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Potential Interactions among Linguistic, Autonomic, and Motor Factors in Speech

ABSTRACT: *Though anecdotal reports link certain speech disorders to increases in autonomic arousal, few studies have described the relationship between arousal and speech processes. Additionally, it is unclear how increases in arousal may interact with other cognitive-linguistic processes to affect speech motor control. In this experiment we examine potential interactions between autonomic arousal, linguistic processing, and speech motor coordination in adults and children. Autonomic responses (heart rate, finger pulse volume, tonic skin conductance, and phasic skin conductance) were recorded simultaneously with upper and lower lip movements during speech. The lip aperture variability (LA variability index) across multiple repetitions of sentences that varied in length and syntactic complexity was calculated under low- and high-arousal conditions. High arousal conditions were elicited by performance of the Stroop color word task. Children had significantly higher lip aperture variability index values across all speaking tasks, indicating more variable speech motor coordination. Increases in syntactic complexity and utterance length were associated with increases in speech motor coordination variability in both speaker groups. There was a significant effect of Stroop task, which produced increases in autonomic arousal and increased speech motor variability in both adults and children. These results provide novel evidence that high arousal levels can influence speech motor control in both adults and children. © 2006 Wiley Periodicals, Inc. Dev Psychobiol 48: 275–287, 2006.*

Keywords: *speech motor control; speech development; speech kinematics; autonomic; Stroop*

INTRODUCTION

Speech production is a complex motor skill that requires the integration of many neural systems. Neural networks responsible for linguistic encoding, emotion, and cognition are active during message formulation, while the speech motor system generates the coordinated muscle commands necessary for overt speech. Interactions between the neural systems responsible for language and those responsible for speech motor control have been frequently observed. In typically developing children, for example, increases in syntactic complexity and utterance length are associated with articulatory simplifications (Prelock & Panagos, 1989), increased articulatory error production (Kamhi, Catts, & Davis, 1984), and increased speech motor variability (Maner, Smith, & Grayson, 2000). Additionally, typically fluent children as well as children who stutter demonstrate higher disfluency rates under conditions of increased length and syntactic complexity (Logan & Conture, 1997; Ratner & Sih, 1987; Silverman & Ratner, 1997; Yaruss, 1999; Zackheim & Conture, 2003).

Influences of length and syntactic complexity on aspects of speech motor control have also been observed in adults. Strand and McNeil (1996) reported that apraxic speakers produced longer vowel and inter-word durations than matched controls, and that group differences were magnified under conditions of increased utterance length and syntactic complexity. Increases in utterance length

have been associated with changes in mean lower lip EMG amplitude in typically fluent adults as well as adults who stutter (Van Lieshout, Starkweather, Hulstijn, & Peters, 1995). Adults who stutter show increased variability in movement patterns across repeated utterances as syntactic complexity and utterance length increase (Kleinow & Smith, 2000). Thus, increases in linguistic complexity can affect speech motor variability in children and adults.

From the studies cited above, one can infer that linguistic complexity contributes to predictable changes in speech motor control and coordination, and specific populations, such as children and adults who stutter, demonstrate increased effects of linguistic loading on speech motor control. This observation corroborates multifactorial models of speech motor control and disorders, which suggest that many variables (such as genetic traits, language processing skills, social/emotional responses, speech motor coordination) interact to affect speech motor control processes. Multifactorial theories of stuttering (Conture, 1990; Smith & Kelly, 1997; Van Riper, 1982), for example, suggest that several variables can interact in complex ways to produce overt stuttering behaviors in people who have speech motor systems vulnerable to those factors. Thus, it is likely that linguistic complexity interacts with other variables that potentially affect speech motor control in typical speakers as well as speakers with communication impairments.

Mental stress, such as that occurring during speaking or cognitive processing, may be one variable that can affect the sensorimotor processes involved in speech production (Weber & Smith, 1990; Zimmermann, 1980). For example, Dromey and Benson (2003) found that, in addition to linguistic loading, the performance of a simultaneously produced distractor task (mental arithmetic) also affected the variability of lower lip movements. Dromey and Benson asserted that limitations in attentional resources required for performance of competing cognitive tasks could explain their findings. While potentially true, it remains unclear how linguistic and/or attentional challenges affect the speech motor system. The hypothesis to be explored in this study is that increased linguistic demands are associated with increased autonomic nervous system (primarily sympathetic) responses, which in turn affect speech motor control processes. To date, there are few studies measuring physiological responses and cognitive load concurrently.

Cognitive loading, or mental stress, has been robustly associated with increases in autonomic arousal as measured by increases in heart rate, blood pressure, and skin conductance measures (for review of psychophysiological data recording and interpretation, see Andreassi, 2000). One might expect that increases in arousal affect speech motor control processes secondary to changes in muscle activation and coordination, and studies of general

motor control support this hypothesis. Muscle activity during stressful tasks has been described in terms of decreased efficiency and increased energy expenditure (Beuter & Duda, 1985; Weinberg & Hunt, 1976), or regression to earlier phases of motor development (Pijpers, Bakker, Oudejans, & Boschker, 2001). Inferring from such studies in general motor control, one may hypothesize that increasing speech demands (specifically by increasing the length and syntactic complexity of the utterance to be spoken) will increase activity in the autonomic nervous system, leading to measurable changes in muscle activity. However, it is unclear if language processing, like many other cognitive tasks, is associated with changes in autonomic arousal. Additionally, it is unknown if increases in language processing affect arousal levels in children and adults to the same degree.

The challenge of the current work is to integrate variables such as linguistic complexity and autonomic arousal into a working model of speech motor development and control. Maner et al. (2000) and Kleinow and Smith (2000) indicated that linguistic variables have more direct effects on speech motor control than originally assumed, and that children and adults with speech disorders may be more vulnerable to the motor effects of linguistic loading. In a model further developed by Smith and Goffman (2004), central networks mediating multi-leveled linguistic (e.g., syntactic, prosodic, phonetic) and motor processes (e.g., pre-motor planning, generation of motor commands to muscles) share bidirectional influences. Drawing on evidence that both the patterning of movement output and its variability is clearly influenced by the linguistic goals and age of the speaker, their model hypothesizes close interactions of cortically mediated networks involved in generating the units of language and movement. They do not consider other neural systems, such the autonomic system, which might play a significant role in modulating the degree of consistency in motor output. One hypothesis we consider is that linguistic processing, an activity that requires mental effort, is associated with increases in autonomic arousal. Heightened ANS activity, in turn, leads to changes in motor output. This model would predict that linguistic complexity and autonomic arousal co-vary, and have interactive and potentially non-linear effects on speech motor control processes. Support for this hypothesis would involve (a) observations that increases in linguistic complexity are associated with increased ANS activity, and (b) observations of increased speech motor variability under conditions of both increased ANS activity and increased linguistic complexity. An alternative hypothesis is that the effects of linguistic loading on the speech motor system are mediated through some other process independent of autonomic activation. In this

alternative model, both linguistic processes and ANS arousal may interact with the speech motor system, but linguistic processes and ANS arousal are not directly related. This alternate hypothesis would be supported by finding that both linguistic complexity and ANS activity are associated with speech variability, but linguistic complexity is not associated with increased ANS activity.

METHODS

Participants

Two gender-balanced groups each composed of 10 participants were recruited through local postings and newspaper advertising. Adults were undergraduates aged 19;0–21;8 ($M = 19.93$ years, $SD = 10.17$ months) and children were 9;2–10;8 ($M = 9.88$ years, $SD = 6.42$ months). Nine- and 10-year-olds were selected because they are mature enough to read sentences from a computer monitor while following specific experimental instructions. They could also complete an hour-long experimental protocol. Additionally, the development of coordinative synergies between the upper lip, lower lip, and jaw for speech shows a plateau between the ages of 7 and 12 years (Smith & Zelaznik, 2004). These investigators showed that 9- and 10-year-olds are much more variable in speech motor coordination than young adults. Thus 9- and 10-year-olds were expected to perform differently on speech motor tasks when compared to young adults in the current study.

All participants spoke standard American English as a first and primary language. As part of a speech, language, and hearing screening, the speaking and listening subtests of the *Test of Adolescent and Adult Language—3rd Edition* [(*TOAL-3*; (Hammill, Brown, Larsen, & Wiederholt, 1994)] were administered to adults, while the *Clinical Evaluation of Language Fundamentals- 3rd Edition* [(*CELF-3*; Semel, Wiig, & Secord, 1996)] was administered to children. Each participant performed within normal limits on these tests. According to self or parent report, all participants had no history of conditions that could potentially affect autonomic recordings such as heart disease, hypertension, and neurological problems. Additionally, participants refrained from caffeine or alcohol consumption 3 hr before participation, and avoided scheduling experimental sessions within 3 hr of stressful events such as college exams or heavy physical activity (Tulen, Moleman, Van Steenis, & Boomsma, 1989). To ensure that participants could perform the reading task without difficulty, all participants had normal or corrected to normal visual acuity, and no history of color blindness or reading problems. Each experimental session lasted approximately 1 hr, which included the screening protocol.

Stimuli

Stimuli (listed in Table 1) consisted of four sentences that systematically varied in length and syntactic complexity. Sentence length was either 11 or 15 syllables, creating a short and long length contrast. Declarative sentences (simple) and sentences containing a subject relative clause (complex) were included to create a contrast in syntactic complexity. A relative clause was used in the "complex" condition because it is a later developing syntactic structure (Bloom, Lahey, Hood, Lifter, & Fiess, 1980). Additionally, Just, Carpenter, Keller, Eddy, and Thulborn (1996) found that the processing of relative clauses is associated with increases in mean response time, more errors, and increases in brain activation over Wernicke's and Broca's areas when compared to processing of conjoined sentences in adult participants. This suggests that inclusion of a relative clause is an appropriate complexity manipulation, even for adult participants. Finally, all four sentences contained a large proportion of bilabial consonants to ensure that upper and lower lip motions were highly targeted during speech.

Procedures

Condition 1—Sentence Production Baseline. DMDX software (Forster & Forster, 2003) was used to visually present sentences on a computer monitor located in front of the participant. Each sentence was displayed for 4.5 s, with an inter-stimulus interval of 2.5 s during which the screen was cleared. The participants were instructed to read the sentence aloud, using habitual rate and intensity, as soon as it appeared on the screen. Sentences were presented in blocks; each block contained four trials of one of the four sentences. The blocks were randomized for each participant. Stimuli were presented until the participant had produced three blocks (12 fluent productions) of each of the four sentences. Productions were deemed fluent if they were free from repetitions, false starts, hesitations, and/or rewording as judged by two independent raters.

Condition 2—Sentence Production Preceded by Stroop Trials. Condition II was identical to Condition I, with the exception that all sentence trials were preceded by a Stroop task. In modern versions of the Stroop Color Word Test [CWT; (Stroop, 1935)], participants are presented with repeated symbols (e.g., XXXX) displayed in different colors, and are asked to name the color in which the symbols are displayed. In the classic experimental condition, the symbols are replaced with color words (e.g., "blue," "red") that are displayed in incongruent ink colors (e.g., the word "red" printed in green ink). Participants are asked to ignore the written information, and name the color in which the words are displayed. Reaction times are significantly longer and error rates are consistently higher in the experimental condition (Stroop, 1935), and results using a wide range of modifications have proven robust (see MacLeod, 1991, for review). Stroop experiments have also been performed with children, and results have indicated that performance improves systematically with maturation from school age to adolescence (Adleman et al., 2002; Demetriou, Spanoudis, Christou, & Platsidou, 2002). The CWT has repeatedly been used as a psychological or cognitive stressor, and performance has been routinely associated with increases in sympathetic nervous system activity in healthy adults (Hoffman, Khan, Papaconstantinou, & O'Herron, 1991; Hoshikawa & Yamamoto, 1997; Hugdahl & Franzon, 1987; Renaud & Blondin, 1997; Tulen et al., 1989).

In the Stroop task trials, four randomly ordered color words (e.g., "blue, pink, green, red") were displayed in colors that were

Table 1.   A Comparison of Stimuli

Description	Sentence
Simple, short	The birds and the butterflies played by the pond
Simple, long	The baby birds and the many butterflies played by the pond
Complex, short	The birds that saw butterflies played by the pond
Complex, long	The baby birds that saw many butterflies played by the pond

Note. These stimuli were used as target sentences in the Stroop and non-Stroop conditions. Sentences vary in number of words (short = 9 words/11 syllables, long = 11 words/15 syllables) and syntactic complexity (simple = absence of relative clause, complex = presence of relative clause).

incongruent to the meaning of the words. Participants were instructed to avoid reading the word, and to respond by naming the color in which the word was displayed. For example, if the word "red" were displayed in blue, the correct response would be "blue." Participants were given four practice trials to ensure that they understood the instructions. They were reminded to use habitual speaking rate and loudness, and to respond as soon as the stimulus appeared on the screen. Sentence production trials identical to Condition 1 followed all Stroop trials. As in Condition 1, trials were continued until the participant had produced three blocks (12 fluent repetitions) of each sentence. Errors on the color words were recorded, but not used in further analyses.

Though 12 repetitions of each sentence in both baseline and Stroop conditions were collected, trials were discarded from individual data due to disfluency, rewording of the sentence, and/or extraneous talking. After such trials were discarded, several speakers had only eight fluent productions for some of the sentences. Thus, for consistency, the first eight fluent utterances per condition were used for analysis for all speakers.

Data Collection and Analysis

Oral Movement. For kinematic data collection, all participants were seated in view of an OptoTrak camera system (Northern Digital, Waterloo, Ontario, Canada) that recorded the movement of small infrared light emitting diodes (IREDS) attached to the upper lip, lower lip, jaw, and head. Upper and lower lip markers were attached at the midline of the vermilion borders of the lips, while the jaw marker was attached to a lightweight splint that projected from under the chin at midline. One IRED was placed on the forehead, and three others were placed on modified sport goggles worn by all the participants. The goggle and head IRED data were used to compute the axis of head motion to correct for artifact resulting from movement of the head (Smith, Johnson, McGillem, & Goffman, 2000).

Testing the effects of stress/arousal and linguistic encoding on the coordinated muscle activity necessary for speech production requires a quantifiable index of speech coordination. Classic studies of speech production have focused on variability in acoustic features, as well as single-point kinematic measurements such as peak displacement and velocity. Smith, Goffman, Zelaznik, Ying, and McGillem (1995), however, measured the lower lip movement variability across repeated productions of an entire phrase. Trial-to-trial variability has been shown to reliably reflect speech motor performance of individuals and to reveal differences in disordered populations under different speaking conditions. The whole trajectory analysis has also been performed on measures of inter-articulator relationships and coordination (Smith & Zelaznik, 2004), and in the present study we adopt their method of examining consistency in coordination of the upper lip, lower lip, and jaw for the production of the entire sentence.

Kinematic signals from the upper lip and lower lip (representing movement of the lower lip plus jaw) IREDS during speech production were imported into Matlab for analysis. The lower lip velocity signal (superior-inferior dimension) was used to define the beginning and ending points for articulator motion (Smith et al., 1995). These points corresponded to the peak velocity of the first opening movement and the last opening movement for each sentence. These start and end points for segmenting the movement data were used to compute the duration of the overall movement sequence. Duration was converted into speaking rate by computing syllables per second.

These start and end points were also used to segment the upper lip kinematic record. Lip aperture (LA) was defined as the distance between the upper lip and lower lip. As the lip aperture signal is a result of actions of the upper lip, lower lip, and jaw muscles, lip aperture reflects the coordination of all three effectors. The LA signals from each condition were linearly time- and amplitude-normalized (Smith & Zelaznik, 2004), and a cumulative LA variability index was computed for each group of eight lip aperture trajectories per subject per condition (Smith et al., 2000; Smith & Zelaznik, 2004). This index reflects the degree of variability in the coordination of the upper lip, lower, and jaw on repeated productions of the utterance (Smith & Zelaznik, 2004). A repeated-measures ANOVA comparing all conditions was performed on the LA variability index and upon the measure of speaking rate. This analysis was designed to detect group effects (young adult vs. children), condition effects (Stroop, syntactic complexity, utterance length) and group X condition interactions.

Autonomic Signals. During the speaking tasks, autonomic data (finger pulse volume, tonic and phasic skin conductance) were also collected. Tonic and phasic skin conductance recordings were obtained using a 0.5 constant voltage system (UFI Bioderm, Model 2701). Electrodes were attached to the skin of the medial phalanges of the index and middle fingers of the right hand (Venables & Christie, 1980), and the hand/arm was stabilized to prevent movement. Finger pulse volume and heart rate were obtained using an infrared photoelectric plethysmograph transducer (UFI Model 1020). The transducer was placed over the distal phalange of middle finger on the right hand.
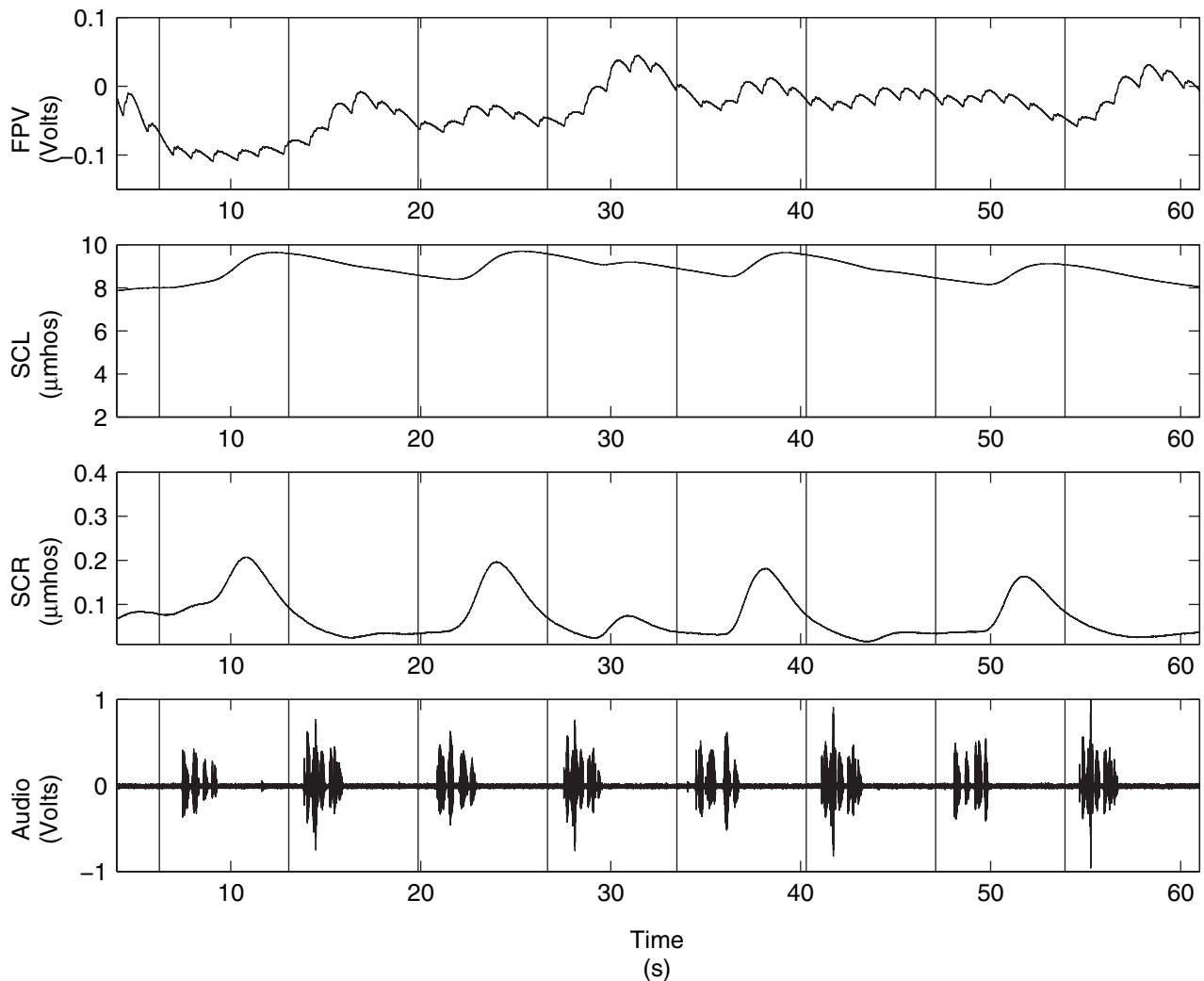
FIGURE 1 Sample autonomic data from one adult subject from the long length, complex, non-Stroop condition (FPV, finger pulse volume; SCL, tonic skin conductance level; SCR, phasic skin conductance response). Heart rate can be inferred from FPV data by calculating the number of peaks/minute. The vertical bars correspond to stimulus onset.

Autonomic signals were sampled at 2,000 Hz and low-pass filtered at 20 Hz. Additionally, a 5 V trigger signal was generated simultaneously with the appearance of stimuli on the monitor. These signals were collected by the OptoTrak as well as the Windaq software, and were used to synchronize the kinematic and autonomic records. Figure 1 shows sample autonomic and acoustic signals that were recorded during one trial of the simple complexity, short-length sentence during the non-Stroop condition. This figure presents heart rate, finger pulse volume, tonic skin conductance level, phasic skin conductance level, and the corresponding audio signal from one adult participant. The vertical lines (trigger signal) in Figure 1 represent the stimulus onset.

Autonomic data were analyzed over epochs beginning with the trigger signaling sentence presentation and lasting until the onset of the next trigger (see vertical lines in Figure 1). The mean peak-to-peak skin conductance response (SCR), mean tonic skin conductance level (SCL), mean heart rate (HR), and mean peak-to-peak finger pulse volume (FPV) corresponding to the utterances used in the kinematic analysis were calculated over each epoch. Intervals in which color words were presented were not analyzed. Epochs over which autonomic data were computed were the same duration (7 s) in the Stroop and non-Stroop conditions. Each of these measures (SCR, SCL, FPV, HR) was entered into separate repeated-measures ANOVAs to detect group effects (young adult vs. children), condition effects (Stroop, sentence), and group X condition interactions. Cardiovascular data (FPV and HR) from one child subject was removed due to excessive noise in the signal.

Effect sizes for all between- and within-groups main effects were computed with D-Stat (Johnson, 1993), a software program frequently used in meta-analytical research. Effect sizes were
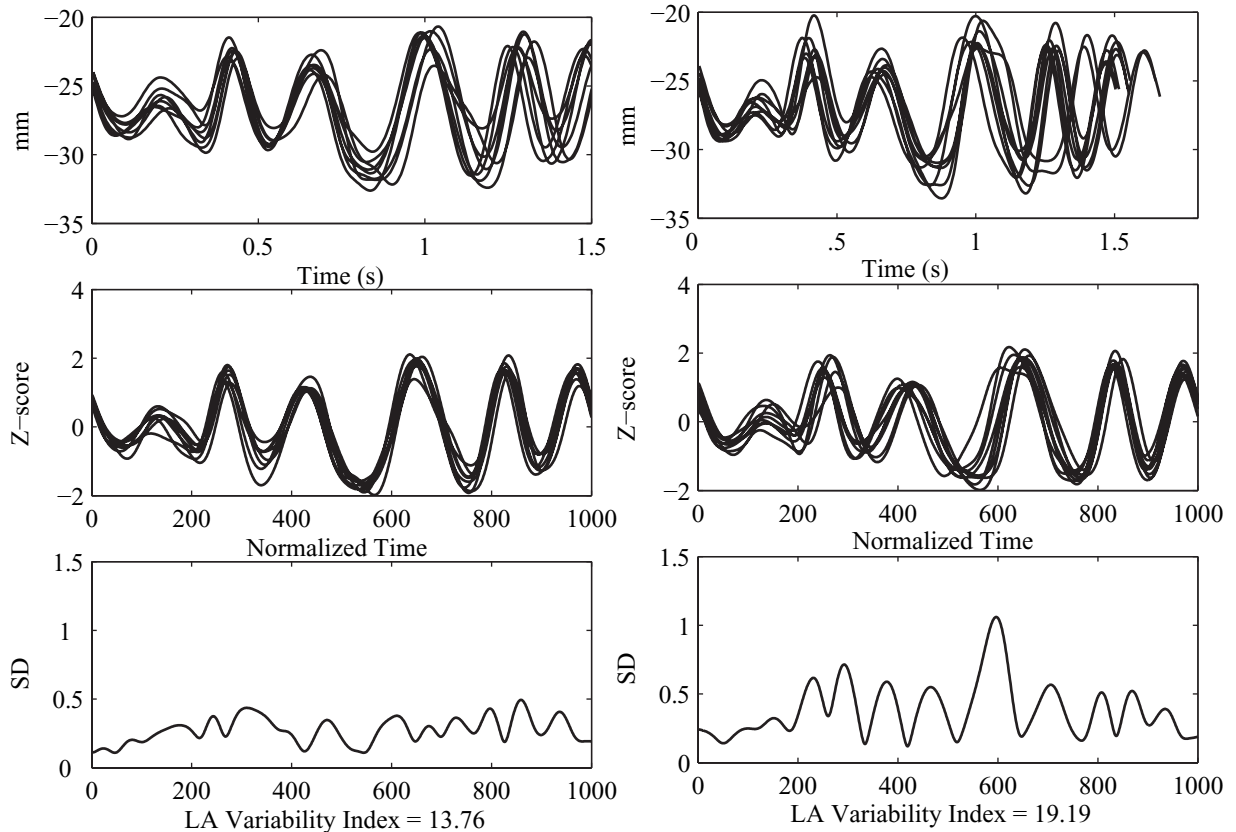
FIGURE 2   Adult LA Coordination Index. Data are from the non-Stroop (left) and Stroop (right), simple complexity, short length sentence condition. In the top panel the original (non-normalized) lip aperture trajectories are plotted as a function of time. Time- and amplitude-normalized trajectories are plotted in the middle panel. The bottom panel shows the standard deviation calculated at 2% intervals in normalized time, with the resultant LA Coordination Index displayed.

computed to investigate group differences independent of sample size.

RESULTS

Stroop Effect on Autonomic Variables

Though performing a Stroop task has been robustly associated with increases in autonomic activity in healthy adults (Hoffman et al., 1991; Hoshikawa & Yamamoto, 1997; Hugdahl & Franzon, 1987; Renaud & Blondin, 1997; Tulen et al., 1989), it was necessary to ensure that the participants in this study were similarly affected by Stroop performance. Additionally, it is important to determine if increased arousal due to the Stroop task (which habituates quickly) could be observed during subsequent reading of the sentence stimuli. Separate repeated-measures ANOVAs were performed to determine the effects of Stroop performance on heart rate, skin

conductance level, skin conductance response, and finger pulse volume for each participant. Again, all autonomic variables were measured during sentence production. In the Stroop condition (sentence production followed performance of a Stroop task), mean heart rate significantly increased [$F(1,17) = 7.95$, $p = .01$, $d = .65$; Cohen, 1988], with no significant Stroop X Group interaction [$F(1,17) < 1$]. Similar findings were observed for skin conductance level (SCL); SCL values were significantly greater in the Stroop condition [$F(1,18) = 54.57$, $p < .001$, $d = 1.65$], with no Stroop X Group interaction [$F(1,18) < 1$]. Skin conductance responses (SCR) did not differ in the non-Stroop and Stroop conditions for both groups. FPV decreased significantly, indicating heightened autonomic arousal, during sentence production in the Stroop condition [$F(1,17) = 30.75$, $p < .01$, $d = 1.27$]. There was also a significant Condition X Group interaction [$F(1,17) = 5.15$, $p = .04$]; children showed greater decreases in FPV during the Stroop task when compared to adults.
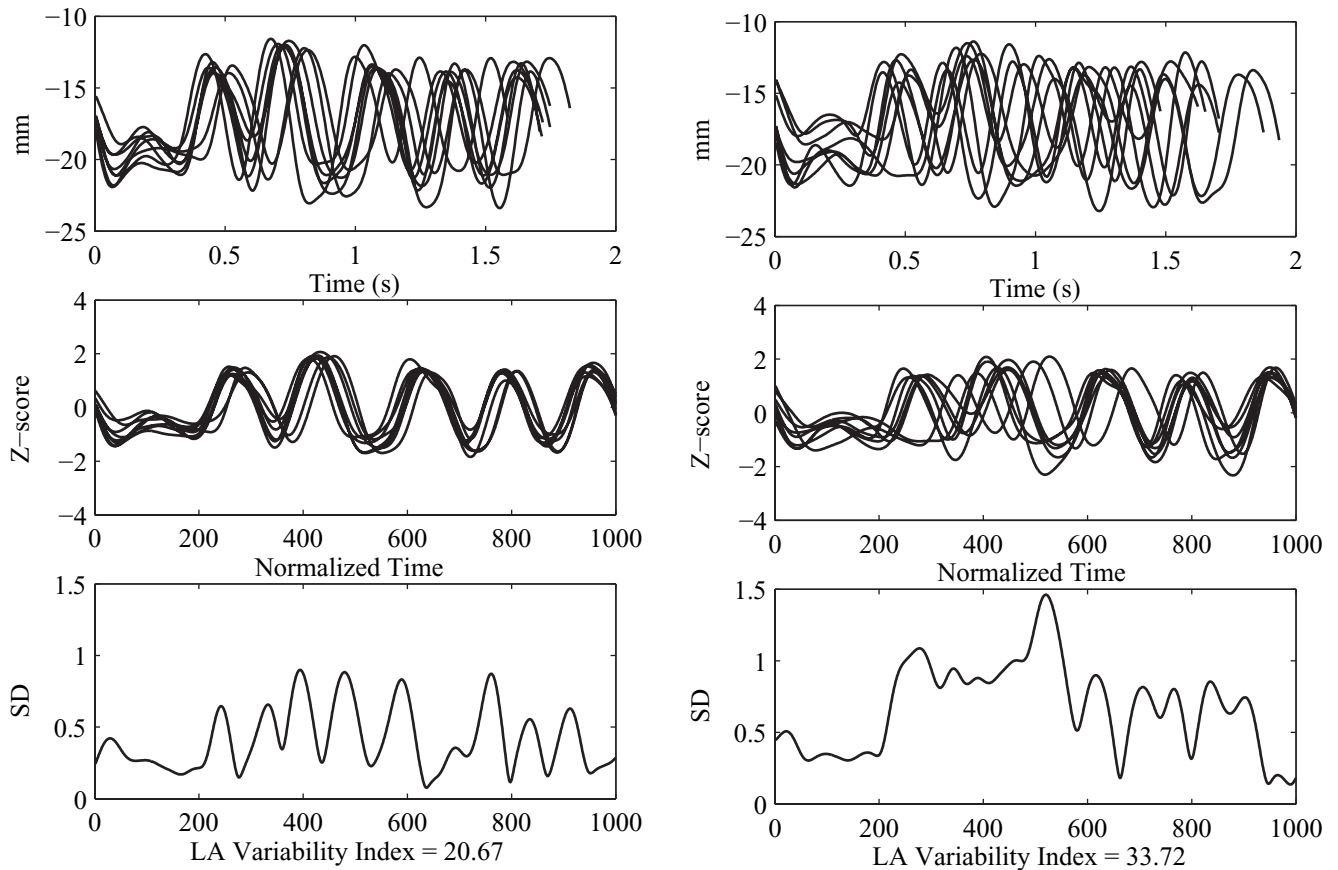
FIGURE 3 LA Coordination Index from one child participant in the non-Stroop (left) and Stroop (right), simple complexity, short length condition. In the top panel the original (non-normalized) lip aperture trajectories are plotted as a function of time. Time and amplitude normalized trajectories are plotted in the middle panel. The bottom panel shows the standard deviation calculated at 2% intervals in normalized time, with the resultant LA Coordination Index displayed.

Stroop Effect on Speech Movements

The LA (lip aperture) variability index was employed as a measure of articulatory coordination across repeated utterances. Higher values of the index indicate more variability (more dispersion) in the set of trajectories for each sentence. Figures 2 and 3 show LA variability index values for the simple complexity, short length condition from one adult and one child in both non-Stroop and Stroop conditions. These figures illustrate the LA difference signal resulting from subtracting the lower lip from the upper lip over time. The time- and amplitude-normalization of the displacement difference waveforms and the calculation of the LA variability index are also shown. While the child's LA variability indices are higher than the adult's in both arousal conditions, both participants show increased LA variability values, indicating greater speech coordination variability, in the Stroop condition when compared to the non-Stroop condition. In fact, the child data shows a marked increase

in the LA variability in the Stroop condition. Figures 4 and 5 show the mean (SE) LA variability index values for both adults and children in the Stroop and non-Stroop conditions during manipulations in linguistic complexity (Figure 4) and length (Figure 5). These figures indicate that the variability indices from the Stroop condition are higher than those from the non-Stroop condition across all linguistic tasks. A repeated-measures ANOVA indicated that mean LA variability index values increased during the Stroop condition [$F(1,18) = 4.94, p = .04, d = .50$]. There was no Stroop X Group interaction [$F(1,18) < 1$] for the LA variability measure, indicating that both speaker groups showed parallel increases in speech production variability in the Stroop condition.

Linguistic Effects

Figure 4 displays both adult and child LA variability index mean (SE) as a function of sentence complexity for the Stroop and non-Stroop conditions. Adults' and children's
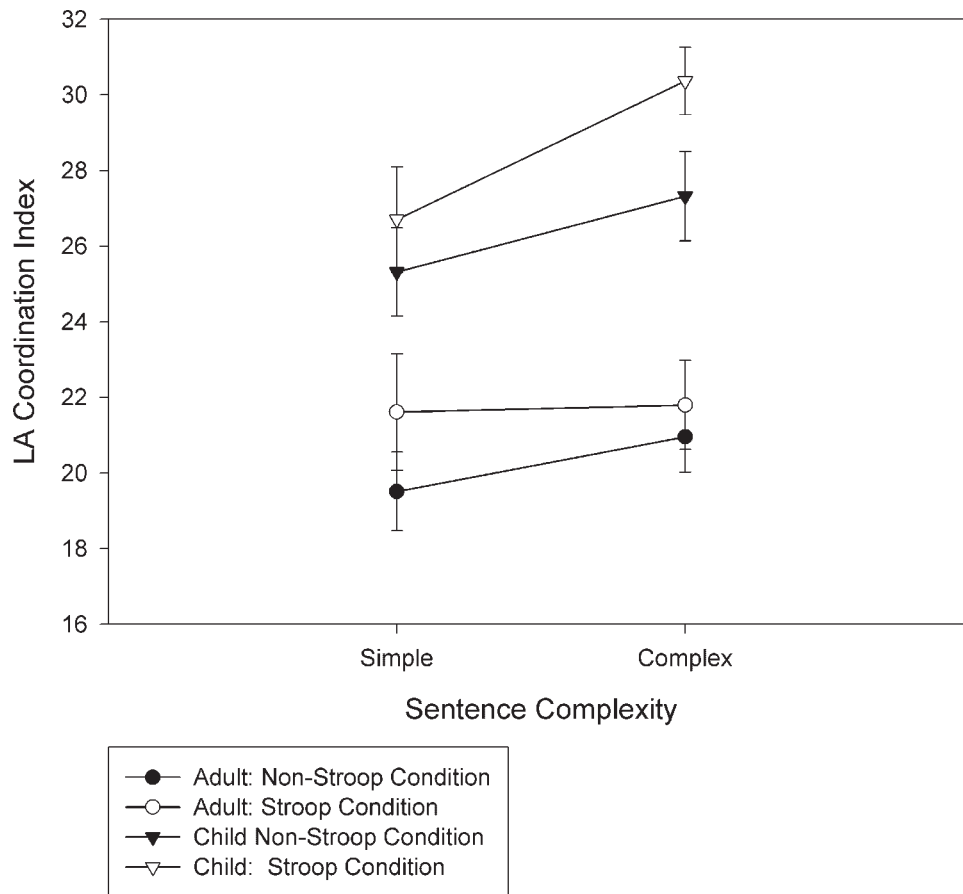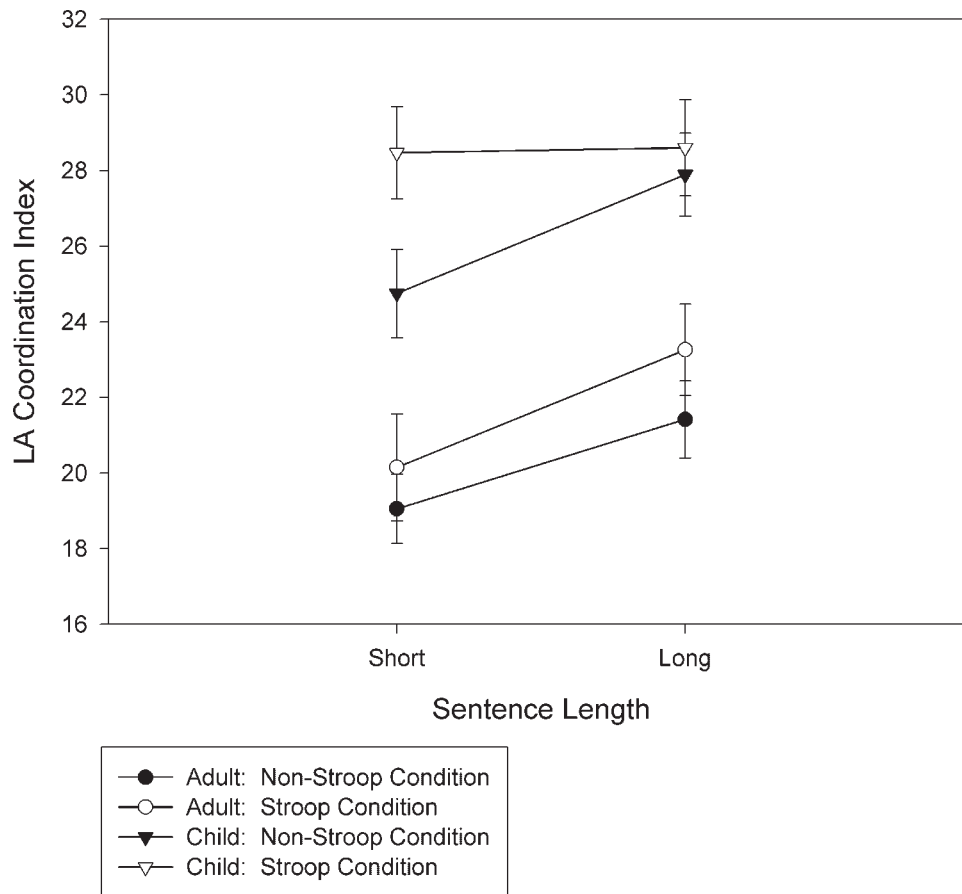
FIGURE 4 The mean (and SE) LA Coordination Index as a function of sentence complexity for adults and children in both the Stroop and non-Stroop conditions.

variability indices rise with increasing syntactic complexity in both arousal conditions, indicating increased movement variability across these tasks, although this trend was not as pronounced for adults in the non-Stroop condition. Figure 5 displays adult and child LA variability index mean (SE) as a function of sentence length for the Stroop and non-Stroop conditions. Again, mean variability indices for adults and children increase as sentence length increases in both the Stroop and non-Stroop conditions. Children in the Stroop condition had the greatest LA variability values, which remained high across the length conditions. A repeated-measures ANOVA indicated that the more complex sentences were associated with higher variability indices [$F(1,18) = 17.21, p = .004, d = .93$] for both groups. The effect of utterance length on the LA variability index was also significant [$F(1,18) = 8.41, p = .01, d = .65$]. No significant interactions between Complexity and Group [$F(1,18) = 3.19$ ns] or Length and Group [$F(1,18) < 1$] were found.

Separate repeated-measures ANOVAs were performed to examine the effects of sentence complexity and sentence length on each of the autonomic variables recorded. Though there was no significant effect of Sentence Complexity on heart rate [$F(1,17) = .003$ ns, $d = .01$], Sentence Length was associated with significantly accelerated heart rate [$F(1,17) = 7.36, p = .01, d = .62$]. No Complexity X Group or Length X Group interactions were noted [all $F(1,18) < 2.4$ ns]. Neither Sentence Complexity [$F(1,18) = .01$ ns, $d = .02$] nor Sentence Length [$F(1,18) = .02, d = .03$] significantly affected SCL. Likewise, SCR was not affected by Sentence Complexity [$F(1,18) = 1.70$ ns, $d = .29$] nor Sentence Length [$F(1,18) = .05, d = .05$]. No Complexity X Group [$F(1,18) < 1$] or Length X Group [$F(1,18) < 1$] interactions were noted [all Fs $(1,18) < 2.6$ ns] for SCL and SCR. While Sentence Complexity did not affect FPV for either group [$F(1,17) = .67$ ns, $d = .18$], longer sentences were associated with significantly reduced FPV values [$F(1,17) = 6.76, p = .02, d = .60$]. These variables did not have any significant interactions [all Fs (1,18) < 2.9 ns].

FIGURE 5   The mean (and SE) LA Coordination Index as a function of sentence length in adults and children for both Stroop and non-Stroop conditions.

Developmental Effects

Heart rate and finger pulse volume data from one child participant were discarded due to excessive noise. As expected, a repeated-measures ANOVA showed that children had higher heart rates than adults [F $(1,17) = 21.13, p = .001, d = 1.47$]. Children also showed higher skin conductance level values than adults across all tasks [F $(1,18) = 12.35, p = .002, d = 1.11$], though no group differences were obtained in skin conductance response. While children's FPV measures were lower than adults', the difference was not significant [$F (1,17) = 2.26$ ns, $d = .48$]. Adults had lower LA variability indices (indicating more consistent motor coordination) than children [$F (1,18) = 17.21, p = .001, d = 1.31$] did.

Speaking Rate

Speaking rates (syllables per second) were similar between adult and child speakers [F $(1,18) = 1.67, p = .21, d = .41$]. Both groups showed increased speech rate during the second (Stroop) condition [F $(1,18) = 5.31, p = .03, d = .52$]. Speaking rate for both groups was slower as syntactic complexity increased [F $(1,18) = 158.35, p < .01, d = 2.81$], but faster as length increased [$F (1,18) = 9.26, p = .01, d = .68$].

DISCUSSION

At the outset of this article, we proposed two alternative hypotheses concerning the relationship among linguistic complexity, autonomic arousal, and speech motor control. One hypothesis was that linguistic complexity affects speech motor control through activation of the ANS. The alternative hypothesis was that linguistic complexity and autonomic activity independently affect speech motor control. Our current results support the second hypothesis, as we observed both linguistic effects and autonomic effects on speech motor variability, but only weak effects of linguistic complexity on autonomic variables in both children and adults.

Autonomic Arousal Affects Speech Motor Coordination

Autonomic arousal levels rose significantly for adults and children during the Stroop condition, as evidenced by increases in skin conductance levels, increases in heart rate, and decreases in finger pulse volume for both speaker groups. Paralleling these increases in autonomic arousal levels, both speaker groups showed significant increases in the LA variability index during the Stroop/high arousal condition, indicating increased speech motor variability under conditions of cognitive load. To our knowledge, this is the first experiment in which speech motor coordination has been directly measured while autonomic levels were manipulated. Our finding that increases in arousal affect speech motor control processes is consistent with earlier studies in which speech motor coordination has been inferred from acoustic data. Caruso, Chodzko-Zajko, Bidinger, & Sommers, 1994 collected cardiovascular, behavioral, and acoustic data as nine adults who stutter and nine matched controls performed the Stroop task. They found that both speaker groups lengthened word and vowel duration under the Stroop condition. Additionally, both speaker groups showed greater consonant-vowel duration and transition extent during the Stroop condition, providing evidence that speech rate decreases under high arousal conditions.

One may argue that increased lip aperture variability indices in the Stroop condition may be a reflection of slower speaking rate. However, in the current study the Stroop condition followed the baseline condition for all speakers. Both speaker groups showed increased speaking rates during the Stroop task, most likely a result of repeated practice. Despite increased familiarity with the stimuli in the Stroop condition, lip aperture variability increased for both groups. Thus, we can conclude that changes in speaking rate do not mirror changes observed in the lip aperture variability index between groups under different speaking conditions.

LA variability index measures from children were significantly higher than those from adults across all tasks in this study, indicating that children aged 9 and 10 reproduce speech behaviors with more variability and/or more flexibility than adults. Increased variability in child speakers may be adaptive, and may indicate flexibility to adapt to changing biomechanics as the child's speech motor system matures (Walsh & Smith, 2002). This result is consistent with literature in speech development that indicates that variability in speech variables (e.g., timing, velocity, amplitude measures) typically decreases with maturation (see Walsh & Smith, 2002, for review). Many authors attribute the fact that speech motor variability decreases with age to maturation of the cognitive-linguistic planning processes required for speech produc-

tion (Smith & Mclean-Muse, 1986; Smith & Goffman, 2004; Smith & Zelaznik, 2004). It is possible that changes in autonomic response to mental loads show similar developmental trends. In fact, in the current study, children showed greater responses on all autonomic measures when compared to adults. This area is understudied in the literature, with few researchers describing the development of autonomic responses in children. Shields (1983) provided a review. Heart rate, as well as heart rate variability, shows a consistent decrease with age (Wenger & Ellington, 1943, as cited in Shields, 1983). In terms of electrodermal activity, Aiello, Nicosia, and Thompson (1979) found that resting SCL decreased across 4th, 8th, and 11th graders. Shields (1983) asserted that SCR is positively associated with intelligence and "cognitive maturity" in children. These observations indicate that autonomic responses change with maturation, which may parallel advances in language skills and reductions in speech motor variability during maturation.

Linguistic Complexity Affects Speech Motor Coordination

Our results corroborate previous findings that increasing length and syntactic complexity are associated with increased speech movement variability for children and adults. While Maner et al. (2000) and Kleinow and Smith (2000) used developmental norms (Brown's stages) as a metric of syntactic complexity, in the current study we use the presence or absence of relative clauses to manipulate complexity. Interestingly, conclusions regarding links between syntactic complexity and speech motor variability in children appear robust to methodological differences in complexity manipulations. Differences in results between Kleinow and Smith (2000) and the current study do exist, however. Kleinow and Smith (2000) reported that the speech motor variability of typically fluent adults was not affected by changes in length or complexity. In the current study increases in both length (complexity held constant) and complexity (length held constant) contributed to significant increases in speech motor variability in both children and adults. The methodological differences between Kleinow and Smith's (2000) study and the current work may explain this disparity. It is likely that the inclusion of a subject relative clause rendered the sentences in the current study more difficult than those in the Kleinow and Smith (2000) study. The present findings suggest that even the speech motor systems of typically fluent adults are affected by increases in linguistic complexity when syntactic structures are more difficult.

The utterances designed to control for length in the Kleinow and Smith (2000) study were not grammatically complete sentences. Rather, the target phrase was

embedded in repeated syllables and in automatic speech to increase length without adding to complexity. No length effects were noted based on these manipulations (Kleinow & Smith, 2000). In the current study, significant effects of length were noted for both children and adults. It is likely that length effects were not observed in the Kleinow and Smith (2000) study because the target phrase was not connected in any meaningful way to the words that preceded and followed it. In the current study, the length controls were well-formed English sentences, potentially providing more valid results concerning the relationship between utterance length and speech motor coordination.

Though sentence length was associated with significantly accelerated heart rate and reduced finger pulse volume values for both children and adults, neither children nor adults showed effects of syntactic complexity on any of the autonomic variables recorded. This was a particularly surprising finding, as several studies have shown that speaking, as a cognitive process, is also associated with increased sympathetic activity. Lynch et al. (1980) reported that diastolic and systolic blood pressure increased rapidly and significantly during conversation. Increases in autonomic nervous system response have also been reported while participants speak in front of groups (Baldwin & Clevenger, 1980), while speakers address strangers or high-status experimenters (Brondolo, Karlin, Alexander, Bobrow, & Schwartz, 1999; Long, Lynch, Machiran, Thomas, & Malinow, 1982), and when loud and/or rapid speech is required (Friedmann, Thomas, Kulick-Ciuffo, Lynch, & Suginohara, 1982). Additionally, Peters and Hulstijn (1984) and Weber and Smith (1990) concluded that speaking is associated with increases in autonomic activity for both adults who do and do not stutter. It is possible that our small sample size, and corresponding low statistical power, limited our ability to find significant effects of linguistic complexity on autonomic variables. Additionally, some interactions may have been significant with a larger sample.

Changes in autonomic variables with increases in utterance length can easily be explained in terms of increased demands on the respiratory system to produce longer utterances. Thus, negative findings linking linguistic complexity and arousal could be interpreted as support for the model in which both linguistic complexity and autonomic arousal affect the speech motor system, but that these variables do not interact. It is likely, however, that the experimental task requiring repetitions of a target may have masked any autonomic effects associated with linguistic complexity due to potential habituation effects (Barry & Sokolov, 1993). Statistical analyses of the autonomic measures associated with only the first production of each sentence indicated that increases in length and complexity are, in fact, associated with increases in sympathetic

nervous system responses. An experimental challenge then, is to reconcile the repeated behaviors needed for the movement coordination analysis with the production of novel stimuli to avoid physiological habituation, as autonomic activity remains a potential mediator between linguistic processing and speech motor control.

SUMMARY

The primary goal of this experiment was to examine the interactions between autonomic arousal, linguistic processing, and speech motor coordination in adults and children. The lip aperture variability (LA Coordination Index) across multiple repetitions of sentences that varied in length and syntactic complexity was calculated under low- and high-arousal conditions. Children had significantly higher coordination indices across all speaking tasks, indicating more variable speech motor coordination. Increases in syntactic complexity and utterance length were associated with increases in the speech motor coordination variability as well as increases in sympathetic nervous system response in both speaker groups. Using a different method to manipulate syntactic complexity, as well as a different metric of speech motor coordination, this study is the first to corroborate similar findings reached by Maner et al. (2000) in typically fluent children and adults. Importantly, the present study is the first to report a clear effect of linguistic complexity on speech motor output that is independent of utterance length effects. Finally, there was a significant effect of Stroop task (associated with increases in arousal) on the speech motor coordination of both adults and children, indicating that high arousal levels can influence speech motor control in both adults and children. This experiment is one of very few studies to measure links between cognitive loading and ANS activity in children, and the first to measure autonomic effects on speech motor control in children and adults. In terms of the hypotheses considered in the introduction about the ANS as a mediator of the effects of linguistic complexity on motor output, our results do not support this model. Rather, the effects of utterance length and complexity appear to operate independently of increases in autonomic arousal. Given consideration of the potential effects of adaptation, we suggest a need to develop a speech motor coordination index that does not require repetition of the linguistic stimuli.

Determining potential interactions between cognitive-linguistic processes, autonomic process, and speech motor control has direct implications for the study of communication disorders. For example, increased autonomic activity has been implicated as a contributing factor in stuttering (Weber & Smith, 1990) as well as certain

voice disorders (Nichol, Morrison, & Rammage, 1993). It is possible that such clinical populations will respond differently to cognitive load. Finally, establishing such interactions may further test the assumptions of multi-factorial models of speech production and disorders.

NOTES

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