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Abstract

Purpose: We examined the effects of physiological arousal on speech motor control and speech motor practice effects in preschool-age children who do (CWS) and do not stutter (CWNS).

Method: Participants included 18 CWS (mean age 4 years, 5 months) and 18 age- and gender-matched CWNS. The participants repeated a phrase "buy bobby a puppy" interspersed with viewing pictures from the International Affective Picture System under two experimental conditions speaking after viewing pictures with (1) negative, and (2) neutral valence. Participants' lip movements were tracked using Optotrak system. The spatio-temporal index (STI; Smith, Goffman, Zelaznik, Ying & McGillem, 1995) and mean utterance duration were calculated to examine speech motor control and speech motor practice effects. Skin conductance level was measured during the experimental conditions to assess participants' physiological level of arousal.

Results: Preschool-age CWS demonstrated greater speech movement variability across all conditions and trials than CWNS. Further, the younger participants produced more variable articulatory movements than the older participants. Participants' speech movement variability did not significantly differ between the negative and neutral experimental conditions and the level of physiological arousal did not have a significant effect on it. There was a non-significant trend of decrease in speech movement variability across the repeated trials in both groups. Last, CWS and CWNS did not differ in their mean utterance duration, suggesting that their articulation rate was similar across all conditions and trials.

Conclusions: Our findings indicate that, compared to preschool-age CWNS, CWS demonstrate less mature speech motor control. However, present findings do not support the hypothesis that CWS benefit less from motor practice relative to CWNS. Given that our conditions elicited

similar levels of arousal in the participants, future research is needed to examine whether physiological arousal disrupts speech motor control in preschool-age children potentially contributing to disruptions of speech fluency and the development of stuttering.

Stuttering typically emerges in preschool years during the time when children undergo rapid development of their speech, language, and emotional regulatory processes. The concurrent development of these various processes has contributed to the formulation of a multifactorial perspective on the etiology and persistence of stuttering (Conture & Walden, 2012; Smith & Weber, 2017). This perspective suggests that speech motor control, linguistic as well as emotional processes may act together to contribute to the onset of stuttering and its progression. However, despite the possibility that emotional processes (i.e., emotional reactivity and regulation) are thought to contribute to childhood stuttering, the effects of emotion on speech motor control in young children who do and do not stutter have not been studied to date. Thus, the purpose of the present study was to investigate potential effects of emotional processes on speech motor control and speech motor practice effects in preschool-age children who do (CWS) and do not stutter (CWNS). What follows is an overview of the effects of emotional processes on kinematic and acoustic parameters of speech, and a description of physiological measures of emotional processes. Further, we consider the potential role of physiological reactivity during speaking on the development of stuttering, leading to our research questions and hypotheses.

Effects of stress on speech motor control. Empirical evidence from fields outside of communication sciences and disorders points to potential ways emotional processes can affect speech motor control and motor learning involved in establishing fluent speech. It is proposed that emotional processes affect motor control through pathways in the central nervous system that involve amygdala and basal ganglia loops (Alm, 2004). Alm (2004) further suggested that the effect of emotion on speech motor control may be related to emotionally-induced variations of dopamine release, a hypothesis that is yet to be confirmed. Multiple studies showed that stress alters learning and memory (e.g., McEwen, 1999, 2000) and can affect performance in learning tasks as well as motor performance in humans (Maki & McIlroy, 1996) and rodents (Metz, Schwab & Welzl, 2001; Metz, Jadavji, & Smith, 2005). Studies in sport psychology and music performance (e.g., Yoshie, Kudo, Murakoshi, & Ohtsuki, 2009) have uncovered debilitating impact of pre-competition anxiety on skilled performance. Given that speaking is a skilled motor activity, it has been proposed that stress (with the associated increased autonomic nervous system arousal, as reviewed below) can disrupt speech motor control (Adams, 1971; Kleinow & Smith, 2006; Van Riper, 1963).

Accordingly, variations in speech motor control in stressful speaking situations have been reported in both normally fluent and stuttering adults (Arenas & Zebrowski, 2013; Caruso, Chodzko-Zajko, Bidinger, & Sommers, 1994; van Lieshout, Ben-David, Lipski, & Namasivayam, 2014; Jackson, Tiede, Beal, & Whalen, 2016), with the latter group showing greater effect of stress on speech than the former. Additionally, for adults who stutter, an increase in stuttering frequency and severity has been observed when speaking under feared or stressful conditions, such as a challenging job interview (Caruso, Chodzko-Zajko, Bidinger, & Sommers, 1994; Brundage, Graap, Gibbons, Ferrer, & Brooks, 2006). These findings, however, cannot be extended to young children who stutter as their speech motor control and other skills are not yet mature and undergo development well into school-age years (Smith, 2006; Walsh & Smith, 2002; Walsh, Smith & Weber-Fox, 2006). Despite that, the effects of stress on speech kinematics have not been studied in children who stutter.

The effect of stress on speech motor control may be more pronounced in children given that their speech motor control (Smith & Zelaznik, 2004) and emotional regulatory processes are less developed than those of adults. Given the evidence that children who stutter may lag behind their normally fluent peers in speech motor control development (Smith, Goffman, Sasisekaran,

& Weber-Fox, 2012; MacPherson & Smith, 2013), they may be especially susceptible to the effects of concurrent emotional processes. Of note are also the research findings indicating that preschool-age CWS may be more emotionally reactive and less able to regulate their emotions than preschool-age CWNS (Eggers, Luc, & Van den Bergh, 2010; Howell et al., 2004; Johnson, Walden, Conture, & Karrass, 2010; Karrass, Walden & Conture, 2006; Ntourou, Conture & Walden, 2013), which could make CWS more vulnerable to higher emotional arousal, potentially affecting their speech motor control. Clinically, there are numerous reports of increased disfluency in stuttering children when they experience emotional arousal, even when it is positive in nature. This association also has some empirical support (e.g., Arnold, Conture, Key, & Walden, 2011). Importantly, recent longitudinal research indicates that preschool-age children who subsequently developed chronic stuttering (relative to those preschoolers who recovered) exhibit more variable speech articulation (Ambrose et al., 2015; Usler, Smith, & Weber, 2017), and stronger and more frequent negative emotions (such as fear) per parent report (Ambrose et al., 2015). Thus, the association between emotional arousal and speech articulation in children who stutter warrants further research.

Effects of stress on speech motor practice.

Motor practice is the initial stage of motor learning. Its effects are typically defined as within-session improvement in motor control, which could be indexed by a decrease in movement variability and duration (Schmidt & Wrisberg, 2004). Research has shown that children's motor movements, including those for speech production, require a certain degree of practice to become adult-like (Green, Moore, Higashikawa, & Steeve, 2000; Green & Nip, 2010; Smith, 2006; Smith & Zelaznik, 2004). Typically-fluent school-age children have been shown to learn novel nonwords by decreasing their speech movement variability and duration with within-session practice (Sasisekaran, Smith, Sadagopan, & Weber-Fox, 2010; Walsh, Smith & Weber-Fox, 2006). Limited research evidence is available on whether CWS differ in speech motor practice effects compared to CWNS (Sasisekaran, Basu & Weathers, 2019). Sasisekaran and colleagues (2019) reported no differences in speech motor practice effects between school-age CWS and CWNS, with both groups displaying a nonsignificant trend of decreased articulatory variability in nonword repetition over within-session practice. Although considerable progress has been made in identifying differences in speech motor control and emotional reactivity in CWS and CWNS, very little information is available on how these processes may interact in typically fluent children (Shirkey & Manning, 1987) and no studies have examined the intersection of these processes in CWS.

Evidence from neuroscience research points to potential mechanisms by which stress affects motor control. Brain regions involved in motor control (including the motor cortex, cerebellum and basal ganglia) have a high number of stress hormone receptors (Metz, 2007), which makes them particularly susceptible to the effects of stress. This link is supported by evidence from animal and human research showing that stress can adversely affect skilled motor performance and motor learning (for review see Metz, 2007). Considering the evidence that stuttering is a neurodevelopmental multifactorial disorder with speech motor, linguistic, and temperamental domains implicated in its development (e.g., Smith & Weber, 2017), it is crucial to examine how emotional factors interact with speech motor factors and whether emotional factors promote or interfere with speech motor learning in developing systems of CWS.

Vocal parameters associated with stress. Compared to the relative paucity of research on the effects of stress on speech motor control, there is body of research on vocal markers of stress (for review see van Puyvelde, Neyt, McGlone, & Pattyn, 2018; Scherer & Moors, 2019).

Psychological stress of cognitive and emotional nature has been shown to affect vocal parameters such as vocal loudness, fundamental frequency and speech rate.

Research findings regarding the effects of stress on adult speech rate are somewhat inconsistent. Some reported a decrease in speech rate under stress conditions (Hicks, 1979 as cited in Kirchhubel, Howard & Stedmon, 2011), whereas other research indicated that speech rate increased with stress (Hecker, Stevens, von Bismarck, & Williams, 1968, Karlsson et al. 2000, Siegman 1993). Other research did not identify any association between stress and speaking rate (Scherer et al. 2002). Specific to adults who stutter, a recent study found no effect of a social stress condition (i.e., delivering a speech in front of a video camera) on the speaking rate. Similarly, typically fluent adults in the study also did not change their speaking rate in response to the social stress condition. However, across all (stress and no-stress) conditions, adults who stutter were speaking faster than typically fluent adults (Bauerly, Jones, Miller, 2019). To our knowledge, only one study examined the effect of emotion on speech rate in preschool-age children who do and do not stutter (Erdemir, Walden, Jefferson, Choi, & Jones, 2018). In that study, the articulatory rate during a narrative was examined in three groups of preschool-age participants: those preschool-age CWS who subsequently developed chronic stuttering, those CWS who subsequently recovered from stuttering and their peers who did not stutter. To elicit an emotional arousal, the participants watched a 4-min video clip designed to elicit negative emotion (such as fear). The study results indicated that only those preschool-age CWS who subsequently developed chronic stuttering had a significantly slower articulation rate (compared to the other two groups) following presentation of the negatively valenced video clip. Articulatory rates of CWS who later recovered from stuttering and CWNS were not affected by the video. Given the somewhat inconsistent findings on whether speech rate increases or decreases during emotional arousal and limited information regarding effects of physiological arousal on speech rate in preschool-age children, we examined the effects of arousal on mean utterance duration for the repeated productions of the same utterance in preschool-age CWS and CWNS in our study.

Neurophysiological correlates of emotional arousal. Neurophysiologic research indicates that activity of the autonomic nervous system is particularly relevant to emotional arousal, cognitive effort and stress (Bradley, Codispoti, Cuthbert, & Lang, 2001; Lang, 2014). The sympathetic branch of the autonomic nervous system activates in response to environmental stimuli (such as psychological, emotional or cognitive stressors) to prepare the body for action. Although the activity of the sympathetic branch of the autonomic nervous system is not sensitive to the valence of the stimulus (e.g., pleasant or unpleasant), it is sensitive to the level of arousal elicited by the stimulus (e.g., being calm or being excited or stressed). The sympathetic nervous system activity can be reliably indexed by measuring the degree of electrodermal activity (Bouscein, 2012). The electrodermal activity measurements are traditionally divided into tonic activity, such as skin conductance level (SCL), and phasic activity, such as frequency of skin conductance responses (SCR). Whereas tonic activity is measured continuously and is associated with the overall state of physiologic arousal, phasic activity (or phasic response) is associated with discrete fluctuations in electrodermal activity elicited by specific stimuli. Both tonic and phasic measures are used to objectively assess the degree of speaker's emotional arousal elicited by certain task.

Purpose of the study. There is a paucity of research on the effects of physiological arousal on speech motor control. The existing research is inconclusive and limited to adults. Further, few studies have objectively assessed or reported whether the emotion elicitation conditions did, in fact, elicit increased arousal in the participants. The present study was carried out to address this gap in knowledge and examine the effects of physiological arousal on speech motor control and speech motor practice effects (the latter defined as the immediate improvement in speech motor control as a result of practice) in preschool-age children who do and do not stutter. We posed the following research questions:

1. Do preschool-age CWS have greater articulatory movement variability than CWNS overall and under emotionally arousing conditions?
2. Do preschool-age CWS have longer utterance duration than CWNS overall and under emotionally arousing conditions?
3. Do preschool-age CWS have a lesser speech motor practice effect than CWNS overall and under emotionally arousing conditions?

We hypothesized that increased physiological arousal during emotionally arousing conditions would result in more variable articulatory coordination in both CWS and CWNS, but that the effects of increased physiological arousal on coordination variability would be significantly greater in CWS compared with their typically developing peers. Given research indicating that an increase in coordination variability may reflect more variable neuromotor commands to achieve movement goals (Wohlert & Smith, 2002), we, like others (MacPherson & Smith, 2013), interpreted an increase in coordination variability as decreased stability in the speech motor system. We also hypothesized that increased physiological arousal during emotionally arousing conditions would be associated with longer utterance duration, particularly for CWS. Findings consistent with these predictions would indicate that the speech motor system of CWS is particularly susceptible to physiological arousal during emotionally arousing conditions, which may contribute to the development of stuttering and to disruptions of speech fluency characteristic of stuttering.

Method

Thirty-six preschool-age children (age range: 38-69 months) and their caregivers completed the study. Participants included 18 CWS (16 boys and 2 girls; mean age 53.89 months or 4 years, 5 months) and 18 CWNS (16 boys and 2 girls; mean age 54.39 months or 4 years, 6 months). CWS were 15 Caucasians, two African Americans, and one child with more than one reported race. CWNS were 16 Caucasians, and two children with more than one reported race. All were paid volunteers recruited through an advertisement in a monthly parent magazine circulated throughout Syracuse and an e-mail advertisement sent to Syracuse University employees. The study procedures were approved by the Syracuse University Institutional Review board. Informed consent by parents and verbal assent by children were obtained.

General Procedures

Data collection procedures took place during two visits to the Syracuse University Stuttering Research Laboratory. Participants' speech, language and fluency skills were assessed during the first visit. The experimental tasks were conducted during the second visit. At the first visit to the lab, participants initially engaged in a spontaneous conversation with the examiner. The conversation was centered on age appropriate toys and was elicited during free play. This conversation was transcribed and analyzed for the frequency of occurrence of stuttered and normal disfluencies (please see the section titled Group classification). Then, the "Sounds in Words" subtest of the Goldman-Fristoe Test of Articulation-2 (GFTA-2; Goldman & Fristoe, 2000) was administered to assess children's articulation. Clinical Assessment of Language Fundamentals – Preschool 2 (CELF-P2; Wiig, Secord & Semel, 2004) was administered to assess participants' overall language ability. Table 1 provides a summary of participants' speech and language characteristics. Lastly, all participants passed a bilateral pure tone hearing screening at 20dB loudness level (frequencies of 1000, 2000 and 4000Hz were tested). Caregivers of all participants reported that their children had normal vision, English as the primary language and no history of neurological diseases or diagnosed speech-language disorders apart from stuttering (for the participants in the CWS group).

Group classification. Participants were assigned to the CWS group if they (a) produced 3% or more of stuttered disfluencies (i.e., sound/syllable repetitions, sound prolongations, or monosyllabic whole-word repetitions) in a 300 word conversational speech sample obtained during free play between the child and the examiner (Tumanova, Conture, Lambert, & Walden, 2014), (b) scored 10 or greater on the Stuttering Severity Instrument-4 (SSI-4; Riley, 2009), and (c) their caregivers expressed concern regarding stuttering. Children whose parents expressed no concern about their child's fluency and who produced less than 3% stuttered disfluencies were assigned to CWNS group. The frequency of stuttered disfluencies was calculated using percent words stuttered. Stuttering frequency and severity characteristics for CWS are presented in Table 2.

Experimental Tasks and Conditions. Figure 1 provides an overview of the time course of the experimental conditions. First, to establish a pre-experimental baseline for each participant's resting skin conductance level, participants viewed an animated screensaver of a three-dimensional fish tank for four minutes. The screensaver contained minimal action and had been previously successfully used to establish baseline levels of skin conductance activity in preschool-age children (e.g., Jones et al., 2014; Tumanova & Backes, 2019). Next, the participants completed two experimental conditions: (1) speaking after viewing pictures with negative valence, and (2) speaking after viewing pictures with neutral valence. The order of the condition presentation (negative vs. neutral) was counterbalanced between the participants. To physiologically validate the levels of emotional arousal that are targeted in each of the experimental conditions, skin conductance level and phasic skin conductance responses were measured during the baseline (screensaver viewing) and two experimental conditions (neutral picture viewing and negative picture viewing conditions). Each experimental condition included two trials, comprising a total of 4 trials for the entire experiment (2 conditions x 2 trials per condition).

One trial lasted approximately 4 minutes. Figure 2 shows the sequence of events for a trial. During each of the four trials participants viewed five pictures (either negative or neutral in valence depending on the condition). The pictures were presented on a 27-inch (diagonal size) computer screen positioned approximately 6 feet away at a participant's eye level directly in front of them. A fixation cross preceded picture presentation to center participant's gaze at the center of the screen. Each of the pictures was displayed at 75% screen size (approx. 20 inches in diagonal size) for 3 seconds. After viewing each picture, the participant was prompted to repeat the target phrase three times following presentations of a voice recording of the target phrase, which was pre-recorded by a female native speaker of American English. This procedure was repeated five times during a trial (see figure 2). For each trial, five different pictures were presented and three repetitions of the target phrase were elicited for a total of 15 repetitions per trial. This number of repetitions per trial was chosen based on the existing research in limb and speech motor control that suggests that the majority of kinematic changes are evidenced early in practice, within 30 repetitions of the task (e.g., Namasivayam & van Lieshout, 2008). After the completion of the first trial participants were given a short break (approx. 2 minutes) during which they were given a sticker. Then, the participants completed the second trial of the first condition. Finally, to re-establish the baseline for autonomic activity measurement before the second condition the participants viewed the animated screensaver again for four minutes. After the second baseline was completed, the second experimental condition was presented (as shown in figure 1).

Speech stimuli. The target phrase that participants repeated was “Buy Bobby a puppy”. This phrase was chosen because it had been previously employed to study speech motor coordination in preschool-age children (e.g., Smith & Zelaznik, 2004). The phrase contained a large proportion of bilabial consonants to ensure that upper and lower lips would be engaged during articulation and preschool-age children produced it without difficulty. Only fluent, error-less productions of the target phrase were included in the analysis. It should be noted that all of the CWS were able to repeat the phrase fluently; there were no instances of stuttering on this phrase throughout the experiment.

Emotion elicitation stimuli. To elicit emotional arousal a set of age-appropriate color photographs from the International Affective Picture System (IAPS; Lang, Bradley & Cuthbert, 2005, 2008) was shown to participants. The IAPS was used because it is widely implemented in experimental investigations of emotion and attention worldwide. The subjective, psychophysiological, behavioral and neurophysiological reactions that are elicited by the affective stimuli in the IAPS have been well documented (for review see Lang & Bradley, 2007).

Each IAPS photograph has an emotional valence rating made by men and women, some pictures have also been rated by children (McManis, Bradley, Berg, Cuthbert, & Lang, 2001). Each IAPS photograph is standardized on the basis of ratings of pleasure/displeasure and level of arousal it elicits. To ensure that the pictures elicit predicted emotional responses in participants, ten pictures with negative valence and ten neutral pictures were selected based on event-related potential studies of children's emotional processing using these specific pictures as stimuli (Hajcak & Dennis, 2009; Solomon et al., 2012). Five IAPS pictures were presented per one trial of a given condition. Two sets of IAPS pictures in each condition were balanced for their valence and arousal ratings and for content. An example of a picture with negative emotional valence is that of a threatening animal, such as an attacking snake. An example of a neutral valence picture is that of household objects, such as a plate. Table 3 and 4 provide detailed information on the IAPS pictures used in this study.

Experimental setup. At the second visit to the lab, participants were seated in front of a computer screen. A microphone was positioned approximately one foot from participant's mouth to record the target phrases spoken by the participants. E-prime software (2016, Psychology Software Tools, Inc.) was used to visually present picture stimuli and a voice recording of the target phrase that participants repeated. E-prime was also used to time-lock picture presentations to the recorded physiological responses.

Movement data of upper lip, lower lip and the jaw during the child's speech was collected using the Optotrak camera system (Northern Digital, Waterloo, Ontario, Canada), an optoelectronic position measurement system that tracks the three-dimensional motion of infrared-emitting diodes (IREDs). IREDs were attached to the participant's upper lip, lower lip, jaw and head. Upper and lower lip markers were attached to the skin using a medical adhesive tape. To correct for potential artifact from movements of the head, participants wore modified transparent sport goggles that had IREDs attached to them. Data collection guidelines established by Smith and colleagues were followed (e.g., Smith, Johnson, McGillem & Goffman, 2000;

Kleinow & Smith, 2006; Smith & Zelaznik, 2004). The Optotrak 16 channel A/D converter allowed the kinematic signal to be acquired with time-aligned audio.

Electrodermal activity was acquired using Biopac MP150 hardware system (Biopac Systems, Inc.) and recorded and analyzed using AcqKnowledge software (ver. 4.3 for PC, Biopac). Hypoallergenic electrodes were attached to the skin of the distal phalanges of the index and middle finger of the left hand (Venables & Christie, 1980) for acquisition of electrodermal activity throughout the experimental tasks. We also collected electrocardiogram data from each of the participants. These data were used to address separate research questions about group differences in emotional reactivity and regulation, not included in this report.

Standardized procedures for electrodermal activity recordings were implemented (Boucsein et al., 2012). The electrodes were connected to a Biopac GSR100C skin conductance amplifier. The electrodermal activity (expressed in microSiemens, μS) was sampled at 1,250 Hz with the gain set at 10 μS/V and a low-pass filter at 1 Hz and subsequently downsampled for the analysis. The data were visually inspected during data collection to monitor for any instances of artifacts. In rare cases when participants pulled off the electrodes during the data collection resulting in intervals of missing data, the “Connect Endpoints” math function of the Biopac AcqKnowledge 4.3 software was then used to correct these artifacts. No more than five percent of the total data for any one condition were corrected using this procedure. To measure tonic arousal, mean skin conductance level was calculated for the baselines and the picture viewing and speaking conditions using AcqKnowledge 4.3 software from a continuous electrodermal activity signal. Following common procedures (e.g., Boucsein et al., 2012) skin conductance level was calculated after phasic responses were removed from the signal. The law of initial values (Wilder, 1958) suggests that baseline skin conductance level values could influence a skin conductance level in other experimental conditions. Thus, we calculated residualized change score for skin conductance level in the two experimental conditions (neutral picture viewing and negative picture viewing conditions) by regressing the skin conductance level during these conditions to the skin conductance level during the first baseline (Llabre, Spitzer, Saab, Ironson, & Schneiderman, 1991; Jones et al. 2014; Zengin-Bolatkale, Conture & Walden, 2015). The residualized skin conductance level change score served as an independent variable (covariate) in the subsequent analyses to examine whether the level of physiological arousal during each of the experimental conditions had an effect on the outcome variables.

Dependent Measures. The spatiotemporal index (STI), a measure of speech coordination developed by Smith and her colleagues (e.g., Smith, Goffman, Zelaznik, Ying & McGillem, 1995) served to quantify speech motor control ability and speech motor practice effects. The STI reflects the degree to which repeated performance of a task produces movement trajectories that converge on a single pattern. Children produce less stable movement trajectories, as reflected in higher values of the STI (e.g. Smith & Goffman, 1998); whereas adults produce more stable movement trajectories as reflected in lower STI values. The STI was chosen due to several advantages including: (1) it has been widely used in published research studies of speech motor control and practice of both young children and adults, (2) the entire movement waveform is used to characterize the observed pattern of behavior and its variability, (3) no assumptions are made about the units of speech production, which is a debated issue.

The kinematic data from the target phrases were processed in custom MATLAB routines (The Mathworks, 2016) following the procedures established by Smith and colleagues (Smith, Goffman, Zelaznik, Ying & McGillem, 1995). In brief, we listened to each repetition of the target phrase and included only those productions that contained no errors or moments of stuttering in the STI calculations. To calculate the STI, the onsets and offsets of each target phrase (e.g., the opening movement following the first [b] in "buy" and the closing movement for the last [p] in "puppy") were extracted from lower lip movement signal. The movement trajectories for the target phrase were visually inspected and the onsets and offsets of each phrase were manually selected using the peak velocity for the two articulatory gestures (for further details, see Walsh, Mettel, & Smith, 2015). An algorithm then established the minimum value, determining the point at which velocity crossed zero within a 100-ms window of the point selected by the researcher. We measured the movement variability within that entire time window. The movement trajectories for the selected segments were then linearly time normalized by setting each extracted record to a time base of 1,000 points and using a cubic spline algorithm to interpolate between points. These segments were then amplitude normalized by setting the mean to 0 and the standard deviation to 1. The rationale for time and amplitude normalization was to rule out differences in rate and loudness; the goal was to assess spatiotemporal patterning. After normalizing the data, standard deviations were computed at 2% intervals in relative time across the extracted records and then summed. The sum of the 50 standard deviations is the STI; a higher value reflects greater movement variability (Smith & Goffman, 1998).

Mean duration of the target phrase, "Buy bobby a puppy", served as the second dependent measure. Duration of each spoken target phrase repeated by the participant was assessed from the same kinematic record as those used to calculate the STI. Movement duration was computed as the time (in seconds, with the precision to the thousandth decimal place) of each original (non-normalized) target phrase, starting at the first [b] in "buy" and ending at the last [p] in "puppy".

Statistical Analyses

Statistical analyses of the data were performed in IBM SPSS version 24 statistics software using linear mixed-effects models (Oleson, Brown, McCreery, 2019). The mixed model design included Group (CWS, CWNS) as a between-participant fixed factor, and Condition (neutral picture viewing, negative picture viewing) and Trial (first, second) as two within-participant fixed factors. Participants' age measured in months and skin conductance level residualized change score were included as independent variables in the model design. We separately examined two outcome variables, speech movement variability (STI for the lower lip) and mean utterance duration.

The mixed-effects model allowed us to test for the overall Group effect, Condition effect and the interaction between Group and Condition to answer Research Question 1. We also tested for the interaction between Group, Condition and Trial to answer Research Question 2. The alpha level was set to .05.

Results

Tests for the main effects and interactions from the linear mixed-effects regression model were completed using Type III *F* tests. Different interaction terms were tested within the model to address Research Question 1 and Research Question 2. Model results for the lower lip STI show that there was neither a significant Group X Condition interaction ($F_{1,133} = .163$, $p = .687$), nor Group X Condition X Trial interaction ($F_{1,89} = .053$, $p = .984$), but there was a significant main effect of Group ($F_{1,133} = 6.001$, $p = .016$). This indicates that CWS produced more variable articulatory movements than CWNS in all conditions and trials. There was also a significant main effect of Age ($F_{1,133} = 7.468$, $p = .007$), indicating that the younger participants produced more variable articulatory movements than the older participants (see Figure 3). The effects of

Condition ($F_{1,133}$ = .066, p = .798) and Trial ($F_{1,133}$ = 1.963, p = .163) were not significant in the model indicating that there is not enough evidence to conclude that participants' speech motor control differs between the negative and the neutral picture viewing conditions or between the first and the second trial of the conditions. The skin conductance level also did not have a significant effect ($F_{1,132}$ = 2.059, p = .154) on the lower lip STI (see Figure 4). See Figure 5 for descriptive statistics for lower lip STI for CWS and CWNS across Conditions and Trials. See Table 5 for group mean lower lip STI and effect sizes for the group difference in lower lip STI across the conditions and trials.

These results indicate that preschool-age CWS have a greater speech movement variability under all conditions (both neutral and negative) than CWNS. This conclusion is supported by medium to large effect sizes for the between-group difference in articulatory variability. Further, the two speaking conditions had similar effects on both CWS and CWNS. There was a non-significant trend of decrease in lower lip STI across repeated trials, indicating improvement in movement stability over short-term practice in both groups. Notably, there was a large effect size for the group difference in the lower lip STI in the second trial of negative condition, which warrants further study.

Model results for the second dependent variable, mean utterance duration, showed neither significant Group X Condition interaction ($F_{1,133}$ = .023., p = .880), nor Group X Condition X Trial interaction ($F_{1,88}$ = .238, p = .870). Also, neither Group effect ($F_{1,133}$ = .285, p = .594), nor Condition effect ($F_{1,133}$ = .925, p = .338), nor Trial effect ($F_{1,133}$ = .044, p = .835) were observed. See Figure 6 for descriptive statistics for the mean utterance duration for CWS and CWNS across Conditions and Trials. See Table 6 for group mean utterance duration and effect sizes for the group difference in mean utterance duration across the conditions and trials. Given that the participants repeated the same phrase, we can draw conclusions about their articulation rate from their mean utterance duration. These results indicate that CWS and CWNS did not differ in their articulation rate across all conditions and trials. Small effect sizes for between-group differences in utterance durations further support this conclusion.

Ancillary Analyses

Physiological arousal during picture viewing.

To better understand participants' physiological arousal during neutral and negative picture viewing, an ancillary analysis was performed to examine condition differences in physiological arousal. Recall that neutral and negatively-valenced IAPS picture stimuli were presented to our participants to elicit physiologic arousal, which was objectively measured by the skin conductance level. The order of the condition presentation (neutral vs. negative picture viewing) was counterbalanced between the participants (half of the participants in each group saw the neutral pictures first and half saw the negative pictures first). However, by counterbalancing the order of the conditions, it is possible that negative stimuli have residual effects on subsequent neutral stimuli. To examine whether the two conditions elicited a different level of arousal in our participants, we conducted a linear mixed model analysis. The model included Condition and Trial as two within-participant (repeated measures) factors and one between-participant fixed factor, the order of condition presentation (neutral vs. negative pictures first). The order of condition presentation was included to examine whether viewing negative pictures first had a priming effect on the level of arousal in the subsequent neutral condition. Skin conductance level in the first baseline was included as a covariate, given that it could influence the skin conductance level in other experimental conditions (Wilder, 1958). The linear mixed effects model tested for the main effect of Condition, and a Condition X Order of Condition Presentation effect.

Model results for the skin conductance level as the dependent variable showed a significant Condition X Order of Condition Presentation interaction ($F_{1,71}$ = 8.127, p = .001) in the absence of a significant Condition effect ($F_{1,138}$ = .036, p = .851). There was also a significant effect of baseline skin conductance level ($F_{1,138}$ = 260.356, p < .0001), which was expected. A follow up analysis for the interaction effect indicated that the participants who were presented with neutral pictures first, had a significantly lower skin conductance level in the neutral condition (t = -2.676, p = 0.009, β = -2.185) and a significantly higher skin conductance level in the negative condition (t = 2.989, p = 0.004, β = 2.583) than the participants who viewed negative pictures first. These results suggest that although all participants increased their skin conductance level from baseline to the picture viewing conditions (see Figure 7), seeing negative pictures first had a priming effect on preschool-age children's physiological arousal. Those participants who saw negative pictures first may have been primed to respond to neutral pictures with a higher level of arousal. As we discuss in the caveats below, although we included physiologic level of arousal in our models examining the two outcome variables (speech movement variability and utterance duration), this priming effect may have influenced our results and should be considered for future studies.

Discussion

The purpose of the present study was to examine the effects of physiological arousal on speech movement variability and speech movement practice effects of preschool-age CWS and CWNS. To the best of our knowledge, this is the first kinematic study to examine the effects of physiological arousal on speech motor control in very young CWS and CWNS. We examined the articulatory kinematics in children as young as 3 years of age, which is very close to the typical age of stuttering onset. We also objectively verified whether our emotional conditions elicited increased arousal in the participants and whether their physiological arousal had an effect on speech movement variability.

The present study resulted in four main findings. First, preschool-age CWS exhibited greater speech movement variability in perceptually fluent speech across all conditions and trials than CWNS. Second, participants' speech motor control did not significantly differ between the negative and the neutral picture viewing conditions and the level of physiological arousal did not significantly predict speech movement variability. Third, although we did not see a significant speech motor practice effect from trial 1 to trial 2 of the target phrase repetition, both groups showed a non-significant trend of decrease in lower lip STI across the repeated trials, indicating improvement in movement stability over short-term practice. Last, the younger participants produced more variable articulatory movements than the older participants. These findings are discussed below.

Higher speech movement variability in CWS

We hypothesized that increased physiological arousal during an emotionally arousing condition, such as viewing of pictures with negative valence, would result in more variable articulatory coordination in both CWS and CWNS, but that the effects of increased physiological arousal on coordination variability would be significantly greater in CWS compared with their typically developing peers. Our results do not support these hypotheses. These results suggest several possible interpretations. Unlike adults, it may be that preschool-age children are not prone to the effects of physiological arousal. Another possibility is that the physiological arousal elicited in our participants was not strong enough to interfere with speech motor control. Indeed, research suggests that that the response to stress depends on the nature, intensity and duration of a stressor following an “inverted U-shape function” (Sapolsky, 2015). Further, the stress reaction in response to a psychological stressor is not determined solely by the actual presence of the stressor and is affected by the individual’s cognitive and psychological evaluation of it, resulting in an individualization of the stress response (Kirchhubel, Howard, & Stedmon, 2011). The IAPS pictures used to evoke a stress response in this study may not have elicited a strong enough level of arousal to interfere with speech motor control. Acknowledging that it can be challenging to select stimuli that are potent enough to elicit sufficient stress, yet ethically appropriate to use with children, future studies should try different approaches to evoking arousal strong enough to impact speech motor control.

Whereas the level of physiological arousal did not affect speech motor control in our participants, we found that that preschool-age CWS exhibited greater speech movement variability across all conditions and trials than CWNS. Following the existing research, we interpreted greater speech movement variability as a sign of less mature speech motor control (MacPherson & Smith, 2013; Wohlert & Smith, 2002). Our findings add to the published evidence that preschool-age CWS tend to have more variable speech motor control and may lag their typically fluent peers in speech motor development (Ambrose, Yairi, Loucks, Seery, & Throneburg, 2015; MacPherson & Smith, 2013; Walsh, Mettel, & Smith, 2015; Usler, Smith, & Weber, 2017). The greater speech movement variability observed in CWS has also been observed in adults who stutter (Smith, Sadagopan, Walsh & Weber-Fox, 2010; Namasivayam & van Lieshout, 2011; Frisch, Maxfield & Belmont, 2016). Specific to preschool-age CWS, the large degree of variability within this population suggests the existence of subgroups (e.g., Schwartz & Conture, 1988; Seery, Watkins, Mangelsdorf, & Shigeto, 2007; Yairi, 2007). The developmental course of stuttering itself, with many preschool-age CWS outgrowing stuttering and some developing chronic stuttering, has provided the evidence for the existence of subgroups (Yairi & Ambrose, 2005). Accordingly, speech movement variability has been examined for its relevance to recovery or persistence of stuttering in young children. Usler and colleagues (2017) reported that CWS who developed chronic stuttering (at the age of 5 to 7 years) had higher speech movement variability than CWNS and those CWS who, by the age of 5 to 7 years, no longer stuttered. Descriptive analysis and visual examination of our data suggest that the variability in speech movement coordination is larger in preschool-age CWS than in CWNS. We conjecture that this variability may be due to the presence of subgroups within our sample of CWS. Given that our participants were preschool-age children, it is likely that some of the CWS in our sample will outgrow stuttering whereas others will not. However, given the cross-sectional design of this study, we cannot make any conclusions regarding the persistence or recovery from stuttering among our participants and its association with speech movement variability.

Our findings that the younger participants produced more variable articulatory movements than the older participants align with the Speech Motor Skill Approach (van Lieshout, Hulstijn, & Peters, 2004). These results suggest that young children's speech motor coordination becomes more stable and the movement variability decreases with maturation, and lend support to the growing number of studies that demonstrated a decrease in speech movement variability in children through maturation and development (Goffman & Smith, 1999; Green, Moore, Higashikawa, & Steeve, 2000; Green, Moore, & Reilly, 2002; Grigos & Patel, 2007; Smith, & Goffman, 1998; Walsh & Smith, 2002).

We also hypothesized that increased physiological arousal during emotionally arousing conditions would be associated with longer utterance duration, particularly for CWS. Our data, however, did not support this hypothesis: we found no significant differences in utterance duration between viewing pictures with neutral or negative valence. Neither were there differences between CWS and CWNS's mean utterance duration, suggesting that the observed significant differences in articulatory variability between CWS and CWNS were not driven by speech rate differences. However, similar to the observed speech kinematic trends, descriptive analysis of our data suggests greater variability in CWS's articulatory rate. Only one published study examined the effect of emotion on articulatory rate with consideration to the existing subgroups of preschool-age CWS (Erdemir et al., 2018). The participants were grouped into those who subsequently developed chronic stuttering, those who subsequently recovered from stuttering and those who did not stutter at any point in their life. Erdemir et al. reported that only those preschool-age CWS who subsequently developed chronic stuttering had a significantly slower articulation rate following presentation of a negatively valenced video clip. Articulatory rates of CWS who later recovered from stuttering and CWNS were not affected by the video. Considering these findings, it is possible a higher variability of articulatory rate in our CWS participants could be due to the existence of subgroups within CWS, a hypothesis that must await further study.

Non-significant trend of improved movement stability over short-term practice

In the context of the simple repetition tasks used in this study, the present findings do not support the hypothesis that CWS benefit less from motor practice relative to CWNS. In general, both groups showed a trend of decreased speech movement variability over two trials (i.e., practice effects). These findings are similar those of Sasisekaran et al. (2019) who examined speech motor practice effects in school-age CWS and CWNS using a non-word repetition task. Similar to our results, Sasisekaran et al. reported no differences in speech motor practice effects between school-age CWS and CWNS, with both groups displaying a non-significant trend of decreased articulatory variability over within-session practice.

Our participants, however, did not show a significant speech motor practice effect from the first to the second trial of the target phrase repetition. Two factors may have influenced these results. The first factor is the relative ease of the target phrase. We chose the target phrase so that our younger, 3-year-old, participants could repeat it successfully. The task in our study was linguistically simple and likely not very taxing to our participants (all them were able to repeat our target sentence without apparent difficulty). The second factor is the number of repetitions participants completed. Guided by prior research, we chose to examine the practice effect over the 15 productions of the target phrase (Namasivayam & van Lieshout, 2008). Given the relative ease of the phrase, the learning may have occurred with fewer repetitions than what we expected. For example, Walsh et al. (2006) reported that typically fluent school-age children showed a reduced articulatory variability between the first and the second five trials of non-word repetition within a single practice session.

Physiological arousal in picture-viewing conditions

Our two experimental conditions elicited a similar level of physiological arousal, which was unexpected. Although all participants increased their skin conductance level from baseline to the picture viewing conditions, there was no significant difference in physiological arousal between the negative and neutral condition. Given that the picture stimuli have been validated for school-age children and adults by numerous research studies, we speculated that the order of condition presentation could have affected the participant's response to the pictures (recall the order of condition presentation was counterbalanced). Our data confirmed this speculation as we observed the priming effect of seeing the negative pictures before the neutral pictures on preschool-age children's level of physiological arousal. However, IAPS pictures have not been validated for preschool-age children. This leaves a possibility that preschool-age children may find neutral IAPS images more stimulating and respond to them differently from school-age children and adults.

Limitations

This study presents the first attempt to induce emotional arousal in preschool-age children for purposes of studying their speech kinematics and it is not without limitations. One of the limitations was that those participants who saw negative pictures first, had a significantly higher physiological arousal during the subsequent neutral condition. This priming effect may have influenced the lack of significant difference in speech motor control between the two conditions and should be considered for future studies.

Another limitation of the study has to do with the number of repetitions we used to assess speech motor practice effects, combined with the relative ease of the target phrase. We chose the target phrase so that our younger, 3-year-old, participants could repeat it successfully. Based on prior research (Namasivayam & van Lieshout, 2008), we chose to examine the practice effect over the 15 productions of the target phrase. Given the relative ease of the phrase, the learning may have occurred within fewer repetitions than what we had expected. Future studies should consider using a more challenging phrase or examining the changes in STI over fewer repetitions (e.g., Walsh et al., 2006).

Conclusions

The study provides an initial examination of the effects of emotional arousal on speech motor control and speech motor practice effects in preschool-age CWS and CWNS. We used an objective psychophysiological measure to assess the level of arousal and its effects on articulatory kinematics in children as young as 3 years of age, which is very close to the typical age of stuttering onset.

Our findings indicate that, compared to preschool-age CWNS, CWS demonstrate less mature speech motor control. Present findings do not support the hypothesis that CWS benefit less from motor practice relative to CWNS. Our results also do not support the hypothesis that the speech motor system of CWS is particularly susceptible to the effects of physiological arousal. However, given that the two picture viewing conditions elicited a similar level of physiological arousal in the participants, future research is needed to examine whether CWS and CWNS differ in their speech motor control under low vs. high arousal conditions.

Considering that people who stutter and their families often report a higher frequency of stuttering when the speaker is excited, nervous or upset (situations associated with increased physiological arousal) we must determine how emotional factors interact with speech motor factors and whether emotional factors promote or interfere with speech motor control and learning in developing systems of CWS. This line of work is clinically significant in its potential to elucidate situational variability of stuttering and inform our assessment and treatment of stuttering in children.

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References

Adams, J. A. (1976). Issues for a closed-loop theory of motor learning. In *Motor Control* (pp. 87-107). Academic Press.

Alm, P. A. (2004). Stuttering and the basal ganglia circuits: a critical review of possible relations. *Journal of Communication Disorders*, *37*(4), 325-369.

Ambrose, N. G., Yairi, E., Loucks, T. M., Seery, C. H., & Throneburg, R. (2015). Relation of motor, linguistic and temperament factors in epidemiologic subtypes of persistent and recovered stuttering: Initial findings. *Journal of Fluency Disorders*, *45*, 12-26.

American Speech Language Hearing Association (2015). Practice Portal/Childhood Hearing Screening. Retrieved from http://www.asha.org/Practice-Portal/Professional-Issues/Childhood-Hearing-Screening/.

Anderson, G. S., Metz, G., & Andersen, J. (2019). The Impact of Acute Stress Physiology on Skilled Motor Performance: Implications for Policing. *Frontiers in psychology*, *10*, 2501.

Arenas, R., & Zebrowski, T. (2013). The effects of autonomic arousal on speech production in adults who stutter: A preliminary study. *Speech, Language and Hearing*, *16*(3), 176-185.

Arnold, H. S., Conture, E. G., Key, A. P., & Walden, T. (2011). Emotional reactivity, regulation and childhood stuttering: A behavioral and electrophysiological study. *Journal of Communication Disorders*, *44*(3), 276-293.

Bauerly, K., Jones, R., & Miller, C. (2019). Effects of social stress on autonomic, behavioral, and acoustic parameters in adults who stutter. *Journal of Speech, Language, and Hearing Research*, 62, 2185-2202.

Boucsein, W. (2012). *Electrodermal activity*. Springer Science & Business Media.

Boucsein, W., Fowles, D., Grimnes, S., Ben-Shakhar, G., Roth, W., Dawson, M., & Filion, D. (2012). Publication recommendations for electrodermal measurements. *Psychophysiology*, *49*(8), 1017-1034.

Bradley, M., Codispoti, M., Cuthbert, B. & Lang, P. (2001). Emotion and motivation: I. Defensive and appetitive reactions in picture processing. *Emotion*, *1*, 276-298.

Brundage, S. B., Graap, K., Gibbons, K. F., Ferrer, M., & Brooks, J. (2006). Frequency of stuttering during challenging and supportive virtual reality job interviews. *Journal of Fluency Disorders, 31(4)*, 325-339.

Caruso, A. J., Chodzko-Zajko, W. J., Bidinger, D. A., & Sommers, R. K. (1994). Adults Who Stutter: Responses to Cognitive Stress. *Journal of Speech, Language, and Hearing Research*, *37*(4), 746-754.

Conture, E. G., & Walden, T. (2012). Dual diathesis-stressor model of stuttering. *Theoretical Issues of Fluency Disorders*, 94-127.

Erdemir, A., Walden, T. A., Jefferson, C. M., Choi, D., & Jones, R. M. (2018). The effect of emotion on articulation rate in persistence and recovery of childhood stuttering. *Journal of Fluency Disorders, 56*, 1-17.

Frisch, S. A., Maxfield, N., & Belmont, A. (2016). Anticipatory coarticulation and stability of speech in typically fluent speakers and people who stutter. *Clinical linguistics & phonetics*, *30*(3-5), 277-291.

Goffman, L. & Smith, A. (1999). Development and differentiation of speech movement patterns. *Human Perception and Performance, 25*, 1-12.

Goldman, R., & Fristoe, M. (2000). Goldman-Fristoe Test of Articulation-Second Edition (GFTA-2). Circle Pines, MN: American Guidance Services, Inc.

Green, J., Moore, C., Higashikawa, M., & Steeve, R. (2000). The physiological development of speech motor control: Lip and jaw coordination. *Journal of Speech, Language and Hearing Research, 43*, 239-255.

Green, J., Moore, C., & Reilly, K. (2002). The sequential development of jaw and lip control for speech. *Journal of Speech, Language and Hearing Research, 45*, 66-79.

Grigos, M. I., & Patel, R. (2007). Articulator movement associated with the development of prosodic control in children. *Journal of Speech, Language, and Hearing Research, 50, 119-130*.

Hajcak, G., & Dennis, T. A. (2009). Brain potentials during affective picture processing in children. *Biological Psychology, 80(3)*, 333-338.

Hecker, M., Stevens, K., von Bismarck, G. & Williams, C. (1968). Manifestations of task-induced stress in the acoustic speech signal. *Journal of the Acoustical Society of America, 44*, 993-1001.

Jackson, E. S., Tiede, M., Beal, D., & Whalen, D. H. (2016). The Impact of Social–Cognitive Stress on Speech Variability, Determinism, and Stability in Adults Who Do and Do Not Stutter. *Journal of Speech, Language, and Hearing Research, 59(6)*, 1295-1314.

Jones, R. M., Buhr, A. P., Conture, E. G., Tumanova, V., Walden, T. A., & Porges, S. W. (2014). Autonomic nervous system activity of preschool-age children who stutter. *Journal of Fluency Disorders, 41*, 12-31.

Karlsson, I., Banziger, T., Dankovicová, J., Johnstone, T., Lindberg, J., Melin, H. et al. (2000). Speaker verification with elicited speaking styles in the VeriVox project. *Speech Communication, 31*, 121-129.

Kirchhübel, C., Howard, D. M., & Stedmon, A. W. (2011). Acoustic correlates of speech when under stress: Research, methods and future directions. *International Journal of Speech, Language and the Law*, *18,* 75-98.

Kleinow, J., & Smith, A. (2006). Potential interactions among linguistic, autonomic, and motor factors in speech. *Developmental Psychobiology*, *48*(4), 275-287.

Lang, P. J. (2014). Emotion's response patterns: The brain and the autonomic nervous system. *Emotion Review, 6(2)*, 93-99.

Lang, P., & Bradley, M. (2007). The International Affective Picture System (IAPS) in the study of emotion and attention. *Handbook of emotion elicitation and assessment*, pp. *29-46*.

Lang, P., Bradley, M., & Cuthbert, B. N. (2005). International Affective Picture System (IAPS): Affective ratings of pictures and instruction manual. Technical Report no. A-6. University of Florida, Gainesville, FL.

Lang, P.J., Bradley, M.M., & Cuthbert, B.N. (2008). International affective picture system (IAPS): Affective ratings of pictures and instruction manual. Technical Report A-8. University of Florida, Gainesville, FL.

Llabre, M. M., Spitzer, S. B., Saab, P. G., Ironson, G. H., & Schneiderman, N. (1991). The reliability and specificity of delta versus residualized change as measures of cardiovascular reactivity to behavioral challenges. *Psychophysiology*, *28*(6), 701-711.

Lucero, J. C., Munhall, K. G., Gracco, V. L., & Ramsay, J. O. (1997). On the registration of time and the patterning of speech movements. *Journal of Speech, Language, and Hearing Research*, *40*(5), 1111-1117.

MacPherson, M. K., & Smith, A. (2013). Influences of sentence length and syntactic complexity on the speech motor control of children who stutter. *Journal of Speech, Language, and Hearing Research*, *56*(1), 89-102.

Maki, B. E., & Mcllroy, W. E. (1996). Influence of arousal and attention on the control of postural sway. *Journal of Vestibular Research*, *6*(1), 53-59.

Metz, G. A. (2007). Stress as a modulator of motor system function and pathology. *Reviews in the Neurosciences, 18*, 209-222.

Metz, G. A., Schwab, M. E., & Welzl, H. (2001). The effects of acute and chronic stress on motor and sensory performance in male Lewis rats. *Physiology & Behavior*, *72*(1), 29-35.

Metz, G. A., Jadavji, N. M., & Smith, L. K. (2005). Modulation of motor function by stress: a novel concept of the effects of stress and corticosterone on behavior. *European Journal of Neuroscience, 22(5)*, 1190-1200.

McEwen, B. S. (1999). Stress and hippocampal plasticity. *Annual Review of Neuroscience*, *22*(1), 105-122.

McEwen, B. S. (2000). The neurobiology of stress: from serendipity to clinical relevance. *Brain Research*, *886*(1), 172-189.

McEwen, B. S. (2007). Physiology and neurobiology of stress and adaptation: central role of the brain. *Physiological reviews*, *87*(3), 873-904.

Namasivayam, A. K., & van Lieshout, P. (2008). Investigating speech motor practice and learning in people who stutter. *Journal of Fluency Disorders*, *33*(1), 32-51.

Namasivayam, A. K., & Van Lieshout, P. (2011). Speech motor skill and stuttering. *Journal of Motor Behavior*, *43*(6), 477-489.

Oleson, J. J., Brown, G. D., & McCreery, R. (2019). The evolution of statistical methods in speech, language, and hearing sciences. *Journal of Speech, Language, and Hearing Research*, *62*(3), 498-506.

Riley G. (2009). Stuttering Severity Instrument for Children and Adults Fourth Edition (SSI-4). Pro-Ed, Austin, TX.

Sapolsky, R. M. (2015). Stress and the brain: individual variability and the inverted-U. *Nature Neuroscience*, *18*(10), 1344-1346.

Sasisekaran, J., Basu, S., & Weathers, E. J. (2019). Movement kinematics and speech accuracy in a nonword repetition task in school-age children who stutter. *Journal of Communication Disorders*, *81*, 105916.

Sasisekaran, J., Smith, A., Sadagopan, N., & Weber-Fox, C. (2010). Nonword repetition in children and adults: Effects on movement coordination. *Developmental Science*, *13*, 521-532.

Scherer, K. R., Grandjean, D., Johnstone, T., Klasmeyer, G., & Banziger, T. (2002). Acoustic correlates of task load and stress. *Proceedings from Seventh International Conference on Spoken Language Processing*.

Scherer, K. R., & Moors, A. (2019). The emotion process: Event appraisal and component differentiation. *Annual Review of Psychology*, *70*, 719-745.

Schwartz, H. D., & Conture, E. G. (1988). Subgrouping young stutterers: Preliminary behavioral observations. *Journal of Speech, Language, and Hearing Research*, *31*(1), 62-71.

Seery, C. H., Watkins, R. V., Mangelsdorf, S. C., & Shigeto, A. (2007). Subtyping stuttering II: Contributions from language and temperament. *Journal of Fluency Disorders, 32(3)*,

Shirkey, E. A., & Manning, W. H. (1987). The effects of emotional arousal and increased speaking rate on children's newly learned /r/ productions. *Journal of Communication Disorders, 20(1)*, 51-60.

Siegman, A.W. (1993) Paraverbal correlates of stress: implications for stress identification and management. In L. Goldberger and S. Breznitz (Eds.) Handbook of Stress. Theoretical and Clinical Aspects, pp 274–299. (2nd Ed.) New York: The Free Press

Smith, A. (2006). Speech motor development: Integrating muscles, movements, and linguistic units. *Journal of Communication Disorders, 39*(5), 331-349.

Smith, A., & Goffman, L. (1998). Stability and patterning of speech movement sequences in children and adults. *Journal of Speech, Language, and Hearing Research*, *41*(1), 18-30.

Smith, A., Goffman, L., Sasisekaran, J., & Weber-Fox, C. (2012). Language and motor abilities of preschool children who stutter: evidence from behavioral and kinematic indices of nonword repetition performance. *Journal of Fluency Disorders*, *37*(4), 344-358.

Smith, A., Goffman, L., Zelaznik, H. N., Ying, G., & McGillem, C. (1995). Spatiotemporal stability and patterning of speech movement sequences. *Experimental Brain Research, 104(3)*, 493-501.

Smith, A., Johnson, M., McGillem, C., & Goffman, L. (2000). On the assessment of stability and patterning of speech movements. *Journal of Speech, Language, and Hearing Research*, *43*(1), 277-286.

Smith, A., & Kleinow, J. (2000). Kinematic correlates of speaking rate changes in stuttering and normally fluent adults. *Journal of Speech, Language, and Hearing Research, 43(2)*, 521-536.

Smith, A., Sadagopan, N., Walsh, B., & Weber-Fox, C. (2010). Increasing phonological complexity reveals heightened instability in inter-articulatory coordination in adults who stutter. *Journal of Fluency Disorders, 35(1)*, 1-18.

Smith, A., & Weber, C. (2017). How stuttering develops: The multifactorial dynamic pathways theory. *Journal of Speech, Language, and Hearing Research, 60(9)*, 2483-2505.

Smith, A., & Zelaznik, H. N. (2004). Development of functional synergies for speech motor coordination in childhood and adolescence. *Developmental Psychobiology, 45*(1), 22-33.

Solomon, B., DeCicco, J. M., & Dennis, T. A. (2012). Emotional picture processing in children: an ERP study. *Developmental Cognitive Neuroscience, 2(1)*, 110-119.

Tumanova, V., & Backes, N. (2019). Autonomic Nervous System Response to Speech Production in Stuttering and Normally Fluent Preschool-Age Children. *Journal of Speech, Language, and Hearing Research, 62*(11), 4030-4044.

Tumanova, V., Conture, E. G., Lambert, E. W., & Walden, T. A. (2014). Speech disfluencies of preschool-age children who do and do not stutter. *Journal of Communication Disorders, 49*, 25-41.

Usler, E., Smith, A., & Weber, C. (2017). A lag in speech motor coordination during sentence production is associated with stuttering persistence in young children. *Journal of Speech, Language, and Hearing Research, 60*(1), 51-61.

van Lieshout, P., Ben-David, B., Lipski, M., & Namasivayam, A. (2014). The impact of threat and cognitive stress on speech motor control in people who stutter. *Journal of Fluency Disorders, 40,* 93-109.

van Lieshout, P., Hulstijn, W., & Peters, H. (2004). Searching for the weak link in the speech production chain of people who stutter: A motor skill approach. In B. Maassen, R. D. Kent, H. Peters, P. van Lieshout & W. Hulstijn (Eds.), Speech motor control in normal and disordered speech (pp. 313-357). Oxford: Oxford University Press.

van Puyvelde, M., Neyt, X., McGlone, F., & Pattyn, N. (2018). Voice stress analysis: a new framework for voice and effort in human performance. *Frontiers in psychology*, *9*, 1994.

Van Riper, C. (1963). *Speech Correction: Principles and Methods*. Englewood Cliffs, NJ: Prentice-Hall.

Venables, P. H., & Christie, M. J. (1980). Electrodermal activity. *Techniques in Psychophysiology*, *54*(3).

Walsh, B., Mettel, K. M., & Smith, A. (2015). Speech motor planning and execution deficits in early childhood stuttering. *Journal of Neurodevelopmental Disorders, 7(1),* 7-27.

Walsh, B., & Smith, A. (2002). Articulatory movements in adolescents: Evidence for protracted development of speech motor control processes. *Journal of Speech, Language, and Hearing Research, 45,* 1119-1133.

Walsh, B., Smith, A., & Weber-Fox, C. (2006). Short-term plasticity in children's speech motor systems. Developmental Psychobiology: *The Journal of the International Society for Developmental Psychobiology,* 48(8), 660-674.

Wiig, E., Secord, W., & Semel, E. (2004). Clinical Evaluation of Language Fundamentals – Preschool 2 (CELF-P2). Psychological Corporation, San Antonio, TX.

Wilder, J. (1958). Modern psychophysiology and the law of initial value. *American Journal of Psychotherapy, 12(2)*, 199-221.

Wohlert, A. B., & Smith, A. (2002). Developmental change in variability of lip muscle activity during speech. *Journal of Speech, Language, and Hearing Research*, 45, 1077–1087.

Yairi, E. (2007). Subtyping stuttering I: A review. *Journal of Fluency Disorders, 32(3)*, 165-196.

Yairi, E., & Ambrose, N. G. (1999). Early childhood stuttering I: Persistency and recovery rates. *Journal of Speech, Language, and Hearing Research, 42(5)*, 1097-1112.

Yairi, E., & Ambrose, N. G., (2005). *Early childhood stuttering*. Austin: Pro-Ed.

Yoshie, M., Kudo, K., Murakoshi, T., & Ohtsuki, T. (2009). Music performance anxiety in skilled pianists: effects of social-evaluative performance situation on subjective, autonomic, and electromyographic reactions. *Experimental Brain Research, 199*(2), 117-126.

Zengin-Bolatkale, H., Conture, E. G., & Walden, T. A. (2015). Sympathetic arousal of young children who stutter during a stressful picture naming task. *Journal of Fluency Disorders, 46*, 24-40.

Zengin-Bolatkale, H., Conture, E. G., Key, A. P., Walden, T. A., & Jones, R. M. (2018). Cortical associates of emotional reactivity and regulation in childhood stuttering. *Journal of Fluency Disorders, 56*, 81-99.

Table 1: Summary of participants' age, speech and language characteristics by group.

Characteristic	Group	Mean	Std	N	Difference Significant
Age (months)	CWNS	54.39	8.28	18	n.s
	CWS	53.89	8.84	18	
GFTA-2 Standard Score	CWNS	107.44	9.12	18	n.s
	CWS	102.56	12.35	18	
CELF-P2 Core Language Score	CWNS	113.33	10.19	18	p = .012
	CWS	104.06	10.65	18	

Note: GFTA-2 = Goldman-Fristoe Test of Articulation – 2; CELF-P2 = Clinical Assessment of Language Fundamentals – Preschool 2; Std = standard deviation;

Table 2: Stuttering severity, assessed by the Stuttering Severity Instrument – 4 (SSI-4; Riley, 2009), for children who stutter (CWS).

Participant Number	Group	Gender	Stuttering Frequency (%)	SSI-4 score	Stuttering severity
1	CWS	F	3	12	mild
2	CWS	F	5	16	mild-moderate
3	CWS	M	7	20	moderate
4	CWS	M	4	12	mild
5	CWS	M	4	14	mild-moderate
6	CWS	M	5	12	mild
7	CWS	M	8	18	moderate
8	CWS	M	6	14	mild-moderate
9	CWS	M	8	20	moderate
10	CWS	M	7	18	moderate
11	CWS	M	9	16	mild-moderate
12	CWS	M	4	10	very mild-mild
13	CWS	M	14	20	moderate
14	CWS	M	5	14	mild-moderate
15	CWS	M	4	10	very mild-mild
16	CWS	M	6	16	mild-moderate
17	CWS	M	3	10	very mild-mild
18	CWS	M	4	16	mild-moderate

Table 3: IAPS pictures presented to the participants in Negative Condition.

Picture ID	Set	Valence	Arousal	Mean Valence	Mean Arousal	Difference Significant
Shark 1930	1	3.79 (3.91)	6.42 (7.71)			
Angry man 2120	1	3.34 (4.14)	5.18 (5.83)			
Snake 1120	1	3.79 (3.92)	6.93 (6.58)	3.17	6.01	n.s.
Soldier 9421	1	2.21 (4.19)	5.04 (5.56)			
Fire 8485	1	2.73	6.46			
Snake 1050	2	3.46	6.87			
Crying boy 2900	2	2.45	5.09			
Face painted man 2780	2	4.77 (6.00)	4.86 (5.69)	3.71	6.05	n.s.
Dog 1300	2	3.55 (4.11)	6.79 (7.11)			
Bear 1321	2	4.32	6.64			

Note: Ratings of valence and arousal taken from IAPS technical report (Lang, Bradley, & Cuthbert, 2008). Rating are based on adult respondents (females and males). For selected pictures ratings by 7-9-year-old children were available, those are included in brackets.

Table 4: IAPS pictures presented to the participants in Neutral Condition.

Picture ID	Set	Valence	Arousal	Mean Valence	Mean Arousal	Difference Significant
Towel 7002	1	4.97	3.16			
Spoon 7004	1	5.04	2			
Bowl 7006	1	4.88	2.33	4.92	2.43	n.s
Shoes 7031	1	4.52	2.03			
Book 7090	1	5.19 (5.97)	2.61 (3.11)			
Fire hydrant 7100	2	6.06 (6.06)	2.94 (2.94)			
Umbrella 7150	2	4.72 (5.89)	2.61 (2.75)			
Lamp 7175	2	4.87	1.72	5.23	2.79	n.s.
Watch 7190	2	5.55	3.84			
Chair 7235	2	4.96	2.83			

Note: Ratings of valence and arousal taken from IAPS technical report (Lang, Bradley, & Cuthbert, 2008). Rating are based on adult respondents (females and males). For selected pictures ratings by 7-9-year-old children were available, those are included in brackets.

Table 5: Descriptive statistics for Lower Lip STI and effect size for the group differences in Lower Lip STI.

Condition	Group	Mean	Std	N	Effect Size (interpretation)
Neutral Trial 1	CWNS	26.763	6.278	18	Cohen's *d* = .33, (medium)
	CWS	29.088	7.821	18	
Neutral Trial 2	CWNS	24.975	7.297	18	Cohen's *d* = .33, (medium)
	CWS	27.385	7.238	18	
Negative Trial 1	CWNS	26.936	6.136	18	Cohen's *d* = .38, (medium)
	CWS	29.532	7.501	18	
Negative Trial 2	CWNS	24.600	5.152	18	Cohen's *d* = .58, (large)
	CWS	28.404	7.677	18	

Note: Std = standard deviation

Table 6: Descriptive statistics for mean utterance duration times (in seconds) and effect size for the group differences in mean utterance duration times.

Condition	Group	Mean	Std	N	Effect Size (interpretation)
Neutral Trial 1	CWNS	1.682	.124	18	Cohen's *d* = -.17, (small)
	CWS	1.641	.309	18	
Neutral Trial 2	CWNS	1.694	.131	18	Cohen's *d* = -.03, (small)
	CWS	1.686	.298	18	
Negative Trial 1	CWNS	1.740	.172	18	Cohen's *d* = -.19, (small)
	CWS	1.695	.277	18	
Negative Trial 2	CWNS	1.697	.150	18	Cohen's *d* = .09, (small)
	CWS	1.717	.271	18	

Figure 1: Time course of the entire experiment.

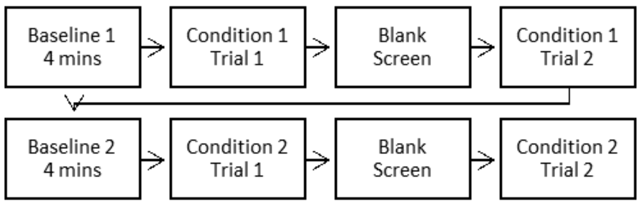

Figure 2: Time course of an individual trial.

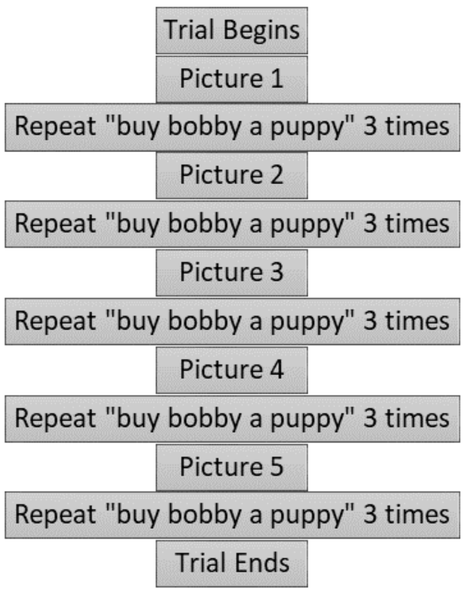

Figure 3: Association between age (months) and lower lip STI for the participants (18 CWS; 18 CWNS).

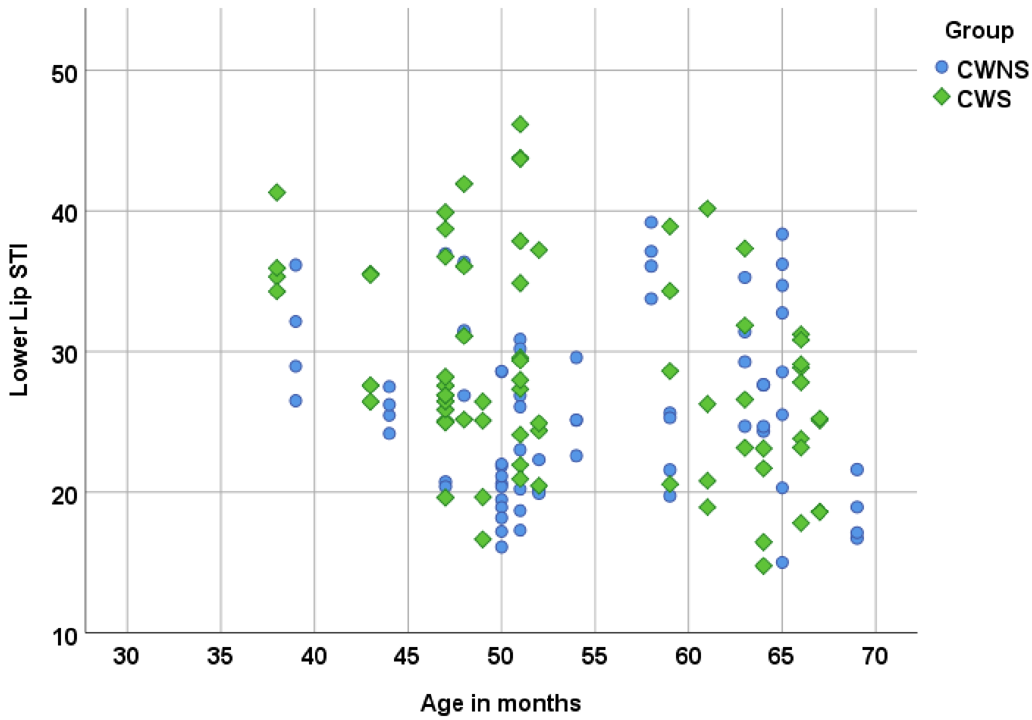

Figure 4: Association between level of physiological arousal during picture viewing and lower lip STI for the participants (18 CWS; 18 CWNS).

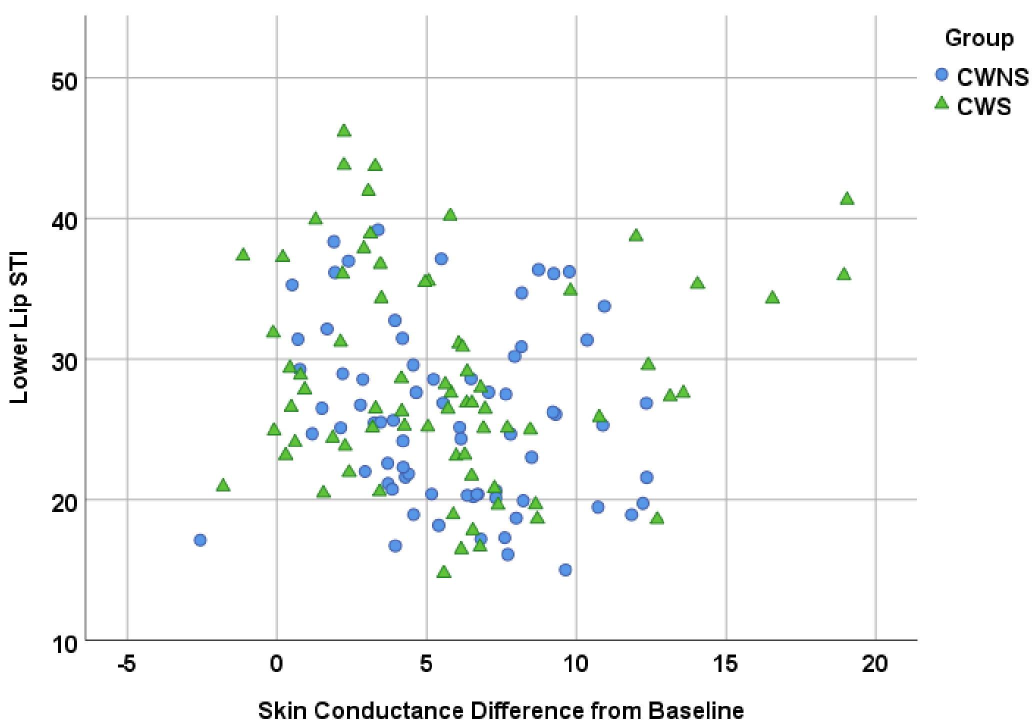

Figure 5: Tukey boxplot of lower lip STI by Group (18 CWS; 18 CWNS), Condition and Trial. The whiskers denote the minima and maxima of the data set. The box is drawn from the first quartile (25th percentile) to third quartile (75th percentile) with a horizontal line denoting the median.

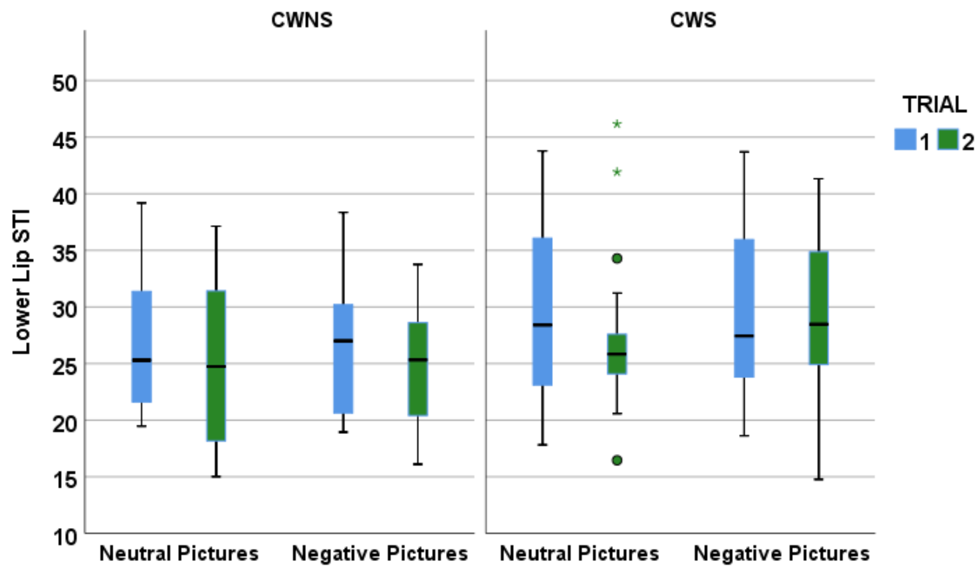

Figure 6: Tukey boxplot of mean utterance duration by Group (18 CWS; 18 CWNS), Condition and Trial. The whiskers denote the minima and maxima of the data set. The box is drawn from the first quartile (25th percentile) to third quartile (75th percentile) with a horizontal line denoting the median.

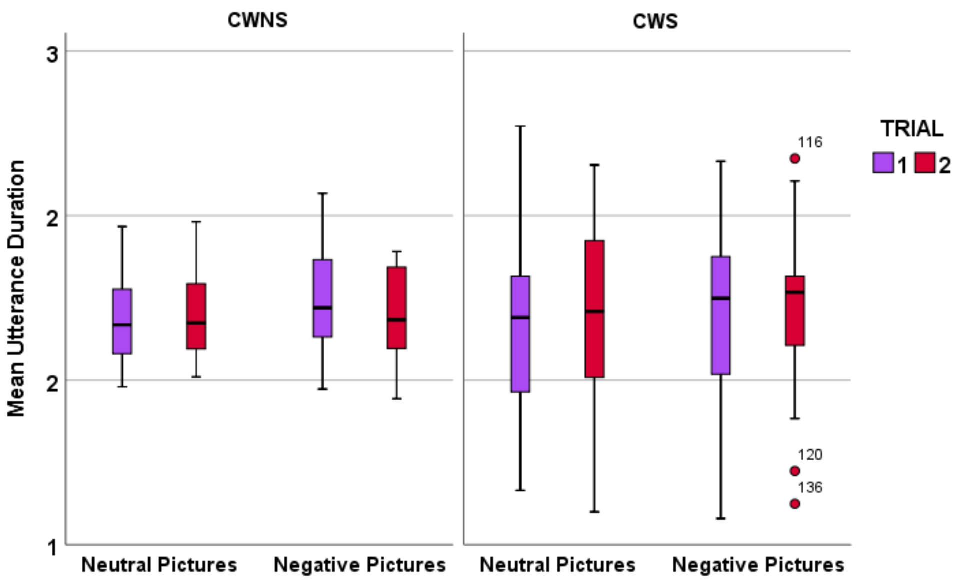

Figure 7: Mean increase in skin conductance level from baseline 1 to picture viewing conditions by order of condition presentation. Data for all participants (N = 36).