

Speech is a complex process requiring precise coordination between the brain and body. Decades of research have focused on the central nervous system in investigations of the brain regions and neural pathways involved in planning, producing, and perceiving speech. Understanding the neurobiology of speech has been instrumental for both basic science and clinical purposes in the diagnosis and treatment of speech disorders. Although this top-down approach has built the foundation of our speech science knowledge, there has been far less research understanding the role of the peripheral nervous system and how the body's response to natural stressors of the environment impacts the higher order planning and lower order biomechanical mechanisms of speech.

The autonomic nervous system (ANS), which is part of the peripheral nervous system, is responsible for regulating automatic processes of the body. These involuntary processes change in response to internal or external stressors. Two major divisions of the ANS, known as the sympathetic and parasympathetic branches, work together to maintain homeostasis. These branches are symbiotic in nature, although their relationship is dynamic, varying between synchronous, asynchronous, and independent, depending on the body's needs at any given point (Hamill et al., 2012).

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Sympathetic arousal typically occurs when the body prepares and undergoes stressful situations, whereas parasympathetic arousal occurs when the body attempts to recover from stress (Bear et al., 2020; Hamill & Shapiro, 2004). Because the sympathetic and parasympathetic branches work in a coordinated fashion that can be difficult to tease apart, this article will refer to autonomic arousal as an umbrella term to encompass the state of the body in response to a stressor. Various organs and bodily systems respond to changes in arousal states, many of which overlap with those responsible for producing speech. For example, sympathetic and parasympathetic arousal impact the respiratory system (Dampney, 2015; Nattie & Li, 2012), causing changes in breathing patterns, which alters the supply of airflow for phonation. Moving up the speech chain, sympathetic innervation has also been found in the larynx (Hisa et al., 1999; Ibanez et al., 2010), potentially impacting vocal fold vibratory patterns. Particularly relevant to the current study, sympathetic nerve stimulation studies have found arousal to result in changes in the sensitivity of sensory receptors including periodontal and intraoral mechanoreceptors, as well as jaw muscle spindles (Cash & Linden, 1982; Edwall & Scott, 1971; Passatore et al., 1985). These changes can impact the articulatory and resonatory aspects of speech. Despite this anatomical evidence of sympathetic innervation among various speech organs and muscles, there is still a considerable gap in the research on how arousal impacts speech production as well as the higher order processes of regulating speech, known as speech motor control. Addressing this gap would allow for a better understanding of how speech is impacted when a person's body responds to natural stressors, which could provide support for broadening clinical diagnoses and treatments to include evaluations and practices that induce autonomic arousal.

To study autonomic arousal in a controlled setting, the body first needs a stimulus to activate the sympathetic nervous system. Although there are diverse stimuli researchers can use to achieve this, modulating cognitive load is an effective and ecological method that has been used in prior speech studies (Dromey & Bates, 2005; Kleinow & Smith, 2006; MacPherson et al., 2017; Walsh et al., 2019). It is important, however, to understand the context in which cognitive loading tasks are being used in research. For example, some studies use cognitive load to induce autonomic arousal in efforts to understand how physiological changes may impact study outcomes (e.g., Dahl & Stepp, 2023); in this way, cognitive load is used as a tool to modulate physiological responses. Meanwhile, other studies use cognitive load challenges to investigate how differences in cognitive processes impact experimental outcomes (Dromey & Bates, 2005); in this way, cognitive load is used as an independent variable to study. A major limiting factor in this line of research is that most studies do not collect physiological data of the ANS. This makes it impossible to parse whether study outcomes are a result of taxing cognitive resources or the body's physiological responses. Moreover, cognitive loading tasks can span a variety of processes such as attention, working memory, and executive function, adding to the difficulty in interpreting the variability in the literature. Likely, there are influences of both cognitive control processes and physiological arousal on study outcomes, and the purpose of this study is to attempt to delineate these effects in speech production and speech motor control.

Cognitive Load, ANS Arousal, and Speech Production

Many studies in the literature investigating the effects of cognitive load on speech production have focused on the voice subsystem, with acoustic outcomes related to vocal quality, pitch, and loudness (Dahl & Stepp, 2023; Helou et al., 2020; MacPherson et al., 2017; Mendoza & Carballo, 1998; Perrine & Scherer, 2020). Within the studies that have focused on the articulatory subsystem in relation to cognitive load, most have used articulatory kinematic measures to capture changes in speech. A common finding observed across these studies is that articulatory coordination becomes more variable with increased cognitive load (Dromey & Bates, 2005; Dromey & Benson, 2003; Dromey & Shim, 2008; Kleinow & Smith, 2006; MacPherson, 2019). The remaining literature comprises studies that have found articulatory acoustic changes with increased cognitive load. Acoustic changes characterized by decreased formant slopes (Yap et al., 2011), speech rates (Caruso et al., 1994; Huttunen et al., 2011), and articulatory velocity coordination (Heaton et al., 2020), as well as increased vowel durations (Caruso et al., 1994), and speech and pause rates (Khawaja et al., 2007; Lively et al., 1993) were associated with higher cognitive loads compared to lower cognitive loads. In summary, cognitive loading seems to be related to decreased articulatory precision, slower vowel productions and formant transitions, differing changes in the speed of running speech, and more frequent pauses. These results are often discussed within the framework of allocating neural resources and balancing speaker demands.

Far fewer studies in the literature have investigated ANS arousal, cognitive load, and articulation together (Heaton et al., 2020; Kleinow & Smith, 2006; Weber & Smith, 1990), which is necessary to understand how the body's regulatory responses impact speech. In addition to changes in kinematic measures, Kleinow and Smith (2006) found accompanying changes in physiological measures indicative of ANS arousal in conditions with increased cognitive load, suggesting potential interactions among speech, cognition, and autonomic arousal. Heaton et al.

(2020) used electrodermal activity (EDA) and acoustic data to predict cognitive load performance and found that EDA measures and articulator velocity coordination significantly predicted performance. Weber and Smith (1990) found that dysfluency was related to ANS arousal during spontaneous speech in a sample of adults who stutter. As discussed above, it's important to understand the context in which cognitive load and ANS arousal are being used in these studies. Kleinow and Smith used a Stroop task to *elicit* ANS arousal while also investigating the cognitive load effects on speech. Heaton et al. used autonomic and acoustic measures in attempts to find physiological and motor indices that could *predict* cognitive fatigue. Weber and Smith used a cognitive speech task to *elicit* ANS arousal with the goals of comparing arousal levels between two speaker groups and determining if arousal related to dysfluency. Because cognitive load and ANS arousal were used differently in these studies, it is difficult to compare results to make conclusions about the interactions among cognitive load, autonomic arousal, and speech.

Cognitive Load, ANS Arousal, and Speech Motor Control

In order to produce efficient speech, neural control systems exist to ensure the correct acoustic targets are being produced. These processes are broadly referred to as speech motor control, and this area of research is dedicated to understanding the neurological processes involved in higher order speech planning and regulating processes. In one computational model of speech motor control (Directions Into Velocities of Articulators; Tourville & Guenther, 2011), it is suggested that there are two parallel control processes working together to monitor (feedback) and update (feedforward) speech. The feedback controller detects and corrects for errors in speech, whereas the feedforward controller drives efficient speech through the use of stored motor programs. In mature systems, speakers rely heavily on the tuned feedforward controller because auditory feedback control is too slow for typical phonemic output (feedback latency ~150 ms). Due to its importance in everyday speech, it is critical to understand factors that may impact the efficacy and efficiency of feedforward control. Feedforward control can be assessed by investigating how well the system can retune its stored motor commands, a process known as sensorimotor adaptation. Through experiments designed to elicit sensorimotor adaptation, researchers use predictably altered auditory feedback to induce errors and evoke changes in the motor programs in efforts to understand feedforward control behaviorally (e.g., Houde & Jordan, 2002; Villacorta et al., 2007). How a person responds to these artificial changes can give an estimate of how well their feedforward control system works (i.e., whether they integrate corrective motor actions for future productions).

A growing body of literature has attempted to investigate trait-related factors that may influence individual responses to sensorimotor adaptation experiments. These factors include auditory acuity (Martin et al., 2018; Villacorta et al., 2007), language experience (Cai et al., 2023), and—most relevant to the current study—general cognitive abilities (Martin et al., 2018). One study has shown that individual cognitive abilities (i.e., those measured from cognitive assessments) do not predict adaptation of speech (Martin et al., 2018). Other studies have taken a "state" focus (i.e., temporarily altering the situation or condition) to understand individual variability in responses to altered cognitive states during sensorimotor adaptation (Krakauer et al., 2024; Scheerer et al., 2016). These studies have incorporated cognitive loading, specifically divided attention, into adaptation tasks to determine the impacts of a cognitively stressful situation. One of these studies found reduced adaptation of voice fundamental frequency in conditions of divided attention (Scheerer et al., 2016). The other study found no differences in adaptation of formants in conditions with and without divided attention (Krakauer et al., 2024). It is unsurprising that there are differences in the impacts of cognitive load on adaptation between subsystems of speech (i.e., voice vs. articulation) since many studies have shown that results from one subsystem do not always translate to the other (Lester-Smith et al., 2020; Perkell et al., 2007; Parrell & Houde, 2019; Weerathunge et al., 2022). However, a critical factor that was not considered in earlier studies is the role of autonomic arousal on sensorimotor adaptation during cognitive loading.

With any task that taxes cognitive resources, it is important to consider the physiological responses that occur as a result of autonomic arousal. Without measuring physiological activity, there is a risk of masking individual differences in responses to cognitive loading. Given that behavioral responses to sensorimotor adaptation paradigms are already variable at the individual level, assessing autonomic responses would provide an avenue for understanding this variability and help to clarify whether observed study outcomes are due to the cognitive loading component or the physiological responses they trigger. This is an important distinction as the effects of ANS arousal may not be the same as the effects of cognitive loading on sensorimotor adaptation. Evidence from the motor literature supports this supposition as ANS arousal has been found to relate to increased motor adaptation in locomotion (Green et al., 2010) and increased sensitivity to errors in upper limb motor control (Edrei et al., 2009). These results contrast the diminishing effects of cognitive load on adaptation described in the speech tasks above,

suggesting ANS arousal could play a critical role in sensorimotor adaptation of speech, but no prior studies have examined these effects. By incorporating autonomic responses in sensorimotor adaptation paradigms, we can start to understand how the bodily responses to stress interact with the neural control systems of speech, which can motivate other clinically relevant questions stemming from motor learning processes. Sensorimotor adaptation is a central component of motor learning—a skill often used in speech therapy—further underscoring the importance of understanding how sensorimotor adaptation is affected by the body's regulatory processes.

Current Study

The current study aims to investigate the association of cognitive load and ANS arousal on the lower order biomechanics of speech production and the higher order planning mechanisms of speech motor control. Two experiments were conducted to carry out the aims of the study, both of which modulated cognitive load to induce ANS arousal. *Experiment 1* assessed lower order speech acoustics (i.e., F_2 slope, vowel articulatory index [VAI], and percent pause time [PPT]) during a continuous speech task. The acoustic measures used in Experiment 1 were chosen to capture various aspects of articulation including speed of vowel transitions, precision, and coordination. *Experiment 2* assessed individuals' ability to update higher order feedforward control, as measured using F_1 adaptation to altered auditory feedback.

Based on prior literature on the effects of cognitive load and ANS arousal on articulation, we hypothesized that acoustic measures of speech during *Experiment 1* would be related to both cognitive load and ANS arousal. Specifically, we predicted F_2 slope would decrease, VAI would decrease, and PPT would increase with increased cognitive load and increased autonomic arousal. The theory driving this hypothesis for the lower order biomechanical outcomes stems from the fact that successful completion of the task requires precise articulation of the correct target (i.e., color of the word). Thus, it is reasonable that with increased cognitive load, the acoustic outcomes would change to ensure correct phonemic goals. However, because autonomic arousal involves downstream physiological systems involved in phonation and articulation, it also seems likely that autonomic arousal will be involved in production. On the basis of studies reporting a role of ANS arousal in (nonspeech) motor adaptation, we hypothesized that increased ANS arousal would be related to increased adaptation of speech during Experiment 2. Due to the multiple speech-related adaptation studies that reported no effects of cognitive load on articulatory adaptation, we predicted that cognitive load would not interfere with this higher order mechanism.

Method

Participants

All participants completed written consent in compliance with the Boston University Institutional Review Board (#2625) and completed both experiments described below. Participants were the same sample described in Tomassi et al. (2025): 30[1] speakers of American English (15 cisgender males, 15 cisgender females; M_{age} = 22.75, SD = 2.62) who were screened for history of speech, language, hearing, neurological, or autonomic disorders. Participants did not have any training in singing and were nonsmokers. Participants were also screened for various confounds that could potentially affect the ANS or cognitive function such as: history of drug/alcohol abuse, diagnosis of mood or psychological disorder, sleep apnea, low/high blood pressure, dermatological conditions, hyperhidrosis, and medication affecting cognition or the ANS. Prior to the experiment, participants self-reported having abstained from caffeine, alcohol, large meals, physical activity, and stressful events for 3 hr to avoid autonomic variability.

Participants completed a pure-tone hearing screening using a Grason-Stadler Version GSI-18 audiometer and over-ear headphones at 25 dB HL at frequencies of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz (American Speech-Language-Hearing Association, 1997). Participants also completed a color vision screening using the Ishihara Color Blindness Test (Ishihara, 1996). The Montreal Cognitive Assessment (MoCA) was used to assess cognitive function (Nasreddine et al., 2005). All participants demonstrated typical cognitive function defined by a MoCA score above 26 (M = 28.3, SD = 1.5). The Composite Autonomic Symptom Score–31 (COMPASS-31) survey was used to assess baseline ANS symptoms and scores ranged from 0 to 21.75 (M = 7.6, SD = 7.8). This survey scores severity of ANS symptoms using a weighted scale from 0 to 100 (Sletten et al., 2012), with scores in the range of 20–40 and 40–100 representing moderate and severe autonomic symptoms, respectively (Kedor et al., 2022; Sletten et al., 2012). Participants were well within the range of low ANS symptom severity, with the highest scores reaching just above the moderate cutoff.

Experimental Design

Experimental procedures were similar to those previously described in Tomassi et al. (2025) and described in more detail below. Participants completed two experiments

[1]The sample size was sufficient to detect a small–medium effect size (η_p^2 = .05) with α = .05 and power of 80% using the repeated-measures within-participant approach.

(Sentence Production and Sensorimotor Adaptation) while autonomic activity was simultaneously recorded. Autonomic signals and measures from the cardiovascular and electrodermal domains were used in this study as they have been shown to be sensitive to both changes in cognitive load and speech (Kleinow & Smith, 2006; Weber & Smith, 1990) and represent both sympathetic and parasympathetic influence.

Instrumentation and Data Processing

Audio Data

Participants wore a SHURE (Version MX153) omnidirectional microphone positioned 45° from midline and 7 cm from the lips for each experiment. The audio signal for the Experiment 1 was pre-amplified with an RME Quadmic and sampled with an RME Fireface UCX sound card at a rate of 44100 Hz and 32-bit resolution and recorded using SONAR Artist acoustic software. The audio signal for Experiment 2 was also pre-amplified with a RME Quadmic but sampled with a MOTU UltraLite (Version mk3) hybrid sound card at a rate of 44100 Hz and 32-bit resolution. During Experiment 2 only, participants wore Sennheiser HD (Version 280) Pro over-ear headphones. To overcome bone conduction and minimize exposure to high sound pressure levels (Weerathunge et al., 2020), auditory feedback was calibrated to +5 dB relative to the microphone. A Bruel & Kjaer coupler and sound level meter were used to accomplish this calibration. Audapter, a software package for configurable real-time manipulation of acoustic parameters of speech in MATLAB, was used for manipulating F_1 during Experiment 2. The software delay between processing speech and delivery of auditory feedback was 20 ms (Kim et al., 2020), which is less than a detectable amount (30 ms; Yates, 1963).

Autonomic Data

All autonomic signals were conditioned via the BIOPAC MP150 Data Acquisition System (Biopac Systems, Inc.) and sampled at 14700 Hz using a National Instruments data acquisition card. Cardiovascular activity was estimated through the pulse signal, which was collected through a Photo Plethysmogram Transducer (TSD200; Biopac Systems, Inc.) secured distally to the palmar surface of the third finger on the right hand. The pulse signal was amplified with a gain factor of 100 using the Biopac Pulse Plethysmogram Amplifier (PPG100C; Biopac Systems, Inc.). The captured signal is a reflection of the infrared light emitted from the transducer, varying with blood flow in the capillaries (Cacioppo et al., 2000). With increased autonomic arousal, vasoconstriction typically occurs, which reduces blood flow to the capillaries, resulting in reduced amplitude of the pulse signal. It is important to note, however, that changes in the cardiovascular signal do not necessarily indicate solely upregulated sympathetic activity as it can also be reflective of parasympathetic withdrawal or a combination of both. This signal was included in the current study because autonomic arousal is being used as an umbrella term to encompass an overall heightened state of the body, influenced by both sympathetic and parasympathetic activity. EDA was estimated through the skin conductance signal using two disposable EDA electrodes (EL507; Biopac Systems, Inc.). A small amount of isotonic gel was placed on the electrodes prior to securing to the distal palmar surface of the first and second fingers on the right hand. A constant voltage (0.5 V) was sent to the electrodes in order to measure conductivity, which was then amplified with a gain of 10 μS/V using the Biopac GSR EDA Galvanic Skin Response Amplifier (GSR100C). With increased autonomic arousal, the conductance between eccrine sweat glands increases (Dawson et al., 2016), and thus, a larger response in the skin conductance signal is observed.

The pulse signal was bandpass filtered from 0.5 to 3 Hz with a 100-order finite impulse response filter and then downsampled to 250 Hz. To gather the main measures of interest from the pulse signal, peaks of the signal were extracted using an automated peak detection algorithm in MATLAB (findpeaks.m, MATLAB release 2018a). All peaks were then manually checked by authors N.E.T. and D.M.T. for quality assurance. *Pulse volume amplitude* was calculated as the magnitude between the peaks and troughs. *Pulse period* was defined as the time between adjacent peaks. Because cardiovascular activity is highly variable between individuals, the pulse metrics were normalized to a baseline state. Each task in Experiments 1 and 2 started with a 30-s rest for the normalization of cardiovascular activity. The normalization process involved identifying two windows during this rest period in which the amplitude of the pulse signal was the highest (indicating low arousal). The pulse volume amplitude and pulse period were calculated and averaged in both rest windows,[2] and the final measure of each of these metrics was used to normalize the task measurements. Thus, the pulse measurements are described as a percentage of baseline, indicating how activity during a task changes with respect to a more restful state.

The tonic skin conductance signal was filtered using a second-order Chebyshev high-pass filter with a cutoff frequency of 0.07 Hz, resulting in the skin conductance response (SCR). The SCR was used to capture phasic (*SCR amplitude* and *percent of event-related responses*)

[2]Each rest window was 5 s long and, on average, contained 5.6 (range: 3.5–7.5) pulse peak/trough pairs per window, which were used in the calculation of the baseline rest measures. These rest measures were compared with the task-related measures, which were calculated using an average of 365.7 (range: 230.1–509.5) pulse peak/trough pairs during the tasks (each approximately 6 min).

and temporal (*SCR rise* and *half-recovery time*) measures of EDA. The onset and peak of each phasic response were manually selected in the filtered signal by author D.M.T. Intrarater reliability analysis was completed through the re-analysis of 20% of the data by author D.M.T. Interrater reliability was assessed on a subset of the data by an additional technician. Reliability was calculated through the intraclass correlation coefficient, and scores were excellent (interrater: r = .97, intrarater: r = .88). The magnitude between the onset and peak of the phasic response was defined as the SCR amplitude. The number of phasic responses relative to the total number of evoking stimuli (i.e., 48 for Experiment 1 and 132 for Experiment 2) was defined as the percent of event-related responses (%SCR events). In Experiment 1, any SCR observed within the timeframe of a block (i.e., presentation of first sentence in the block to end of the last 8 s break) was considered an event-related response. The 8-s breaks were included because they were within the range of the time interval that the body could respond from a sentence (i.e., SCR latency ~1–3 s, SCR rise time ~1–3 s, SCR half-recovery time ~2–10 s; Boucsein, 2012; Dawson et al., 2016). Because SCRs typically occur in response to a stimulus, any spontaneous SCR in the 30-s rest prior to each set, though rarely observed, was not included in the analysis. The time between the location of the onset and peak of the response was defined as the rise time. The time between the location of the peak and when the response decays half of its maximum amplitude was defined as the half-recovery time.

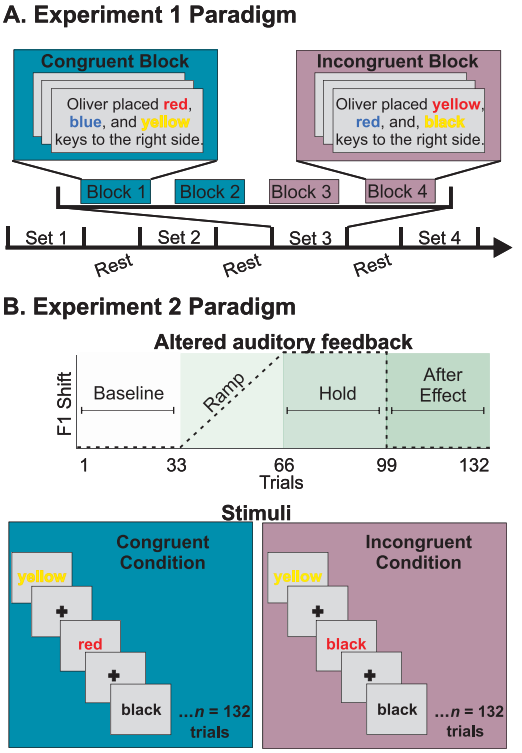


Figure 1. Schematic of Experiment 1 paradigm described in panel A and schematic of Experiment 2 paradigm described in panel B. In Experiment 1, participants produced a total of 48 sentences with Stroop-imbedded words. In Experiment 2, participants sustained the first vowel of the font color for 132 trials per condition while exposed to predictably altered auditory feedback.

Experiment 1: Sentence Production

Experimental Design

During Experiment 1, participants read aloud sentences with embedded Stroop words. Each trial consisted of one sentence containing three Stroop words ("red," "yellow," "black," or "blue") in the center of the sentence. The font color of these Stroop words either matched the phonetic description (congruent condition) or mismatched the phonetic description (incongruent condition). Participants were asked to say the color of the font, rather than the word. The experiment was block designed such that each block comprised four sentences (see Figure 1, panel A). Participants completed four sets of four blocks per set (two congruent and two incongruent). The sentences (see the Appendix) contained the same number of words and target words with phonetic features that were ultimately used to extract specific articulatory acoustic information for analysis. Specifically, some of these target words contained corner vowels for measuring VAI, whereas others contained a diphthong for measuring F_2 slope. Target words for each sentence can be found in Table 1. The order of the sentences was pseudorandomized such that each sentence only appeared once per block. Thus, participants read each sentence 16 times by the end of the experiment.

Breaks were implemented throughout the experiment to avoid autonomic habituation. Each block followed a

Table 1. Stimuli for articulatory acoustic measures.

Stimuli				
Phonetic target				**# / participant**
/i/	**/a/**	**/u/**	**/aɪ/**	***N***
Lee	Spotted	Flew	Kite	16
He	Knots	Blue	Tied	16
Keys	Oliver	Blue	Right	16
VAI			F_2 slope	48

Note. Each word was extracted from a sentence to calculate the corresponding articulatory acoustic measure (i.e., vowel articulatory index [VAI] or F_2 slope). Each combination of words was produced within a sentence 16 times for a total of 48 measures for analyses for each participant.

30-s break in which participants were asked to relax and breathe calmly. These breaks were used to gather autonomic data at rest for normalization purposes (detailed in the analysis section). An 8-s break was given after each trial (as indicated by the time the participant stopped speaking) to provide sufficient time for the ANS to respond to and recover from the stimulus (Boucsein, 2012; Dawson et al., 2016). To avoid any persisting autonomic arousal, the incongruent blocks always followed the congruent blocks. To reduce habituation, each block contained a "foil" sentence at the end in which there were no colored words.

Acoustic Data Analysis

Acoustic measures analyzed from Experiment 1 included: PPT, F_2 slope, and the VAI. For the measures other than PPT, pauses were removed from the speech signals prior to calculating the acoustic measure. Pauses were identified and removed by passing the signal through a low-pass filter and using the envelope of the signal to establish an appropriate voicing threshold. The default threshold was set at 0.01 and was adjusted accordingly to ensure that all speech segments, regardless of the speech level in relation to silence, were preserved. Any part of the signal that did not reach the threshold in the unfiltered signal was deemed a pause and removed. The remaining signal was manually examined for any errors in pause removal. To ensure reliability of this process, the technician responsible for manually examining the signal for errors reanalyzed a portion of the total data (i.e., 20%), and an author (N.E.T.) analyzed the same subset to ensure intra- and interreliability. The intraclass correlation coefficient was used to assess reliability of signal preservation and resulted in good reliability scores (intrarater: r = .93, interrater: r = .87). PPT was used to gain insight on changes in speaking rate and was calculated with the following formula:

$$PPT = 100 \times \frac{time_{\text{total}} - time_{\text{pauses removed}}}{time_{\text{total}}} \quad (1)$$

The VAI was used as a measure of vowel centralization and has been found in the literature to relate to intelligibility (Skodda et al., 2013). To calculate VAI, the average F_1 and F_2 of three corner vowels (/a/, /i/, /u/) in each sentence (see Table 1) were determined manually in Praat and used in the formula:

$$VAI = \frac{\mathrm{F2}/i/ + \mathrm{F1}/a/}{\mathrm{F1}/i/ + \mathrm{F2}/a/ + \mathrm{F1}/u/ + \mathrm{F2}/u/} \quad (2)$$

Because all participants had relatively stable vowel productions (i.e., diphthongization due to certain dialects was not identified), the entirety of the vowel was used in the VAI calculation.

The slope of F_2 was used as an acoustic correlate of diphthong clarity, which was found to relate to intelligibility (Kent et al., 1989), and was calculated manually in Praat using the F_2 trajectory over time for words that contained the diphthong: /aɪ/ (see Table 1). This diphthong was chosen as it requires large changes in supralaryngeal vocal tract configuration and thus results in large F_2 transitions, which allowed technicians to easily identify the start and end. Given that identifications of diphthongs were completed manually, a portion of the data was reanalyzed by the technician as well as an additional technician to assess intra- and interrater reliability using the intraclass correlation coefficient and resulted in good reliability scores (intrarater: r = .87, interrater: r = .83). Since the reliability was sufficient, all data from the original technician were used in the analyses to ensure consistency.

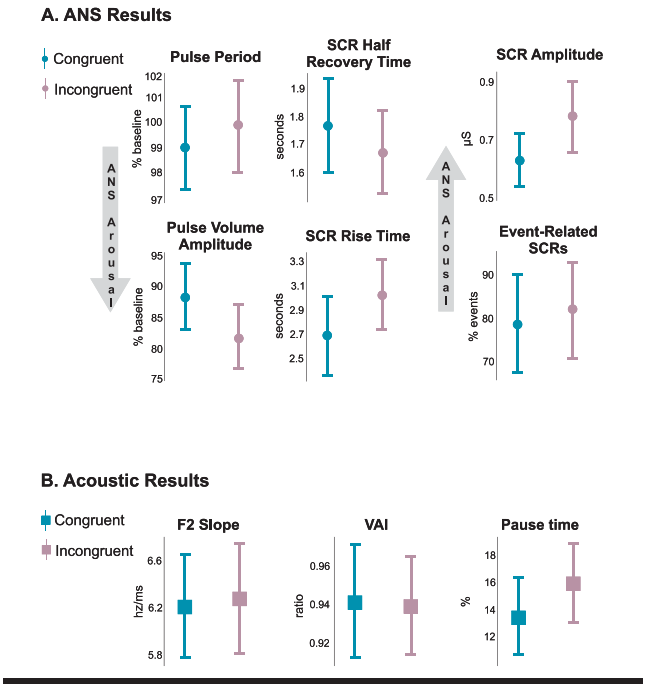
Statistical Analysis

Minitab (Version 21.2) was used for all initial statistical procedures. R software (version 4.3.1) was used to assess any follow-up mediation tests. Prior to addressing the main study questions, various statistical tests were performed to ensure the tasks were sufficiently modulating the intended systems (see the Appendix for a detailed description of these procedures). To assess how autonomic arousal and cognitive load affect typical running speech, linear mixed-effect models were implemented with the data from Experiment 1. Participants were included as random variables, condition (incongruent/congruent) was a categorical variable, autonomic measures were continuous variables, and acoustic measures (PPT, F_2 slope, and VAI) were the responding variables. In any model in which cognitive load (but not autonomic arousal) or autonomic arousal (but not cognitive load) was significant, follow-up mediation analyses were assessed to determine if the factors were influencing one another's effect on the outcome variable. This analysis provides an opportunity to parse apart the effects of these factors and their specific contributions to the outcome variables. Effect sizes were calculated for any significant factor using η_p^2 with .01, .09, and .25 as thresholds for small, medium, and large effects, respectively (Witte & Witte, 2017).

Results

Group autonomic and acoustic data during Experiment 1 are visualized in Figure 2. Results of the mixed effect model describing the relationships between autonomic arousal, cognitive load, and the acoustic features of speech during Experiment 1 can be found in Table 2. Specifically, the %SCR events was significantly associated with F_2 slope, with a medium–large effect size, such that speakers with a larger percentage of SCRs tended to

Figure 2. Experiment 1 autonomic results are described in panel A and acoustic results are described in panel B. Error bars represent 95% confidence intervals. Gray arrows in panel A indicate direction of expected change in the autonomic measures that typically reflect arousal. Results of the multivariate analysis of variance suggest that all autonomic variables change with respect to condition. ANS = autonomic nervous system; SCR = skin conductance response; VAI = vowel articulatory index.



produce shallower F_2 slopes. All other variables in the models of acoustic measures were insignificant. The mediation analysis assessing the influence of %SCR events on condition yielded an insignificant effect.

Experiment 2: Sensorimotor Adaptation

Experimental Design

In Experiment 2, participants sustained vowels embedded within words under predictable changes in auditory feedback (explained in the next paragraph) in two cognitive load conditions. Similar to Experiment 1, each condition started with a 30-s resting period to collect baseline ANS. The stimuli (see Figure 1, panel B) were single color words ("red," "yellow," "black") in which participants were asked to sustain the first vowel of the color of the font (/æ/ in black or /ɜ/ in red and yellow) for 1 s. The font color matched the phoneme in all trials during the congruent condition. In the incongruent condition, however, the font color mismatched the phoneme in 33% of the trials and matched in 66% of the trials to avoid autonomic habituation (O'Gorman & Jamieson, 1975). All trials were used in both congruent and incongruent conditions for all statistical analyses, and conditions were counterbalanced across participants.[3]

Altered auditory feedback of the participant's own voice was systematically varied over four phases (see Figure 1, panel B) with each phase consisting of 33 trials, totaling 132 trials. During the *baseline* phase, no perturbation was applied to the auditory feedback. During the *ramp* phase, F_1 was gradually shifted upward by 0.94%, with each successive trial reaching 30% above the participant's true F_1 by the end of the phase. This level of perturbation was maintained during the *hold* phase and removed during the *after-effect* phase. The perturbation amount was chosen as it successfully crosses vowel boundaries once applied (therefore inducing a perceived auditory error) and is a standard size used in the literature (e.g., Tourville et al., 2008).

Acoustic Data Analysis

To analyze F_1 responses to altered auditory feedback, F_1 was estimated online with Audapter. The mean F_1 during the 40- to 120-ms post–vowel onset of each trial was calculated. This time frame was used to avoid feedback-based adjustments (Burnett & Larson, 2002; Larson et al., 2001; Tourville et al., 2008) and coarticulation effects. Each trial's mean F_1 was then normalized as a percentage of the average baseline phase. The average normalized F_1 values for each of the three other phases were used in the main statistical analyses.

Statistical Analysis

As in Experiment 1, Minitab 21.2 was used for all main statistical procedures, and R was used for follow-up mediation tests. To assess how autonomic arousal and cognitive load affect sensorimotor adaptation, a linear mixed-effect model was used with the data from Experiment 2. The model assessed the responding variable of sensorimotor adaptation (as measured by the change in F_1 relative to the baseline phase) against the following independent variables: participants as random variables; condition, order of condition, and phase (baseline, ramp, hold, after-effect) as fixed variables; and autonomic measures as continuous variables. Interactions among fixed variables were also assessed. Effect sizes were calculated for all significant factors using η_p^2 with .01, .09, and .25

[3]Combining congruent and incongruent trials in the incongruent condition was necessary to (a) ensure the timeline for autonomic arousal was being sufficiently accounted for, (b) be comparable to the congruent only condition, and (c) keep the adaptation analysis as similar to prior literature and altered auditory feedback techniques.

Table 2. Results of the mixed-effect models for acoustic outcomes of Experiment 1.

Dependent variable	Effect	*df*	*F*	*p*	η_p^2	Effect size
VAI	Condition	1	0.00	.99	—	
	SCR amplitude	1	0.62	.44	—	
	SCR rise time	1	0.02	.89	—	
	SCR half-recovery	1	0.73	.39	—	
	Event-related SCRs	1	0.00	.99	—	
	Pulse volume amplitude	1	2.52	.11	—	
	Pulse period	1	3.08	.08	—	
F_2 slope (Hz/ms)	Condition	1	1.26	.27	—	
	SCR amplitude	1	1.41	.24	—	
	SCR rise time	1	0.93	.34	—	
	SCR half-recovery	1	2.25	.14	—	
	Event-related SCRs	**1**	**6.76**	**.01**	**.12**	**Medium–large**
	Pulse volume amplitude	1	0.26	.61	—	
	Pulse period	1	1.79	.19	—	
Pause time (%)	Condition	1	2.28	.14	—	
	SCR amplitude	1	1.17	.29	—	
	SCR rise time	1	1.30	.26	—	
	SCR half-recovery	1	0.59	.45	—	
	Event-related SCRs	1	0.25	.62	—	
	Pulse volume amplitude	1	0.01	.92	—	
	Pulse period	1	1.47	.23	—	

Note. Statistically significant *p* values < .05 are in bold. VAI = vowel articulatory index; SCR = skin conductance response.

benchmarks for small, medium, and large effects, respectively (Witte & Witte, 2017). Similar to Experiment 1, mediation analyses were conducted if either condition (but not autonomic measures) or autonomic measures (but not condition) were significant. Based on the results from Experiment 2, several post hoc analyses were conducted. First, Tukey pairwise comparisons were used to interpret significance within the levels of the phase variable. Next, paired *t* tests were used to assess how the order of conditions affected F_1 responses. Specifically, raw F_1 values during the baseline phase were compared between the first and second conditions.

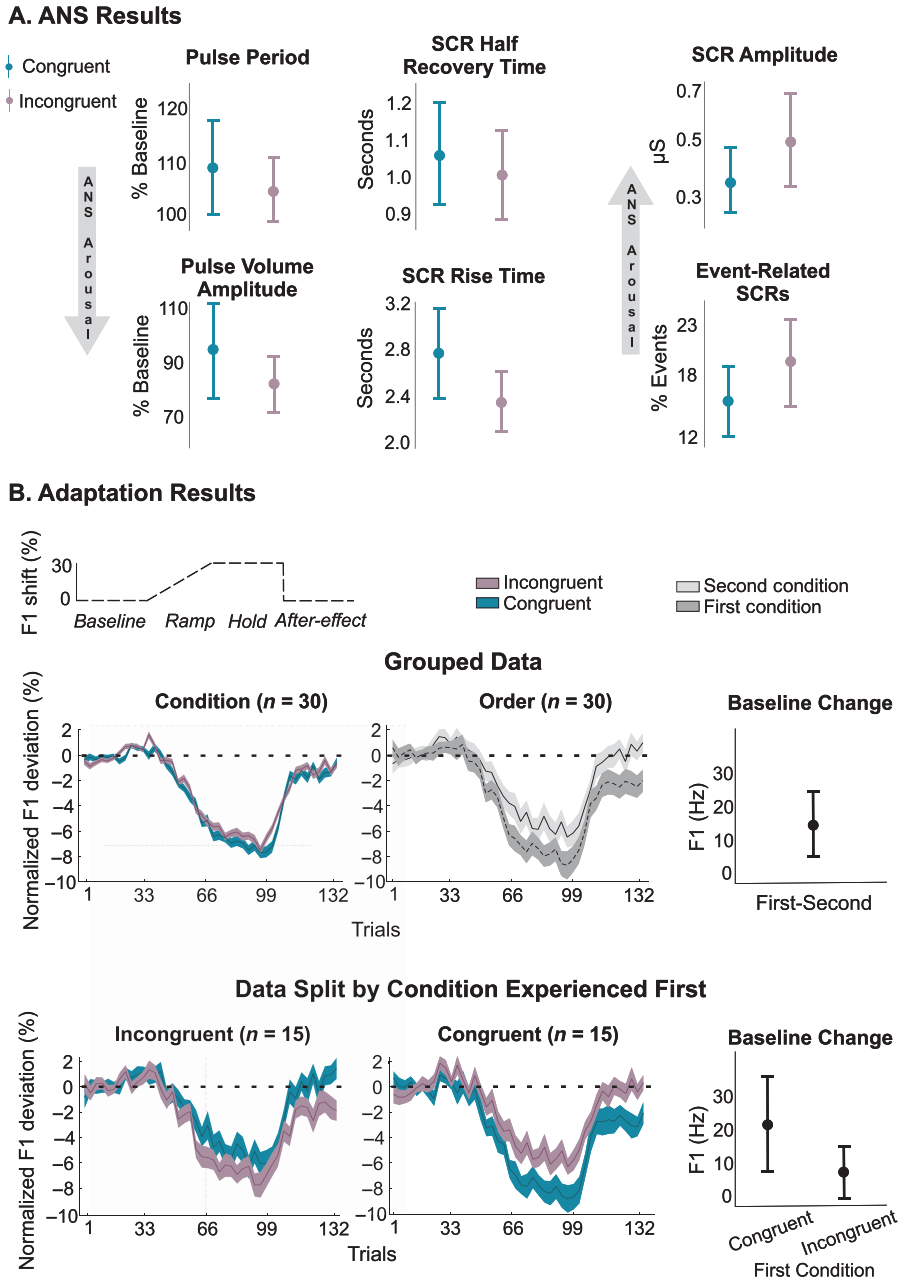
Results

Group autonomic and adaptation data during Experiment 2 are visualized in Figure 3. Results of the mixed effect model describing the relationship between autonomic arousal, cognitive load, and sensorimotor adaptation can be found in Table 3. As expected, phase of altered auditory feedback was a significant factor in the model with a medium–large effect size. Regarding autonomic factors, pulse period was significantly associated with F_1 adaptive responses with a small–medium effect size. Specifically, reduced pulse periods—indicative of *increased/higher* arousal—were observed with *increased* adaptive behavior. The follow-up mediation analysis on the effects of pulse period on condition with respect to F_1 adaptive responses yielded insignificant results. The order of condition presented during the experiment was significantly associated with F_1 adaptive responses (small–medium effect). Whichever condition participants received second within the experiment resulted in *smaller* responses to F_1 perturbations. *Post hoc* analyses of this order effect indicate that participants significantly *decreased* their F_1 values in the baseline phase from the first to the second condition.

Discussion

The purpose of this study was to understand how autonomic arousal and cognitive load relate to speech production and sensorimotor adaptation. We hypothesized that increased autonomic arousal and cognitive load would relate to *shallower* F_2 slopes and *smaller* VAIs during sentence-level speech production as well as increases in sensorimotor adaptation. We found a relationship between autonomic arousal and lower order acoustic indices of speech production and higher order indices of sensorimotor adaptation. Specifically, the frequency of reactivity of the ANS (measured by %SCR events) was associated with shallower F_2 slopes during running speech in Experiment 1. Moreover, increased vasoconstriction evidenced by shorter pulse periods was associated with greater

Figure 3. Experiment 2 autonomic results are described in panel A and adaptation are described in panel B. Error bars and shading represent 95% confidence intervals. Gray arrows in panel A indicate direction of expected change in the autonomic measures that typically reflect arousal. Results of the multivariate analysis of variance suggest that all autonomic variables change with respect to condition. Panel B visualizes the group data separated by condition and order and indicates the amount of change between the baselines of the first and second condition presented. Panel B also describes how we split the data based on which condition the participants received first and further visualizes how this impacts the amount of baseline change observed between the first and second condition. ANS = autonomic nervous system; SCR = skin conductance response.



adaptation in Experiment 2. We did not find a significant relationship between cognitive load and lower order speech acoustic indices or higher order indices of sensorimotor adaptation.

Experiment 1 Findings

The main finding from Experiment 1 was that %SCR events was associated with F_2 slope. With *increased* %SCR

Table 3. Results of the mixed effect model for F_1 responses in Experiment 2.

Dependent variable	Effect	*df*	*F*	*P*	η_p^2	Effect size
F_1 sensorimotor adaptation responses	Condition	1	1.01	.315	—	
	SCR amplitude	1	2.14	.145	—	
	SCR rise time	1	2.16	.142	—	
	SCR half-recovery	1	0.01	.762	—	
	Event-related SCRs	1	0.02	.884	—	
	Pulse volume amplitude	1	0.44	.508	—	
	Pulse period	**1**	**10.75**	**.001**	**.05**	**Small–medium**
	Phase	**3**	**12.98**	**< .001**	**.17**	**Medium–large**
	Order	**1**	**12.41**	**.001**	**.06**	**Small–medium**
	Order × Condition	3	1.71	.201	—	
	Phase × Condition	3	0.32	.809	—	

Note. Statistically significant p values < .05 are in bold. SCR = skin conductance response.

events—indicative of *increased* arousal—F_2 slope *decreased*. A reduced F_2 slope indicates slower or less change within the vowel sound, affecting its perceptual clarity. Thus, our results suggest that higher levels of ANS arousal are associated with less pronounced articulatory transitions. Prior literature has found a relationship between ANS arousal and articulatory kinematic variability, and although our results do not capture acoustic variability, they provide evidence for an effect of ANS arousal on speech acoustics and thus support the literature of potential interactions among these systems (Kleinow & Smith, 2006; Weber & Smith, 1990).

We hypothesized a relationship between cognitive load and our acoustic measures such that F_2 slope would decrease, VAI would decrease, and PPT would increase with increased cognitive load. Thus, the lack of condition effect on our acoustic measures was unexpected. A potential reason for the lack of condition effect could be from the influence of including autonomic measures in the model. To test this theory, mediation tests were conducted on models with significant factors (i.e., F_2 slope in Experiment 1) to determine if the effects of cognitive load and autonomic arousal were interacting. The insignificant result suggests that the effects of autonomic arousal on F_2 slope were not mediating or masking the effects of condition on F_2 slope. It is also possible that these measures (specifically F_2 slope and VAI) are not sensitive to changes in cognitive load. The prior literature that investigated cognitive load on features of articulation has reported changes in various acoustic and kinematic measures that capture similar phenomena as F_2 slope and VAI (i.e., vowel transitions; Yap et al., 2011; and articulatory precision; Heaton et al., 2020), but these specific measures have not been studied with respect to changes in cognitive load. It is interesting that cognitive load affected PPT when analyzed in isolation (i.e., using a paired t test; see the Appendix), but not in the model with autonomic measures. It is possible that there was a large amount of within-participant variability that was being accounted for in the mixed-effect model as the random slopes, leaving less variance to be accounted for by the condition factor. It is also possible that adding the autonomic factors could have reduced the unique variance accounted for by condition (even if they were not significant) and thus could have diluted the effect of condition. This result highlights the nuanced nature of individualized stress responses and the need to investigate their effects on speech separately from the effects of cognitive loading.

Despite the significant finding suggesting that increased sympathetic arousal (as indicated by increased %SCR events) relates to changes in F_2 slope, none of the cardiovascular measures were significant in the model. It is possible that metrics attempting to capture activity of the same branch of the ANS actually change in opposite directions (i.e., directional fractionation; Hare, 1972; Kreibig, 2010). This discrepancy could be useful in interpreting the specific autonomic signatures to unique contexts (such as during speech under a cognitive loading task). Moreover, a change in a certain physiological system (i.e., electrodermal), but not another (i.e., cardiovascular), could be the result of specific central involvement during a given situation. For example, EDA has been found to correlate with neural activity in the anterior cingulate cortex and prefrontal cortex, which are associated with cognitive and emotional processing. Thus, a significant finding of an electrodermal measure in the current study points to potential influence of these more central processes in this study task. This result emphasizes the importance of taking a multifaceted approach when understanding how "state"-level manipulations impact speech.

Experiment 2 Findings

The main finding from Experiment 2 was that higher autonomic arousal levels were related to increased adaptation, aligning with our hypothesis. Specifically,

decreases in pulse period (indicative of heightened arousal) were significantly associated with increases in F_1 adaptation. Similar to the discussion above in the Experiment 1 Findings section, the findings from Experiment 2 show directional fractionation with respect to sympathetic involvement in sensorimotor adaptation. Interestingly, cardiovascular activity, but not EDA, was significantly associated with adaptation. This finding aligns with our prior work in which cardiovascular activity (but not EDA) similarly affected vocal motor adaptation (Tomassi et al., 2025). The effect of the cardiovascular system on sensorimotor adaptation across different domains of speech underscores the generalizability of this result. As described above, directional fractionation could provide some insight on potential influence of central processes for a specific task. Relevant for the current discussion, cardiovascular measures are controlled in the brainstem and specifically by the medulla oblongata (Gordan et al., 2015). This area relays sensory information to and from the cerebellum as part of an integral role in maintaining and coordinating movement, which is particularly important during sensorimotor adaptation. Our results highlight the potential impact on this structure whose dual role in controlling cardiovascular activity and transmitting sensory information is challenged through this task.

Cognitive load condition did not significantly relate to F_1 responses, providing evidence for the use of cognitively demanding stimuli in future altered auditory feedback experiments to increase the ecological validity of future studies. The lack of condition effect on F_1 adaptation aligns with our previous voice findings (no significant effect of condition on $F0$ adaptation; Tomassi et al., 2025), which suggests no differences in how cognitive processes may affect adaptation of these two subsystems. These findings are also in line with prior literature that has found no effects of divided attention on F_1 adaptation (Krakauer et al., 2024), further corroborating the limited effects of cognition on the control processes involved in sensorimotor adaptation. The insignificant mediation results testing whether autonomic arousal was masking or being mediated by condition further support the specificity of physiological responses on sensorimotor adaptation separate from the effects of cognitive load.

An unexpected finding from Experiment 2 was the significant order effect on F_1 responses. The order in which participants received the conditions was related to adaptation such that whichever condition was received second resulted in *decreased* adaptation. Post hoc analysis revealed that this was likely due to participants retaining their adjusted acoustic target for future productions, as observed by a change in the baseline phase between conditions (see Figure 3). Visually, it appears that this retention was more prominent if the low cognitive load condition was provided first (see Figure 3). However, the interaction between order and condition was not significant in the model, and it is likely that a larger sample is required to power such an effect. This retention phenomenon (i.e., the maintenance of a learned skill or command) is not well understood in the speech motor control literature, and few studies have documented it in their paradigms (Lametti et al., 2014; Parrell & Niziolek, 2021). Of these studies, only one (Parrell & Niziolek, 2021) has provided statistical evidence of retained adaptation (tested by assessing how much adaptation persisted 10 min after removal of altered auditory feedback). Some studies have investigated a similar concept referred to as generalization (Parrell et al., 2024; Rochet-Capellan et al., 2012). These studies have found evidence of updated speech motor commands transferring to new and/or different auditory targets. Retention and generalization are both important aspects of successful adaptation and can be used to determine the stability and flexibility of learned motor commands. These concepts are key aspects of many therapeutic approaches and thus more work in understanding them is critical.

Limitations and Future Directions

A major purpose of this study was to understand the role of autonomic arousal in speech production and speech motor control. Although we did find a significant effect of autonomic arousal in some models, it is important to note that this effect was not globally observed in all autonomic measures in the significant models. In other words, an effect of autonomic arousal was discussed in the study if at least one of the six autonomic measures was significant in a model and all six autonomic measures were never simultaneously significant in any model. The number of autonomic measures included in the study was rationalized by the fact that these measures are highly variable in the literature and are not well established in the speech field. We included measures from two different physiological systems (electrodermal and cardiovascular) to attempt to capture sympathetic and parasympathetic characteristics while also accounting for the fact that some measures would be more accurate for detecting quicker and/or more subtle changes. For example, we included cardiovascular measures because they are derived from a tonic signal that changes quickly with autonomic fluctuations, which was necessary to use for Experiment 2 as the stimuli were short and fast-paced. Future studies should investigate these autonomic measures in-depth to understand which are best suited for speech studies with and without altered auditory feedback.

The length of time between cognitive load conditions is a limitation of the study that should be considered. The time between cognitive loading blocks in Experiment 1 was established based on prior literature with

similar experimental designs that found this amount of time was sufficient for ANS measures to return to a baseline state (Weber & Smith, 1990). Thus, autonomic fatigue was not a major concern with this limitation. However, this length of time may have impacted sensorimotor adaptation processes in Experiment 2, which could have contributed to the significant order effect. Participants completed the experiment with a 5-min break between conditions, and it is possible this rest was too short for participants to recover their typical acoustic targets. Although this retention finding was likely the result of the limited rest between conditions, it poses an interesting question of the length of time that motor programs stay integrated postexposure to an auditory error. The research pertaining to this idea is limited (Lametti et al., 2014; Parrell & Niziolek, 2021), and future studies could explore this question within the realm of motor learning to understand how timing affects retention.

Other possible limitations of the study that did not directly impact significant findings but may have contributed to the null findings include the sample of participants and the cognitive task employed. First, the sample of participants consisted of young adults with typical speech and autonomic function. It is possible that this sample was too homogenous to observe relationships in our study outcomes, and future studies could investigate these systems in speakers with motor speech disorders and/or atypical autonomic function. Second, the cognitive loading task in the current study was limited to the processes associated with the Stroop task (i.e., response inhibition, selective attention, etc.), and it could be interesting to understand how differences in cognitive loading impacts autonomic arousal during speech production and adaptation. Perhaps increasing cognitive load with other tasks such as a public speaking (taxing multiple cognitive processes including working memory, attention, executive function, etc., and known to invoke heightened autonomic arousal) would lead to more observable differences in the production and adaptation of speech.

Conclusions

The current study aimed to understand the roles of autonomic arousal and cognitive load on speech production and speech motor control. Results suggest that autonomic arousal relates to both speech production and adaptation. Autonomic arousal was associated with less pronounced formant transitions during speech production (Experiment 1) but enhanced speech motor control through greater adaptation (Experiment 2). Cognitive load was not statistically significantly related to the outcomes of either of these experiments. An unexpected order effect during sensorimotor adaptation was found, which emphasizes the importance of understanding timing and carry-over effects when investigating factors that may impact adaptation. Future work is necessary to support the physiological findings of the study to understand how "state" influences individual variability.

Data Availability Statement

The data from the current study are not available publicly due to the use of participant voice recordings that we are unable to de-identify.

Acknowledgments

This study was funded by National Institute on Deafness and Other Communication Disorders Grants DC016270 (awarded to Cara E. Stepp and Frank H. Guenther), T32 DC013017-08 (awarded to Cara E. Stepp), DC018000 (awarded to Bridget Walsh), and DC015446 (awarded to Robert E. Hillman), as well as fellowships earned by the first author (Nicole E. Tomassi) including the Association for Computing Machinery's Special Interest Group of High Performance Computing Fellowship and the Acoustical Society of America's Raymond H. Stetson Scholarship in Phonetics and Speech Science.

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Appendix

Detailed Description

Sentence Task Stimuli:

Congruent:

Lee flew **red**, **yellow**, and **black** kites at the spotted yard
He tied **blue**, **red**, and **yellow** knots on top of
Oliver placed **red**, **blue**, and **yellow** keys to the right side

Incongruent:

Lee flew **blue**, **black**, and **red** kites at the spotted yard
He tied **yellow**, **black**, and **blue** knots on top of it.
Oliver placed **yellow**, **red**, and **black** keys to the right side

Motor Target:

Lee flew red, yellow, and black kites at the spotted yard
He tied blue, red, and yellow knots on top of it.
Oliver placed red, blue, and yellow keys to the right side

Assessing Experimental Fidelity

Experimental fidelity was assessed prior to investigating the study aims to ensure that all target systems were being modulated appropriately. First, to determine if the Stroop task was sufficiently taxing, percent pause time (PPT) was assessed between conditions. Pauses have been shown in the literature as an indicator of increased cognitive load (Khawaja et al., 2007); thus, this measure should be sufficient for determining whether the task presented a significant cognitive challenge. PPT was compared between the cognitive load conditions using a paired *t* test. This test yielded significant results (with a large effect size) such that higher pause percentages were found in the incongruent condition, relative to the congruent condition, indicating that the Stroop task successfully challenged the participants. Next, multivariate analyses of variance were used to ensure that the cognitive loading task was effectively arousing the autonomic nervous system. The model was statistically significant for both experiments with medium–large effect sizes. Next, paired *t* tests were used on F_1 responses in the hold and after-effect phases, relative to baseline, to ensure that the altered auditory feedback in the adaptation experiment was sufficiently inducing an integration response. Effect sizes were calculated using Cohen's *d* with 0.2, 0.5, and 0.8 as small, medium, and large thresholds, respectively (Cohen, 1977). We found significant results in the hold phase versus baseline phase and after-effect phase versus baseline phase with a large and a medium effect size, respectively.

The Relationship Between Speech Production and Sensorimotor Adaptation During Increased Cognitive Load

To determine if the way in which speakers change their speech during increased cognitive load requires coordination between lower order biomechanical and higher order control processes, we compared speech production during typical running speech (Experiment 1) to sensorimotor adaptation (Experiment 2). Pearson's correlation was used to compare the between-condition changes in F_1 adaptation during Experiment 2 and the between-condition changes in acoustic measures of running speech during Experiment 1 to assess whether any effects of cognitive load on higher and lower order processes of speech were generalizable across these different speech processes. The average normalized F_1 values for the after-effect phase were used in this comparison. Isolating the after-effect phase to understand sensorimotor adaptation is common in the literature as the persistence of behavior after the removal of the perturbation suggests integration of motor commands has occurred. Overall, there were no statistically significant correlations among the between-condition changes in any of the acoustic variables (i.e., F_2 slope, vowel articulatory index, PPT) during Experiment 1 and the between-condition changes in the F_1 adaptation responses (after-effect phase) during Experiment 2.