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Research Article

Effects of Social Stress on Autonomic, Behavioral, and Acoustic Parameters in Adults Who Stutter

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Purpose: The purpose of this study was to assess changes in autonomic, behavioral, and acoustic measures in response to social stress in adults who stutter (AWS) compared to adults who do not stutter (ANS).
Method: Participants completed the State–Trait Anxiety Inventory (Speilberger, Gorsuch, Luschene, Vagg, & Jacobs, 1983). In order to provoke social stress, participants were required to complete a modified version of the Trier Social Stress Test (TSST-M, Kirschbaum, Pirke, & Hellhammer, 1993), which included completing a nonword reading task and then preparing and delivering a speech to what was perceived as a group of professionals trained in public speaking. Autonomic nervous system changes were assessed by measuring skin conductance levels, heart rate, and respiratory sinus arrhythmia (RSA). Behavioral changes during speech production were measured in errors, percentage of syllable stuttered, percentage of other disfluencies, and speaking rate. Acoustic changes were measured using 2nd formant frequency fluctuations. In order to make comparisons of speech with and without social–cognitive stress, measurements were collected while participants completed a speaking task before and during TSST-M conditions.
Results: AWS showed significantly higher levels of self-reported state and trait anxiety compared to ANS. Autonomic nervous system changes revealed similar skin conductance level and heart rate across pre–TSST-M and TSST-M conditions; however, RSA levels were significantly higher in AWS compared to ANS across conditions. There were no differences found between groups for speaking rate, fundamental frequency, and percentage of other disfluencies when speaking with or without social stress. However, acoustic analysis revealed higher levels of 2nd formant frequency fluctuations in the AWS compared to the controls under pre–TSST-M conditions, followed by a decline to a level that resembled controls when speaking under the TSST-M condition.
Discussion: Results suggest that AWS, compared to ANS, engage higher levels of parasympathetic control (i.e., RSA) during speaking, regardless of stress level. Higher levels of self-reported state and trait anxiety support this view point and suggest that anxiety may have an indirect role on articulatory variability in AWS.

The neurophysiological underpinnings to developmental stuttering have been largely studied with focuses in emotion (e.g., Bowers, Saltuklaroglu, & Kalinwoski, 2012; Choi, Conture, Walden, Jones, & Kim, 2016; Jones et al., 2014; Zengin-Bolatkale, Conture, Key, Walden, & Jones, 2018; Zengin-Bolatkale, Conture, & Walden, 2015) and speech motor control (e.g., Bauerly & De Nil, 2011; Namasivayam, Van Lieshout, & De Nil, 2008; Smith & Kleinow, 2000), among others (Logan & Conture, 1995; Spencer, Packman, Onlsow, & Ferguson, 2005). With regard to emotion, research has identified higher levels of anxiety (Alm, 2014; Craig & Tran, 2014) and increases in emotional reactivity (Bowers et al., 2012) in adults who stutter (AWS) compared to adults who do not stutter (ANS). At the same time, kinematic and behavioral studies have shown slower (Bauerly & De Nil, 2011; Huinch, Wouters, Hulstijn, & Peters, 2001; Smits-Bandstra, De Nil, & Saint-Cyr, 2006) and more variable (Smith & Kleinow, 2000) performance in AWS compared to ANS when completing speech and nonspeech tasks, lending implications for limitations or impairments in speech motor control (Namasivayam & Van Lieshout, 2011). Acoustic analysis has also revealed shorter formant transition times (Subramanian, Yairi, & Amir, 2003; Yaruss & Conture, 1993), longer transition durations in the second formant

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(F2; Dehqan, Yadegari, Blomgren, & Scherer, 2016), larger F2 frequency extents (Dehqan et al., 2016), and greater variability in the vowel steady state (Bauerly, 2018; Robb, Blomgren, & Chen, 1998). Although considerable progress has been made identifying differences in both emotion and speech motor control in AWS, very little attention has been focused on how these two processes interact in this population.

Emotion and the Autonomic Nervous System

While emotions are defined at a conscious level through higher level cognitive processes, the physiological changes that drive our emotions are governed by autonomic nervous system activity (Ledoux, 1996; Lewis, Haviland-Jones, & Barrett, 2008; Sonnemans & Frijda, 1994). Physiological changes in autonomic nervous system activity such as increases in heart rate (HR) and skin conductance levels (SCLs) are assumed to accompany changes in a person's cognitive state (Ledoux, 1996). Two main branches that govern autonomic processes related to emotion are the sympathetic and parasympathetic branches. These two branches of the autonomic nervous system work complementary to one another and on a continuous basis to help respond to day-to-day stimuli. The sympathetic nervous system or "fight or flight" function prepares the body for emotionally arousing responses by influencing a number of physiological changes in the body, such as increases in HR, dilation of the pupils, and sweating of the eccrine glands (i.e., skin conductance response; Bradley, Codispoti, Sabatinelli, & Lang, 2001). Although there are a number of direct measures for assessing sympathetic arousal (i.e., emotional reactivity), SCLs and HR have been used extensively in psychophysiological research (Coan & Allen, 2007). Studies have reported that feelings of anxiety and/or social stress are accompanied with increases in blood pressure, HR, and SCLs, thus triggering an emotional response aimed at building defensive behaviors that have been observed when responding to both nonspecific and specific environmental threats (Bradley, Codispoti, Cuthbert, & Lang, 2001; Coan & Allen, 2007; Hagenaars, Van Minnen, 2005).

The parasympathetic nervous system or "rest and digest" function works in a reciprocal pattern to sympathetic input by acting to regulate heightened emotions by decreasing HR by way of the myelinated vagal input to the heart. A well-documented measure of parasympathetic input is respiratory sinus arrhythmia (RSA), which is a measure of the amplitude of periodic fluctuations variability in HR occurring at the frequency of spontaneous respiration (Calkins, 1997; Porges, Doussard-Rossevelt, Portales, & Greenspan, 1996). Higher baseline RSA (higher HR variability) is found to be associated with greater social adaptability and responsiveness, whereas lower RSA (decrease in variability) is reported when responding to emotionally arousing conditions, regardless of valence (Gilissen, Koostra, van Ijzendoorn, Bakermans-Kranenburg, & van der Veer, 2007; Suess, Porges, & Plude, 1994; E. J. Weber, Ven Der Molen, & Molenaar, 1994). Decreases in RSA are assumed to allow for increases in sympathetic control, enabling the performer to respond to stimuli in their environment (Porges et al., 1996).

Effects of Emotion on Speech Motor Control

While emotions have been shown to elicit changes in motor control such as increases in reaction time (M. Chen & Bargh, 1999), movement speed (Gross, Crane, & Fredrickson, 2012), and force production (Coombes, Cauraugh, & Janelle, 2006; Coombes, Naugle, Barnes, Cauraugh, & Janelle, 2011) using nonspeech effector systems, such as finger extension tasks (Coombes et al., 2006), there is little known about the effect of emotion on articulatory control during speaking. The majority of studies assessing the effects of emotion on speech motor control have relied on changes in acoustic properties, such as the mean and range of fundamental frequency (F0). F0 is a measure of the vibratory rate of a speaker's vocal folds during phonation, involving both intrinsic and extrinsic laryngeal muscle groups as well as respiratory control. F0 has been shown to increase under conditions eliciting excitation or anxiety, regardless of valence (Bachorowski & Owren, 1995; Goberman, Hughes, & Haydock, 2011; I. R. Murray & Arnott, 1993; Owren & Bachorowski, 2007; Rochman & Amir, 2013; Scherer, 1986). The effects of emotion on articulatory speed, amplitude, and coordination of movement deserve further attention, particularly with the stuttering population where emotion, particularly anxiety (Craig & Tran, 2014), is thought to play a role in stuttering severity (Alm, 2014; Bauerly, 2018).

Measures of Anxiety in AWS

Higher levels of both trait and state anxiety have been consistently reported in the literature (for a review, see Craig & Tran, 2014). Trait anxiety refers to an individual's general tendencies to respond with anxiety toward a perceived environmental threat (Speilberger et al., 1983). Elevated levels of trait anxiety in AWS (Alm & Risberg, 2007; Craig, 2003; Craig & Tran, 2014; Iverach et al., 2009; Manning & Beck, 2013) have been suggested to play a role in the severity of the disorder (Iverach & Rapee, 2014) and has been found to improve following cognitive-based treatment approaches (Blomgren, Roy, Callister, & Merrill, 2005). Importantly, trait anxiety may influence state anxiety in individuals or the level of unpleasant emotional response they experience to a transient threatening event (Davis, Shisca, & Howell, 2007; Speilberger et al., 1983).

While generally higher levels of state anxiety have been reported in children and adolescents who stutter, regardless of social context (Davis et al., 2007; Mulcahy, Hennessey, Beilby, & Byrnes, 2008), elevated state anxiety in AWS (Craig, 2003; Peter & Hulstijn, 1984) is thought to be specific to social situations (Craig & Tran, 2014; Messenger, Onslow, Packman, & Menzies, 2004) where negative consequences (e.g., negative peer reactions, exclusiveness) are expected. From this perspective, it can be posited that AWS are at risk for heightened social anxiety. Social anxiety is associated with fear of negative evaluation and negative consequences and, in the case of an AWS, would be expected to increase over time as a consequence of negative experiences (Iverach & Rapee, 2014). The majority of studies assessing social anxiety in AWS have relied on self-reports (Craig & Tran, 2014), leaving questions as to what physiological indices are correlated with anxiety and the extent these differences affect speech motor control.

The few studies that have incorporated physiological measures as indexes of emotional reactivity have reported differences in AWS compared to ANS during speaking. For instance, Bowers et al. (2012) reported significant increases in SCL in AWS when anticipating a feared versus neutral sound and decreases in SCL when choral reading, a fluency provoking situation. Anticipating that a sound or word will be stuttered is one situation thought to elicit elevated levels of stress in AWS. Other situations reported in the literature include giving a job interview (Brundage, Graap, Gibbons, Ferrer, & Brooks, 2006) and speaking in front of an audience (Jackson, Tiede, & Whalen, 2016). Alm (2014) suggested that increases in social anxiety may interfere with the fluent flow of speech in AWS as a greater emphasis is placed on external factors such as a listener's perception.

At a neurological level, a recent study by Yang, Jia, Siok, and Tan (2017) found increased functional connectivity between limbic areas associated with state (i.e., amygdala) and trait (i.e., hippocampus) anxiety and frontal cortical areas (i.e., prefrontal gyrus) associated with motor control in AWS compared to controls. When engaged in conversation with a stranger, however, Toyomura, Fujii, Yokosawa, and Kuriki (2018) found decreased activity in the prefrontal cortices in AWS compared to ANS. The authors interpret these findings to suggest a decrease in the use of emotion regulation strategies as the frontal cortex interacts with the amygdala to form part of a neural circuitry that plays a role in emotional regulation. Results also showed increased activity in the right amygdala in AWS compared to ANS, and these differences were positively associated with self-ratings of discomfort and stuttering severity rates. Results such as these suggest that processes related to social anxiety may have a negative effect on speech motor control in this population.

Behavioral and Acoustic Measures of Speech Motor Control in AWS

Evidence for differences in speech motor control in the stuttering population has been documented in behavioral (Namasivayam & Van Lieshout, 2011) and neurological (Civier, Tasko, & Guenther, 2010) paradigms. While inconsistencies are reported in the literature (e.g., Frisch, Maxfield, & Belmont, 2015), the majority of studies incorporating speaking tasks at the word or sentence level have elicited slower reaction times (Huinch et al., 2001), slower movement durations (Bauerly & De Nil, 2011; Smits-Bandtsra et al., 2006), and greater across-sentence variability (Smith & Kleinow, 2000) in both children and AWS (Loucks & De Nil, 2001; Usler, Smith, & Weber, 2017). Supporting evidence for speech motor differences in AWS stems from acoustic analyses where atypical formant transitions (Robb & Blomgren, 1997; Yaruss & Conture, 1993), longer transition durations in F2 (Bauerly & Paxton, 2017; Dehqan et al., 2016), and greater variability in the vowel steady state (Bauerly, 2018; Robb et al., 1998) have been found in AWS. Not all acoustic studies have yielded differences in AWS, however (e.g., Sussman, Byrd, & Guitar, 2011).

Speaking rate during connected speech has also been used to measure speech motor control where a slower articulatory rate is assumed to reflect a response to extraneous demands (e.g., Sawyer, Chon, & Ambrose, 2008) and has been found associated with decreases in voice onset times (Allen & Miller, 1999), as well as increases in vowel durations (Kessinger & Blumstein, 1998). While speaking rate has been investigated extensively in the stuttering population (Erdemir, Walden, Jefferson, Choi, & Jones, 2018; Hall, Amir, & Yairi, 1999; Kloth, Janssen, Kraaimaat, & Brutten, 1995; Tasko, McClean, & Runyan, 2007; Tumanova et al., 2011), results are contradictory. Some research has shown slower speaking rates in both children and AWS (Bloodstein, 1944; Meyers & Freeman, 1985), whereas others have found no differences (Chon, Ko, & Shin, 2004; Kelly & Conture, 1992). At the same time, slower articulatory movements have been reported in AWS using behavioral (Bloodstein, 1944), kinematic (Archibald & De Nil, 1999; Zimmerman & Hanley, 1983), and acoustic (Prins & Hubbard, 1988) paradigms; however, many of these studies use reading tasks that are difficult to compare with spontaneous speech as they differ in confounding factors such as cognitive and language processing (Bloodstein, 1944; Bosshardt & Nandyal, 1988; Van Lieshout, Hulstijn, & Peters, 1991).

Effects of Emotion on Speech Motor Control in AWS

The dynamic systems model (Smith & Weber, 2017) has taken into account the vast literature on motor control and incorporated it into a model that defines stuttering as consisting of a speech motor system that is developmentally unstable, more variable, and more susceptible to breakdown from linguistic (e.g., Kleinow & Smith, 2000) and/or emotional demands (e.g., Jackson et al., 2016). While a variable speech motor system is essential in order for the speaker to respond to internal demands (e.g., anticipation) or environmental stressors (e.g., giving a speech), too much variability may reflect a less organized, unstable speech motor system. From this perspective, social demands may lead to increases in speech motor variability as it forces AWS to transition out of their "fluent operating space" (Smith & Weber, 2017, p. 249). This viewpoint is similar to other frameworks, such as the demands and capacity model (Starkweather & Gottwald, 1990) and the speech motor skills approach (Namasivayam & Van Lieshout, 2011).

There have been frequent reports of increases in stuttering frequency and severity (i.e., use of secondary behaviors) in AWS during anxiety-inducing conditions (e.g., Bowers et al., 2012). However, studies are just beginning to show the emotion–motor relationship in people who stutter using experimental paradigms. In young children, Erdemir et al. (2018) found that children with persistent stuttering, compared to those who recovered or nonstuttering children, exhibited significantly slower speaking rates during a narrative that followed a negative emotion condition. Studies assessing the effects of social cognitive stress on speech motor control in AWS, compared to ANS, have found slower reaction times (Hennessey, Dourado, & Beilby, 2014; Van Lieshout, Ben-David, Lipski, & Namasivayam, 2014), slower word durations (Caruso, Chodzko-Zajki, Bidinger, & Sommers, 1994), and larger interlip phase differences (Van Lieshout et al., 2014). Increases in the F2 frequency extent (Bauerly & Paxton, 2017) of consonant–vowel (CV) transitions have been reported in AWS compared to controls when speaking under emotional conditions that were either positively or negatively valenced. A follow-up study by the same author (Bauerly, 2018) reported increases in F2 frequency fluctuations (FFF2) in AWS compared to controls when producing the vowel steady state of consonant vowel tokens under negative arousing conditions (e.g., viewing image of a dog threatening to attack). Increases in FFF2 are a reflection of variability in tongue movement, and results were suggested to reflect a decrease in stability due to emotional influences. Similar results of increased F2 frequency variability were also reported in Evans (2009) where AWS, compared to ANS, completed a speaking task under a variety of cognitively stressful conditions. Jackson et al. (2016) also found an increase in across-sentence lip variability in AWS compared to control when repeating sentences in front of an audience; however, when assessing within gestural control, results showed a decrease in intergestural coupling (i.e., less flexible). One limitation to the studies of Jackson et al. and others (Bauerly & Paxton, 2017; Hennessey et al., 2014) is that objective measures were not used to assess emotional responses, and therefore, little is known about the emotional reactivity and regulatory processing in AWS during these social stress situations.

Trier Social Stress Test

One way to assess social stress is with the Trier Social Stress Test (TSST). The TSST is a highly standardized and well-validated protocol for inducing social evaluative threat. Kirschbaum, Pirke, and Hellhammer (1993) originally developed the TSST to induce an increase in autonomic arousal in healthy volunteers. Since then, numerous studies have found reliable elevations in HR, skin conductance, blood pressure, and several endocrine stress markers in response to the TSST's social-evaluative threat (for a review, see Foley & Kirschbaum, 2010). Since its development, the TSST has been modified to meet the needs of various research studies. The TSST generally consists of (a) an anticipation period, (b) a test period in which participants are required to prepare and deliver a speech (convince listeners why they are the perfect candidate for an open position) and perform mental arithmetic in front of an audience, and (c) a debriefing (recovery) period.

Objectives

The purpose of this study was to assess changes in autonomic, (i.e., SCL, HR, RSA), behavioral (i.e., errors, stuttering frequency, speaking rate), and acoustic (i.e., FFF2) measures in response to social stress from a modified version of the TSST (TSST-M). In order to invoke social stress, participants were required to prepare and deliver a speech to a group of professional speech writers. This investigation addressed four specific aims described in the following sections.

First, this study assessed group differences in state and trait anxiety measures using the State–Trait Anxiety Inventory (STAI; Speilberger et al., 1983). Based on previous reports (Craig & Tran, 2014), it was predicted that AWS would show significantly greater levels of trait and state anxiety compared to controls.

Second, this study assessed group differences in autonomic activity (i.e., SCL, HR, RSA) during resting baseline. Based on previous research (Peters & Hulstijn, 1984; C. M. Weber & Smith, 1990), it was predicted that AWS would not differ from ANS for any of the autonomic measures at resting baseline.

Third, this study assessed group differences in autonomic activity (i.e., SCL, HR, RSA) when speaking under no-stress speaking conditions. Based on previous studies (Caruso et al., 1994; C. M. Weber & Smith, 1990), it was predicted that AWS would show an autonomic pattern similar to ANS. That is, both groups would show similar sympathetic (i.e., SCL and HR) and parasympathetic (i.e., RSA) activity when completing the monologue and nonword reading tasks.

Fourth, this study examined the effects of social stress on autonomic (i.e., SCL, HR, RSA), behavioral (i.e., errors, stuttering frequency, speaking rate), and acoustic (i.e., F0, FFF2) parameters when undergoing the TSST-M. Given findings that AWS show increases in SCL when anticipating a feared word (Bowers et al. 2012) and increases in stuttering frequency (Bowers et al., 2012; Brundage et al., 2006) when speaking under socially stressful conditions, we hypothesized that AWS would show greater increases in SCL and HR and greater decreases in RSA compared to ANS when preparing and delivering a speech and when completing a nonword reading task under social stress conditions. Adhering to the multifactorial dynamic model (Smith & Weber, 2017), we predicted that AWS will show increases in FFF2 when reading nonwords under emotionally arousing conditions, which would reflect greater instability in articulatory movement. Given the evidence for social anxiety (Craig & Tran, 2014) in AWS and the effects heightened emotion can play on movement speed (M. Chen & Bargh, 1999; Gross et al., 2012), it was predicted that AWS, compared to ANS, would show faster speaking rates that were accompanied by increases in stuttering frequency and higher levels of F0 when producing a speech under social stress conditions.

Method

Participants

Eleven AWS (seven men, four women), with an average age of 26.2 years (range: 19–42), and 12 ANS (seven men, five women), with an average age of 25.2 years (range: 19–48), participated in this study. General subject inclusion criteria included the following: (a) English as the primary language; (b) self-reported negative medical history of neurological disorders or drug use affecting speech production; (c) self-reported negative history of psychiatric or developmental disorders; (d) self-reported negative history of cardiac arrhythmia or high blood pressure; (e) self-reported negative history of speech or language problems, other than stuttering for AWS; (g) self-reported good ocular health and no history of visual or auditory pathologies; and (h) pure-tone conduction hearing thresholds within clinically normal limits (< 20 dB HL from 1000 to 3000 Hz).

Stuttering specific inclusion criteria for AWS included the following: (a) no formal speech fluency treatment in the last year; (b) onset of stuttering in childhood (prepuberty); (c) a minimum of 3% within-word disfluencies in at least one of the speaking conditions (reading, conversation); and (d) classified as either mild, moderate, or severe on the stuttering severity index (Riley, 1994). Table 1 summarizes participant characteristics, including age, gender, treatment history, and scores from the Stuttering Severity Instrument–Fourth Edition (Riley, 1994), the STAI (Speilberger et al., 1983), and the S-24 (Erickson, 1969). Mean scores for the S-24 for AWS and ANS were 12.2 (*SD* = 6.71) and 7.3 (*SD* = 6.29), respectively.

This research was approved by the institutional review boards at Plattsburgh State University and Syracuse University. Written consent was obtained by all participants.

Instrumentation

Biopac MP 160 (Biopac Systems, Inc.) was used to acquire skin conductance and HR measures. The mean SCL was used as an index of sympathetic autonomic activity. SCL, a measure of electrodermal activity, is dependent on activation of sweat glands (Boucsein, 2012) and is exclusively regulated by the sympathetic nervous system. SCL was recorded with Ag/AgCl electrodes secured to the distal phalanges of the index and middle fingers of the nondominant hand connected to an electrodermal activity 100C amplifier module from Biopac MP 160 system (Biopac Systems, Inc.) and digitized at 1250 Hz. Any missing data artifacts were corrected using the “connect endpoints” math function of Biopac Acqknowledge 5.0 software.

An electrocardiogram (ECG) signal was used to detect HR measures in beats per minute (BPM) using two disposable Ag/AgCl electrodes applied to the skin surface just below the right clavicle and the other at the 12th rib laterally on the left side. The electrodes were connected to an ECG 100C amplifier from Biopac MP 160 system (Biopac Systems, Inc.), bandpass filtered to remove high-frequency noise and low-frequency drift (0.5 Hz: high pass cutoff; 35 Hz: low pass cutoff) with gain settings adjusted to 2,000 mV. The ECG signal was recorded at a sampling rate of 1250 Hz. Participants were fitted with a head-mounted condenser microphone (AKG C410) positioned 6 cm from their lips.

Stimuli

STAI

All participants completed the STAI developed by Speilberger et al. (1983). The STAI is a self-report questionnaire that is considered to be a psychological inventory assessing an individual’s state (i.e., transient feeling about an event) and trait (i.e., overall disposition) anxiety levels. Both the State (STAI-S) and Trait (STAI-T) portions of the STAI include 20 questions to which individuals rate themselves using a 4-point Likert scale. The STAI-S includes statements related to how the individual presently feels, such as “I feel worried” with the following responses: 1 = *not at all*, 2 = *somewhat*, 3 = *moderately so*, and 4 = *very much so*. The STAI-T includes states related to how the individual feels in general, such as “I worry too much over something that really doesn’t matter” with the following responses: 1 = *almost never*, 2 = *sometimes*, 3 = *often*, and 4 = *almost never*. High scores are correlated with high levels of anxiety.

Emotional Stimuli

The TSST was adapted to meet the objectives of the current study by replacing the mental arithmetic task with a nonword speaking task. Also, in order to compare the effects of emotional stress on speech motor control, the speaking tasks were also carried out prior to the TSST conditions. A detailed description of this TSST-M is discussed in the Procedure section.

Speech Motor Stimuli

Monologue speaking task. Performance on a 5-min monologue task was used to assess changes in behavior and acoustic parameters associated with speaking under social stress conditions. For prestress conditions, participants were asked to describe their dream job. For TSST-M conditions, following a 5-min preparation condition, participants were asked to give a speech as to why they would be a good candidate for their ideal job. Similar procedures have been used in psychophysiological research (e.g., Birkett, 2011; see Kudielka, Hellhammer, & Kirschbaum, 1997, for

Table 1. Participant information.

Participant	Group	Gender	Age (years;months)	Therapy (years)	SSI-4	STAI State	STAI Trait	S-24
1	AWS	F	21	> 4	9	32	28	16
2	AWS	F	24;9	> 4	27	35	45	18
3	AWS	M	23;6	> 10	30	32	42	22
4	AWS	F	21;3	> 10	9	21	29	3
5	AWS	M	29	> 10	32	24	30	8
6	AWS	M	21;6	> 10	10	38	35	8
7	AWS	M	21;4	> 5	22	32	47	IC
8	AWS	M	21;11	> 10	20	25	35	18
9	AWS	F	19;11	> 1	8	26	39	17
10	AWS	M	39;1	> 10	26	49	43	4
11	AWS	M	31;1	> 10	5	25	29	8
1	ANS	M	25	n/a	n/a	30	30	12
2	ANS	M	25;3	n/a	n/a	32	44	7
3	ANS	F	19;11	n/a	n/a	27	36	IC
4	ANS	F	21;2	n/a	n/a	23	26	IC
5	ANS	F	48;1	n/a	n/a	22	29	3
6	ANS	M	27;8	n/a	n/a	31	37	3
7	ANS	M	23	n/a	n/a	33	37	6
8	ANS	M	21	n/a	n/a	25	33	10
9	ANS	F	18	n/a	n/a	22	23	3
10	ANS	F	30	n/a	n/a	28	27	0
11	ANS	M	22;1	n/a	n/a	29	36	7
12	ANS	M	20;6	n/a	n/a	43	72	22

Note. Three of the participants failed to complete the S-24 questionnaire. SSI-4 = Stuttering Severity Instrument–Fourth Edition; STAI = State–Trait Anxiety Inventory; AWS = adults who stutter; F = female; M = male; IC = incomplete; ANS = adults who do not stutter; n/a = not applicable.

a review). Please see the TSST-M section for a description of the procedures.

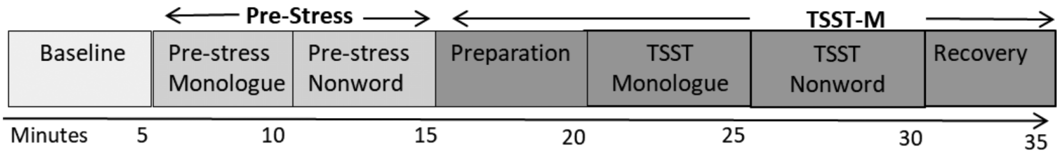
Nonword reading task. Performance on a nonword reading task was used to assess changes in acoustic parameters associated with social stress. For this, participants were instructed to read 10 monosyllabic nonsense word sequences, 20 times, under both prestress and TSST-M conditions. Nonwords have been used in previous research with AWS (e.g., Bauerly & De Nil, 2011; Smith, Sadagopan, Walsh, & Weber-Fox, 2010) and are considered to be useful for observing speech motor control with lexical–semantic, lexical–phonological, and cognitive processing demands reduced. A CVC structure varying in consonants and vowels was used in order to provide a closer representation to the complexities of natural speech. Five of the 10 nonwords used for analysis contained an initial alveolar or velar sound, followed by the vowel /i/, /a/, /ae/, or /o/ and a final nonliquid consonant. These CV pairs were chosen because they require relatively extensive changes in vocal tract configuration, resulting in larger F2 transitions and variability, which is one of the focuses of the current study. Stimuli were derived from the English Lexicon Project (Balota et al., 2007) using a random word generator. The syllables were selected based on the criteria that the words were orthographically legal and pronounceable but not derived from the root of real words and that the initial and final position of each word consisted of nonliquid consonants (to aid in acoustic analysis). Sequences were presented for 15 s each, with a 3-s interstimulus interval, and were randomized and counterbalanced across participants using Superlab 5.0 software (Stimulus Presentation Software; Cedrus, Inc.). Fifteen seconds was a sufficient amount of time for the participants to complete the sequence. No participant failed to complete the sequence in this time period. Following this, the sequence disappeared, and a new sequence was presented on the screen. Each sequence contained the same CVC nonwords, but in a different order. An example of a speech sequence is "/bup gak dob, jeb, zat, bit, jeb, tup, baz, put/." Participants were asked to "read the 10 nonwords out loud at their normal speaking rate" and to "try to not make any mistakes."

No documentation was made as to whether or not an AWS was using a fluency technique while completing the monologue and nonword reading task. However, all participants reported that they had not been enrolled in any treatment in at least a year prior to participating in the study. Also, the examiner, who is a certified American Speech-Language-Hearing Association–certified clinician with extensive experience working with AWS, noted that none of the participants appeared to be using fluency techniques during the experiment.

Procedure

This study consisted of one lab visit divided into four parts: (a) pretest measures and setup; (b) baseline; (c) prestress speaking tasks (i.e., pre–TSST-M); and (d) a TSST-M including a preparation (Prep), social evaluation (TSST-M monologue, TSST-M nonword reading), and recovery period. See Figure 1 for an outline of procedures.

Figure 1. Experimental setup for baseline, prestress, and Trier Social Stress Test–Modified (TSST-M) conditions.



Pretest Measures and Setup

For pretest measures, participants completed the STAI and were then taken into the testing room where they sat in a comfortable chair with armrests. Participants were then placed with physiological equipment for measuring SCL and BPM and asked to rest quietly for 5 min.

Baseline

Baseline physiological measures were recorded. Following this, participants were allowed to practice five repetitions of a 10 CVC nonword sequence that was similar to the one used during the procedures.

Prestress Speaking Tasks

The prestress speaking tasks consisted of a pre–TSST-M monologue and pre–TSST-M nonword reading task. To initiate the pre–TSST-M monologue, participants were asked to describe their dream job to the primary investigator. They were asked to speak for 5 min. If they finished before 5 min, they were prompted to continue speaking by providing them with the following instruction: "You still have time remaining." Physiological and acoustic measures were recorded.

Participants were then asked to complete the pre–TSST-M nonword reading task. For this, a laptop on a roller desk was positioned in front of them, and they were instructed to read aloud the 10 monosyllabic nonsense word sequence depicted on the screen at their normal speaking pace. Participants were asked to "read the 10 nonwords out loud at your normal speaking rate" and to "try to not make any mistakes." The AWS were told "if you stutter, just continue on with the rest of the sequence." Following the last nonword sequence, participants were asked to sit quietly for 5 min.

TSST-M

Preparation. The TSST-M began with the "preparation phase" where the following script was read by the examiner: "This is the speech preparation portion of the task; you are to mentally prepare a five-minute speech describing why you would be a good candidate for your ideal job. Your speech will be videotaped and reviewed by a panel of judges trained in public speaking. You have five minutes to prepare and your time begins now." A digital timer was set for 5 min, and the examiner left the room. Physiological measures were recorded for this 5-min preparation phase.

Social evaluation. After 5 min, the primary investigator returned to the room to begin the "social evaluative phase" of the TSST-M, which included the TSST-M monologue and nonword reading task conditions. The primary investigator positioned a video camera approximately 4 ft from the participant and began recording. The examiner then pulled out a paper and pen for note taking and gave the following instructions: "This is the speech portion of the task. You are to deliver a speech describing why you would be a good candidate for your ideal job. You should speak for the entire five-minute period. Your time begins now." If the participant stopped talking before the 5 min was over, the investigator prompted: "You still have time remaining." At the end of the 5-min speech, the participant completed the same nonword speaking task as described above. Participants were asked to "read the following 10 nonwords out loud at your normal speaking rate" and to "try not to make any mistakes." They were also told that "your production of these words will also be reviewed by the panel of judges trained in public speaking." The participant was video-recorded for the entire duration of this task. Physiological measures were recorded for these 5-min speech production tasks.

Recovery period. For the posttest recovery period, the participant was informed that the speaking part of the study was complete and to sit comfortably for 5 min. Physiological measures were collected. Equipment was then removed, and the examiner debriefed the participant on the true nature of the study. The participant was informed that their performance was not going to be evaluated by anyone and that their speaking would only be used to assess changes from emotion.

Analysis and Dependent Variables

Measures of Autonomic Activity

SCLs. Using Biopac's Acqknowledge software, tonic SCL were obtained by first subtracting the phasic skin conductance from the raw waveform. The tonic SCLs were then down-sampled to 125 Hz, and a mean SCL was obtained for consecutive 30-s epochs within 4 min of each condition. The mean SCL for each 4-min condition was used for analysis. Baseline levels of SCL reflect resting levels of sympathetic nervous system activity. Any changes in responses in SCL reflect sympathetic activation in response to an environmental stimulus.

HR. Biopac's Acqknowledge software processed the ECG signal by detecting the peak of the R-wave and timing the sequential interbeat intervals (IBIs) in milliseconds; this was done for each condition. The IBI time series was then processed to correct for artifacts due to ventricular arrhythmias and faulty detections due to movement. Only four participants required hand correction from artifact, and corrections occurred in less than 10 s of the data. A trachogram was then derived from the ECG signal, and HR in BPM was measured for consecutive 30-s epochs within each condition. Similar to SCL measures, HR values were derived for sequential 30-s epochs for the first 4 min of each condition and averaged. Analysis procedures are similar to that of Jones et al. (2014).

RSA. RSA was derived by first obtaining an ECG for each participant using Biopac MP150 system (Biopac Systems, Inc.). The raw ECG was first bandpass filtered to remove high-frequency noise. Using Biopac's Acqknowledge software, the peak of the R-wave and the timing of the sequential IBIs in milliseconds were performed on each ECG signal and for each condition. The IBI time series was then processed using Acqknowledge software to correct for artifacts due to ventricular arrhythmias and faulty detections due to movement. HR variability (R–R intervals) was measured within the respiratory frequency band (0.15–0.4 Hz), a procedure reported by Berntson, Cacioppo, and Quigley (1991). Using Biopac's Acqknowledge RSA spectral analysis routine, R–R interval processing was used to measure RSA and HR variability on consecutive time slices along the ECG waveform [ln(HF (s^2/Hz) * 1,000,000 (s^2 to ms^2) * Fs (resample freq)]. Similar to SCL measures, RSA values were derived for sequential 30-s epochs within each condition and averaged. Analysis procedures follow standards reported in Berntson et al. (1991).

To assess interrater reliability for SCL, HR, and RSA, 25% of the data for SCL, HR, and RSA were randomly selected and measured by a trained researcher (at the graduate level). Bivariate correlations for values derived from the first author and trained researcher were all significant ($p < .01$) for SCL (.98), HR (.99), and RSA (.89).

Change scores for autonomic measures. The three autonomic measures, SCL, HR, and RSA, were prepared for analysis by first computing change scores from baseline and prestress measures. For measuring change during the prestress TSST-M talking conditions, baseline measures were subtracted from the pre–TSST-M (monologue and nonword reading) conditions. For measuring change during the TSST-M conditions, baseline and prestress TSST-M measures were subtracted from the TSST-M conditions. More specifically, baseline measures were subtracted from the TSST-M preparation and recovery conditions; pre–TSST-M monologue was subtracted from the TSST-M monologue, and pre–TSST-M nonword reading was subtracted from the TSST-M nonword reading. Obtaining change scores from prestress talking conditions allowed for a better representation of change due to emotion as speaking alone can lead to increases in sympathetic activity (Arnold, MacPherson, & Smith, 2014).

Measures for the Monologue Task

Speech samples were digitized to a computer at a sampling rate of 22 kHz using Biopac DA100C module. Waveforms were converted to sound files and retrieved in Praat software, Version 5.3.13 (Boersma, 2001). The speech samples were orthographically transcribed from the first 4 min of each monologue task by a trained graduate student. Each utterance was marked for stuttering-like disfluencies (SLDs), including sound-syllable repetitions, monosyllabic whole-word repetitions, audible or inaudible sound prolongations, and other disfluencies (ODs) including phrase repetitions, interjections (e.g., "um, uh"), and revisions (Erdermir et al., 2018; Sawyer et al., 2008; Tumonova, Zebrowski, Throneburg, & Kayikci, 2011). Each utterance was also marked with pauses that exceeded 250 ms. For reliability, the first author listened to each of the speech samples in their entirety, and if there were differences between the first author and trained graduate student, they were resolved through repeated listening. Procedures are identical to that of Sawyer et al. (2008). A mean %SLD and %OD was then calculated for each pre–TSST-M and TSST-M monologue speaking task.

For analysis of speaking rate and F0, the duration of the SLDs, ODs, SLD/ODs, and pauses were subtracted from the overall duration of the utterance, leaving only the fluent sample used for analysis. Following this, the number of syllables spoken was divided by the total duration (seconds) of the remaining utterances (Erdermir et al., 2018; Guitar, 2004) to obtain speaking rate. F0 was obtained for each of these fluent utterances using the automated voice analysis routine by Praat (Boersma, 2001), and a mean was obtained for each condition. To assess interjudge reliability, 25% of the data for F0 was randomly selected and assessed by the first author. Bivariate correlations reached significance at .89 ($p < .001$).

Measures for the Nonword Reading Task

Speech samples were digitized to a computer at a sampling rate of 22 kHz using Biopac DA100C module. Waveforms were converted to sound files and retrieved in Praat software, Version 5.3.13 (Boersma, 2001). For both groups, CVC nonwords that were produced in error were excluded from further analysis. Errors were defined as a distortion, incorrect substitution, or missing sound. The number of errors produced by AWS for the prestress (M = 17.0, SD = 11.0) and TSST-M (M = 14.2, SD = 9.5) conditions was not significantly different than the number of errors produced by ANS during the prestress (M = 14.9, SD = 11.5) and TSST-M (M = 14.2, SD = 13.1) conditions ($p > .05$). For AWS, CVC nonwords that were produced with a disfluency were excluded from further analysis. *Disfluencies* were defined as a sound repetition, prolongation, or blockage of sound. The number of nonwords that were produced with a disfluency for AWS under prestress (M = 22.5, SD = 16.7) and TSST-M (M = 21.0, SD = 17.2) conditions was not significantly different ($p > .05$).

Using Praat software, Version 5.3.13 (Boersma, 2001), a combined waveform and wideband (300–400 Hz) spectrographic display was used to identify time points of the beginning and ending of each CVC nonword. For analysis of FFF2, consonant vowel tokens were down sampled to 11.5-kHz sampling rate using Praat software (Boersma, 2001). The onset of the vowel portion was defined on the spectrograph as the onset of the first glottal pulse (indicating vowel production) following the release of the initial consonant. Next, the glottal pulse occurring 40 ms after the first glottal pulse was identified. A 40-ms time period past the first glottal pulse has been used in previous studies assessing FFF2 and is considered to be a safe determination of the onset of the vowel steady state (D. Howell, 2007; Robb et al., 1998). From this starting point, the following 10 consecutive glottal pulses were identified, and the visual center of the F2 energy band was analyzed for frequency (Hz) using 12-coefficient linear predictive coding methods (coefficients to the 12th order) in Praat software (Boersma, 2001). This resulted in 10 F2 values taken for the steady-state portion of the vowel. FFF2 was determined by calculating the absolute difference in Hz among these consecutive F2 values and determining the average of this difference (Gerratt, 1983). Procedures are identical to that of Y. Chen (2009).

To assess interrater and intrarater reliability, 10% of the CVC nonwords from each participant's sample were reassessed by the first author, and another individual trained in acoustic analysis. Pearson product correlations were .87 for interjudge reliability and .92 for intrajudge reliability. For an additional interrater reliability measure, FFF2 means were compared for 10% of the CVC nonwords from each participant and were not significantly different from each other ($p > .05$).

Statistical Analysis

All statistical analyses were performed using SPSS Version 22.0. Statistical procedures are organized by the study's four main objectives and described in the following sections.

Group Differences in Self-Reported Anxiety Levels

Independent *t* tests were used to examine group differences for measures of state and trait anxiety (Speilberger et al., 1983).

Group Differences in Autonomic Measures During Resting Baseline

Independent *t* tests were used to examine group differences at baseline for the autonomic measures of SCL, BPM, and RSA.

Group Differences in Autonomic Measures During Prestress Speaking Conditions

In order to investigate the autonomic changes during speaking under prestress conditions, separate 2 × 2 repeated-measures analyses of variance (ANOVAs) were conducted for SCL, HR, and RSA between groups (AWS vs. ANS) and across the two pre–TSST-M (prestress monologue, prestress nonword) speaking conditions using the change scores from resting baseline (e.g., prestress monologue–resting baseline).

Effects of Social Stress on Group Differences for Autonomic, Behavioral, and Acoustic Measures During TSST-M Conditions

Effects from social stress on autonomic activity during TSST-M conditions. To test for the effects of social stress on autonomic nervous system activity, separate 2 × 4 repeated-measures ANOVAs were conducted for the change scores of SCLs, HR, and RSA between groups (AWS vs. ANS) and across the four TSST (preparation, TSST monologue, TSST nonword, and recovery) conditions. Change scores were derived from subtracting the pre–TSST-M and baseline, resting conditions from the TSST-M conditions.

Effects from social stress on the monologue speaking task. To test for the effects from social stress on speaking rate and F0 from the monologue task, separate 2 × 2 repeated-measures ANOVAs were conducted between groups (AWS vs. ANS) and across pre–TSST-M monologue and TSST-M monologue conditions. To test for the effects of social stress on %SLD and %OD, paired-samples *t* tests were conducted for AWS and ANS separately.

Effects from social stress on the nonword reading task. To test for the effects from social stress on errors and FFF2 from the nonword reading task, separate 2 × 2 repeated-measures ANOVAs were conducted between groups (AWS vs. ANS) and across the pre–TSST-M nonword reading and TSST-M nonword reading conditions.

Results

All variables were normally distributed ($p > .05$) as assessed by Shapiro–Wilks test of normality on studentized residuals. Mauchly's tests of sphericity were not statistically significant ($p > .05$), with the exception of FFF2 where Mauchly's test of sphericity was statistically significant for the two-way interaction ($p = .042$); therefore, findings are reported using the Greenhouse–Geisser method for this variable.

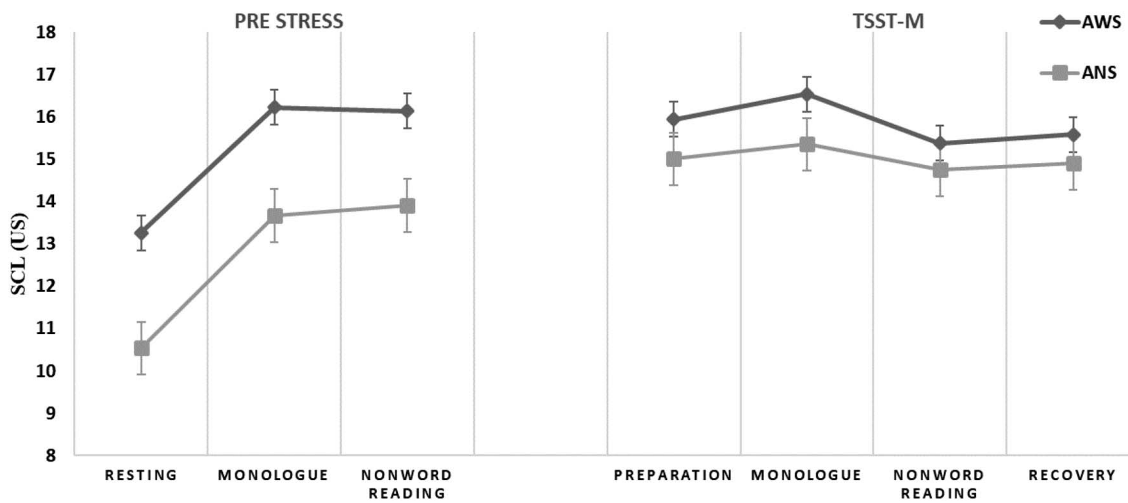
Group Differences in Self-Reported Anxiety Levels During Resting Baseline

AWS reported significantly higher mean STAI-T scores ($M = 46.7$, $SD = 5.5$) compared to ANS ($M = 41.5$, $SD = 2.5$), $t(21) = 2.95$, $p = .041$. AWS also reported significantly higher mean STAI-S scores ($M = 45.3$, $SD = 5.5$) compared to ANS ($M = 40.5$, $SD = 8.2$), $t(21) = 1.61$, $p = .024$.

Group Differences in Autonomic Activity During Resting Baseline

Higher mean SCL at baseline (see Figure 2) were found for AWS ($M = 13.26$, $SD = 8.35$) compared to ANS ($M = 10.92$, $SD = 6.8$), but these group differences were not significant ($p = .076$). No significant group differences in HR levels were found for AWS ($M = 80.54$, $SD = 8.58$) compared to ANS ($M = 78.77$, $SD = 14.09$) at baseline ($p > .273$; see Figure 3). Significantly higher RSA values

Figure 2. Means for skin conductance level (SCL) for adults who stutter (AWS) and adults who do not stutter (ANS) across baseline (resting, monologue, and nonword reading tasks) and Trier Social Stress Test–Modified (TSST-M) conditions (preparation, monologue, nonword reading, resting tasks). Error bars show the standard error of the mean.



were found at baseline in AWS (M = 8.01, SD = 1.14) compared to ANS (M = 6.75, SD = 1.17), $t(21)$ = 2.607, p = .016.

Group Differences in Autonomic Measures During Prestress Speaking Conditions

Separate 2 × 2 multifactor repeated ANOVAs were conducted for SCL, HR, and RSA between groups (AWS vs. ANS) and across pre–TSST-M speaking conditions (i.e., prestress monologue, prestress nonword) by using the change scores from baseline resting measures. No significant interactions were found between groups and across pre–TSST-M monologue and pre–TSST-M nonword reading tasks for SCL (p = .371), HR (p = .345), and RSA (p = .706). Refer to Table 2 for means and standard deviations for SCLs, HR, and RSA across conditions.

Effects of Social Stress on Autonomic, Behavioral, and Acoustic Measures During TSST-M Conditions

Effects from social stress on autonomic activity during TSST-M conditions. To test for the effects of social stress

Figure 3. Means for heart rate in beats per minute (BPM) for adults who stutter (AWS) and adults who do not stutter (ANS) across baseline (resting, monologue and nonword reading tasks) and Trier Social Stress Test–Modified (TSST-M) conditions (preparation, monologue, nonword reading, resting tasks). Error bars show the standard error of the mean.

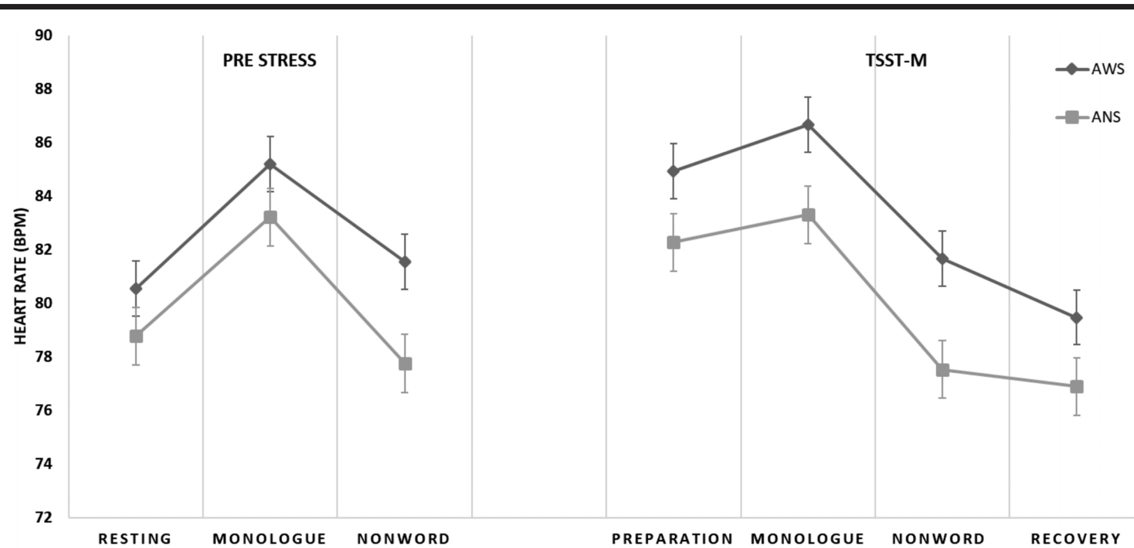


Table 2. Means (*M*) and standard deviations (*SD*) for skin conductance level (SCL), SCL change, heart rate (HR), HR change, respiratory sinus arrhythmia (RSA), RSA change during prestress (resting, monologue, nonword) and Trier Social Stress Test–Modified (TSST-M; preparation, monologue, nonword, recovery) conditions.

Group	Conditions	SCL *M* (*SD*)	SCL change *M* (*SD*)	HR *M* (*SD*)	HR change *M* (*SD*)	RSA *M* (*SD*)	RSA change *M* (*SD*)
AWS							
	Pre-stress						
	Resting	13.26 (8.3)*	—	79.85 (8.6)	—	8.07 (1.1)*	—
	Monologue	16.22 (8.7)	2.96 (1.9)	84.39 (10.7)	4.65 (4.0)	8.09 (2.1)	−.02 (1.9)
	Nonword	16.14 (9.4)	2.88 (2.3)	80.80 (9.2)	1.01 (2.6)	7.79 (2.1)	−.27 (1.8)
	TSST-M						
	Preparation	15.94 (8.9)	2.81 (1.6)	83.05 (9.2)	4.38 (6.9)	7.81 (1.9)	−.26 (1.7)
	Monologue	16.54 (7.57)	3.28 (1.8)	84.14 (9.3)	6.11 (9.6)	8.08 (3.1)*	−.01 (1.9)
	Nonword	15.37 (8.79)	2.28 (1.7)	81.11 (8.1)	1.13 (1.7)	7.59 (2.2)	−.48 (1.8)
	Recovery	15.58 (8.28)	2.31 (1.6)	79.49 (7.6)	−1.20 (5.5)	7.70 (2.4)	−.37 (2.1)
ANS							
	Pre-stress						
	Resting	10.53 (7.03)*	—	78.77 (14.1)	—	6.75 (4.1)*	—
	Monologue	13.66 (5.77)	3.13 (2.1)	83.21 (12.3)	4.43 (5.0)	7.37 (1.5)	.62 (1.2)
	Nonword	13.90 (5.72)	3.37 (2.4)	77.75 (13.5)	−1.02 (2.8)	6.94 (1.0)	.19 (1.1)
	TSST-M						
	Preparation	15.00 (6.1)	4.47 (2.2)	82.27 (12.1)	3.49 (6.5)	7.02 (1.6)	.26 (0.9)
	Monologue	15.35 (6.1)	4.82 (2.6)	83.31 (11.4)	4.53 (5.1)	7.02 (1.4)*	.27 (1.3)
	Nonword	14.75 (6.79)	4.22 (2.7)	77.52 (11.9)	−1.24 (4.1)	6.71 (1.1)	−.03 (0.8)
	Recovery	14.89 (6.5)	4.51 (2.6)	76.89 (12.1)	−1.88 (4.4)	6.84 (1.2)	.09 (0.7)

Note. Em dashes are referring to "0," indicating no change at that point. AWS = adults who stutter; ANS = adults who do not stutter.
*$p < .05$.

on SCL, HR, and RSA, separate 2 × 4 repeated ANOVAs were conducted using the change scores from pre–TSST-M conditions (i.e., resting, monologue, nonword reading). No significant group ($p = .076$) or Group × Condition ($p = .327$) interaction was found for SCL (see Figure 2). There was a significant main effect for SCL across conditions, $F(1.91, 38.23) = 23.7$, $p = .001$, e2 =.543.

Results for HR also showed no significant Group × Condition interaction ($p = .345$) or main effect for group ($p = .322$). However, a significant main effect for condition, $F(3, 63) = 3.22$, $p = .03$, e2 = .152, was found where both groups increased HR levels during TSST-M preparation and TSST-M monologue conditions (see Figure 3).

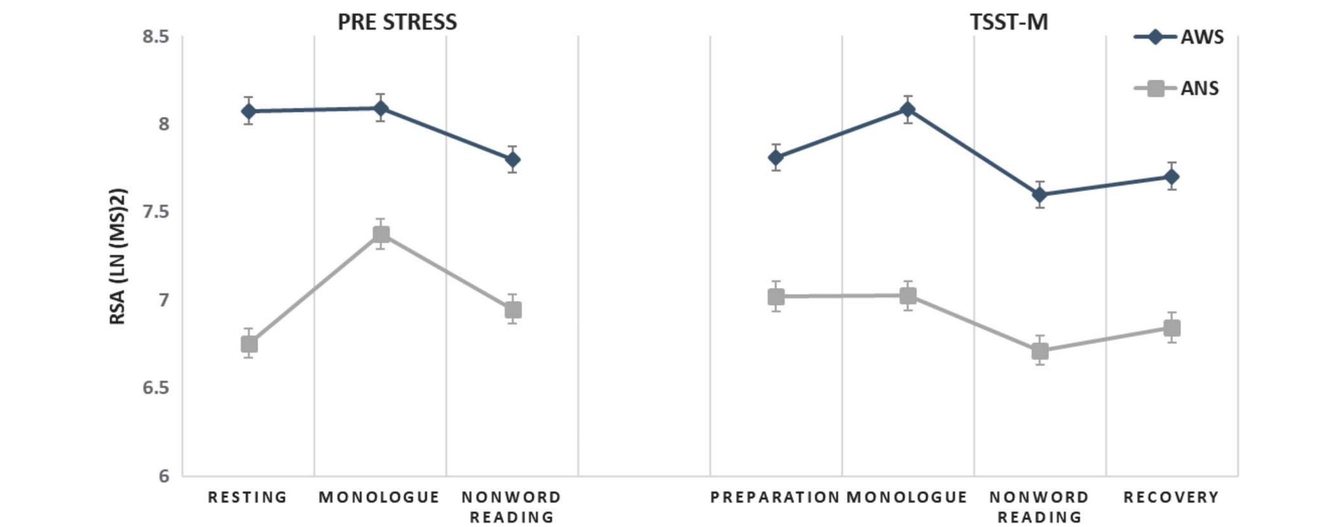
Results for RSA indicated a significant Group × Condition interaction, $F(3, 63) = 3.72$, $p = .017$, e2 = .17 (see Figure 4). No group or condition main effects were found, however. Post hoc between-group comparisons showed significantly higher RSA levels in AWS compared to ANS during the TSST-M monologue task ($p = .031$). There were no significant differences found between groups for the other conditions. Refer to Table 2 for the means and standard deviations for SCLs, HR, and RSA across conditions.

Effects from social stress on the monologue speaking task. To test for the effects of social stress on speaking rate and F0 from the monologue task, separate 2 × 2 multifactor repeated ANOVAs were conducted for group (AWS vs. ANS) across the pre–TSST-M and TSST-M conditions. Results for speaking rate showed significantly faster speaking rates in AWS during the monologue tasks ($M = 301.67$, $SD = 32.65$) compared to ANS during the monologue tasks ($M = 249.30$, $SD = 53.42$), $F(1, 21) = 10.29$, $p = .004$, partial e2 = .329, conditions (see Figure 5). No significant Group × Condition interaction was found, nor was there a condition main effect. Results for F0 indicated no significant Group × Condition interaction, nor was there a significant group or condition main effect (see Figure 6).

Paired-samples *t* tests were conducted to test for differences in %SLD and %OD between the prestress and TSST-M conditions for AWS and ANS separately. AWS did not show significant differences in %SLDs across the pre–TSST-M monologue ($M = 2.68$, $SD = 2.6$) and TSST-M monologue ($M = 3.09$, $SD = 3.4$) conditions ($p > .05$), nor were there significant differences in %OD for either the AWS ($p > .05$) across the pre–TSST-M monologue ($M = 5.44$, $SD = 2.3$) to TSST-M monologue ($M = 6.05$, $SD = 2.9$) or the ANS ($p > .05$) across the pre–TSST-M monologue ($M = 3.38$, $SD = 1.8$) to TSST-M ($M = 3.89$, $SD = 2.5$) conditions.

Effects from social stress on the nonword reading task. To test for the effects of social stress on error rate and FFF2 from the nonword reading condition, separate 2 × 2 multifactor repeated ANOVAs were conducted for group (AWS vs. ANS) across the pre–TSST-M and TSST-M conditions. Results showed that error rate did not significantly differ between groups or across conditions. Results for FFF2 indicated a significant Group × Condition interaction, $F(1, 21) = 4.803$, $p = .040$, partial e2 = .186, $E = .709$. Descriptive analysis showed that this interaction was due to a larger FFF2 decline in the AWS from the pre–TSST-M ($M = 74.5$, $SD = 19.5$) to the TSST-M

Figure 4. Means for respiratory sinus arrhythmia (RSA) for adults who stutter (AWS) and adults who do not stutter (ANS) across baseline (resting, monologue and nonword reading tasks) and Trier Social Stress Test–Modified (TSST-M) conditions (preparation, monologue, nonword reading, resting tasks). Error bars show the standard error of the mean.



(M = 59.36, SD = 29.9) nonword reading conditions compared to the ANS who showed a slight increase in FFF2 from pre–TSST-M (M = 49.13, SD = 29.9) to TSST-M nonword reading (M = 55.64, SD = 35.7) conditions (see Figure 7). This was confirmed in an individual sample t test where larger differences in FFF2 between prestress and TSST-M conditions were found in AWS (M = 19.35, SD = 20.5) compared to ANS (M = 11.32, SD = 9.9), $t(21)$ = 4.68, p = .042 (two-tailed).

Discussion

The primary purpose of this study was to assess the effects of social stress on autonomic nervous system activity and to determine the effect of these stress-induced physiological changes on the behavioral and acoustic parameters in AWS and ANS. Findings showed significant increases in self-reported levels of STAI-T and STAI-S in AWS compared to ANS. No significant differences in SCL or HR measures were found between groups, suggesting similarities in sympathetic nervous system activity before and during a socially stressful situation. However, differences in parasympathetic nervous system activity emerged in AWS as they showed significantly greater RSA levels at resting baseline. At the same time, the nonword reading task elicited a significant interaction for FFF2, where AWS showed increased FFF2 under pre–TSST-M conditions compared to controls that decreased to meet levels found

Figure 5. Mean speaking rates (syllable/minute) for adults who stutter (AWS) and adults who do not stutter (ANS) while speaking in monologue under pre–Trier Social Stress Test (TSST; prestress) and TSST (social evaluative) conditions. Error bars show standard deviation of the mean.

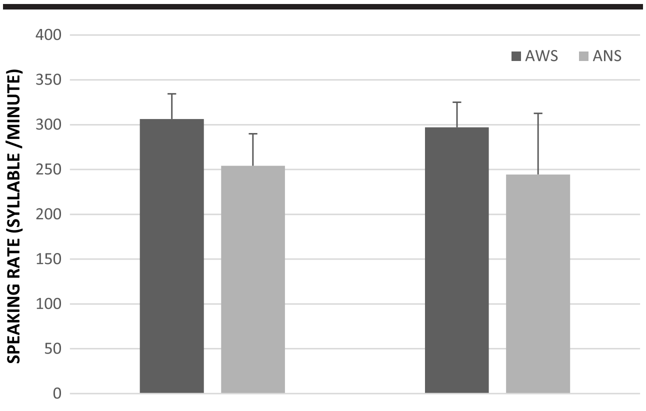


Figure 6. Mean fundamental frequencies (F0) for adults who stutter (AWS) and adults who do not stutter (ANS) while speaking in monologue under pre–Trier Social Stress Test (TSST; prestress) and TSST (social evaluative) conditions. Error bars show the standard error of the mean.

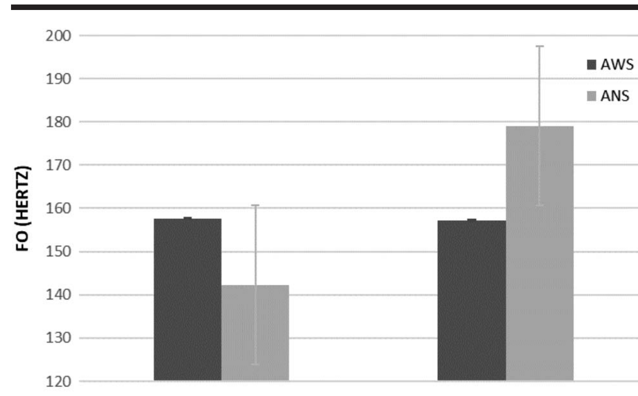
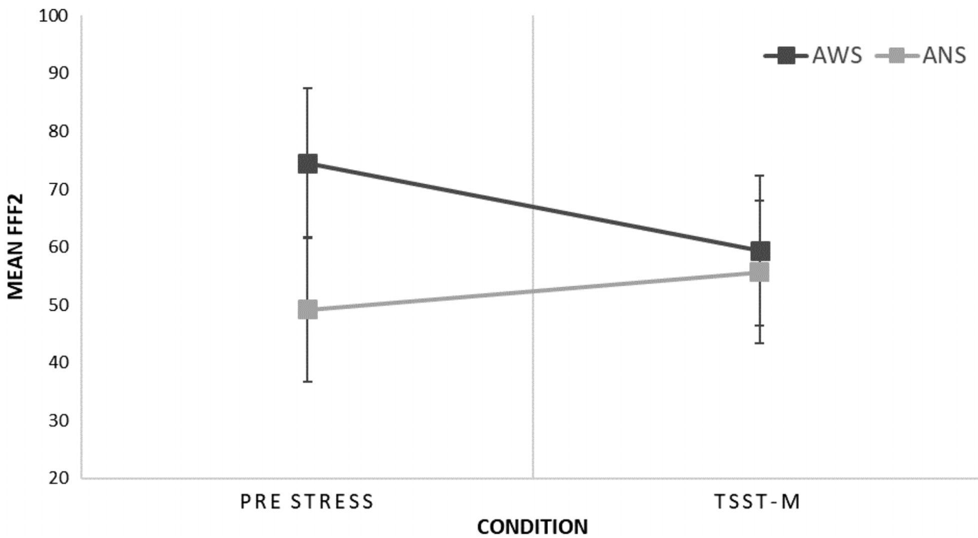


Figure 7. Mean formant frequency fluctuations for the second formant (FFF2) for adults who stutter (AWS) and adults who do not stutter (ANS) while producing the nonword speaking task during pre–Trier Social Stress Test (TSST; prestress) and TSST (social evaluative) conditions. Error bars show the standard error of the mean.



in controls when speaking under TSST-M conditions. Decreased FFF2 or, in other words, increases in tongue stability when speaking under social stress was not found in controls. No significant differences were found for F0 during the monologue tasks. AWS showed significantly faster speaking rates when speaking in monologue under both pre–TSST-M and TSST-M conditions compared to ANS; however, no significant Group × Condition interaction was found. Also, no significant differences were found for %SLD or %OD in either group across conditions.

In summary, although emotional reactivity did not differ between groups, AWS demonstrated a more parasympathetic dominant system. In addition, social stress appeared to have an effect on speech motor control in AWS as they exhibited a decrease in tongue variability, a trend not shown in ANS.

Resting Levels of Physiological Activity

AWS showed significantly higher parasympathetic nervous system activity, as indexed by measures of RSA, during resting, baseline conditions compared to ANS. When considering the significantly higher levels of self-reported state and trait anxiety in the AWS compared to controls prior to exposure to the experimental tasks, it can be speculated that the AWS may have had a high level of stress going into the experiment, and this required increased RSA in an attempt to regulate their heightened emotions. While several studies report decreased RSA levels in adults with anxiety disorders (Lyonfields, Borkovec, & Thayer, 1995; Thayer, Friedman, & Borkovec, 1996), some reports of a hyperactive RSA have also been found in this population. It is suspected to reflect a hypervigilance to their surroundings (Jonsson, 2007) and a response mechanism to chronic stress (Mathewson et al., 2013). Adhering to this line of thinking, AWS who perceive social-communicative situations as stress-inducing and employ continuous monitoring of their speech may, in response, develop increased levels of related anxiety, especially prior to engaging in a speaking task. It can therefore be suspected that these AWS exhibited a tonic increase in RSA as a regulatory response to the stressor in this study. In support, several studies have reported a reduction in HR in AWS compared to ANS when speaking during stress (Caruso et al., 1994; C. M. Weber & Smith, 1990), which may be due to parasympathetic influences (i.e., RSA). Alm (2014) proposed that parasympathetic inhibition on the heart may result in a "freezing response" that interferes with the fluent flow of speech. Further assessment of autonomic activity is warranted in AWS using larger sample sizes by determining tonic, resting RSA levels and comparing these responses to self-reports of anxiety.

Impact of Speaking Under Prestress Conditions

The significantly higher levels of self-reported state anxiety in the AWS may explain the faster speaking rate observed during the pre–TSST-M monologue task. Faster speaking rates are commonly reported when speaking under emotionally arousing conditions (Bacharaowski & Owren, 1995; Goberman et al., 2011; Owren & Bachorowski, 2007; Scherer, 1986). It is possible that the social stress that comes with evaluation during speaking may have been present in the AWS during the pre–TSST-M conditions.

Higher levels of FFF2 were also observed in the AWS during the pre–TSST-M nonword reading task. FFF2 is a measure of articulatory steadiness (Y. Chen, 2009), and the higher levels of FFF2 observed in the AWS may indicate a vulnerable, unstable speech motor system. Many studies have shown that AWS lack the ability to produce stable speech motor programs (Smith & Weber, 2017; Sussman et al., 2011). These studies measured both kinematic (Smith et al., 2010) and acoustic measures (Bauerly, 2018; Robb & Blomgren, 1997) by incorporating nonwords similar to the task used in the current study. Results from the current study support the existing literature that suggests AWS exhibit an underlying deficit in speech motor control (Smith & Weber, 2017).

When considering the significantly high levels of STAI anxiety in AWS compared to ANS, simultaneous with high baseline RSA, it can be speculated that AWS approached the study tasks with high levels of anxiety, which resulted in faster speaking rates and increased articulatory variability.

Impact of Social Stress

On a physiological level, AWS showed emotional reactivity and regulatory processes that were similar to controls during social stress. In other words, on an emotional level, AWS did not differ in how they coped with social stress when compared to ANS. Descriptively, SCL remained high for both groups during TSST-M speaking conditions (monologue and nonword reading), which indicated the need for an increase in sympathetic input in response to heightened demands from social stress. Interestingly, HR levels when reading out loud were similar between pre–TSST-M and TSST-M conditions, indicating no apparent audience effect when reading out loud.

Acoustic analysis revealed the FFF2 of AWS decreased to a level comparable to that of the ANS when reading under social stress conditions, and this change was not an effect from changes in emotional processes as physiological processes were not found to differ between conditions for the nonword reading task. A decrease in variability was also found in Jackson et al. (2016) where AWS exhibited an increased intragestural stability of lip movement compared to controls when producing sentences in front of an audience. Jackson et al. interpreted these findings to suggest that, when AWS are speaking in front of an audience, they engage an internal focus of attention (Wulf, McNevin, & Shea, 2001), which subsequently leads to greater speech motor stability. Although the current findings showed AWS decreased in variability levels to what was observed in controls, a less flexible motoric system may be detrimental to performance as variability is thought to aid in responsiveness, particularly to changes from environmental demands (Chow, Davids, Button, & Koh, 2008). In support, Namasivayam and Van Lieshout (2011) suggested that a decrease in variability may have a negative effect on AWS as it reflects a speaker who is taking too much control over their speech movements, which may, in turn, render the system more susceptible to breakdown. It is possible that the increase in variability in AWS compared to ANS, frequently reported in the literature (Bauerly, 2018; Smith & Kleinow, 2000; Usler et al., 2017), serves as a support mechanism used to help stabilize the system when speaking under social or cognitive demands.

Implications and Future Directions

The present findings do not support differences in the emotional reactivity of AWS when responding to a social stress condition. That is, AWS showed similar SCL and HR patterns to ANS when responding to the task of preparing and delivering a speech. However, AWS showed increased levels of RSA during both prestress and TSST-M conditions. At the same time, AWS showed increased levels of self-reported anxiety. Together, these findings suggest that increased engagement of emotional regulation strategies were required in AWS, regardless of whether there was a social evaluative component. Results lend support for continued research into the assessment of RSA levels under varying speaking conditions in both adolescents and AWS and determining whether those who show high, tonic RSA levels are developing coping behaviors in response.

One potential limitation to our study can be found in the use of the repetitive, nonword reading task. Repeating the CVC nonwords could have allowed for practice effects to take place, subsequently leading to the decrease in FFF2 found in AWS. However, we suspect that this was not the case because the stimuli were presented in random order. Also, ANS did not show practice effects as their FFF2 values remained the same from prestress to TSST-M conditions.

One shortcoming to this study is that we did not ask participants to rate their perceived level of social stress following the TSST conditions. Although the TSST is a widely acceptable tool for eliciting social stress, individual differences are documented (Tininenko, Measelle, Ablow, & High, 2012; Yim, Quas, Rush, Granger, & Skoluda, 2015), and therefore, it is possible that some of the participants did not feel that the task of preparing and delivering a speech was stressful.

We also have to consider the possibility that the emotional responses of AWS to the reading versus speaking task were affected by the use of covert behaviors (e.g., avoidance). In this case, AWS could have experienced more stress compared to ANS during the nonword reading task where some covert behaviors, such as replacing a word or circumlocution, were not possible. However, physiological data showed a decrease in SCL and HR on reading compared to speech task for both groups, and therefore, we can assume that the nonword reading task was not particularly stressful for AWS.

Due to the low sample numbers, we were unable to assess correlations between autonomic and acoustic measures. Future studies incorporating larger sample sizes will allow for stronger comparisons between different emotional and motoric processes.

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