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Nonword repetition and nonword reading abilities in adults who do and do not stutter

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Abstract

Purpose—In the present study a nonword repetition and a nonword reading task were used to investigate the behavioral (speech accuracy) and speech kinematic (movement variability measured as lip aperture variability index; speech duration) profiles of groups of young adults who do (AWS) and do not stutter (control).

Method—Participants were 9 AWS (8 males, *Mean age* = 32.2, *SD* = 14.7) and 9 age- and sex-matched control participants (*Mean age* = 31.8, *SD* = 14.6). For the nonword repetition task, participants were administered the Nonword Repetition Test (Dolloghan & Campbell, 1998). For the reading task, participants were required to read out target nonwords varying in length (6 vs. 11 syllables). Repeated measures ANOVA were conducted to compare the groups in percent speech accuracy for both tasks; only for the nonword reading task, the groups were compared in movement variability and speech duration.

Results—The groups were comparable in percent accuracy in nonword repetition. Findings from nonword reading revealed a trend for the AWS to show a lower percent of accurate productions compared to the control group. AWS also showed significantly higher movement variability and longer speech durations compared to the control group in nonword reading. Some preliminary evidence for group differences in practice effect (seen as differences between the early *vs*. later 5 trials) was evident in speech duration.

Conclusions—Findings suggest differences between AWS and control groups in phonemic encoding and/or speech motor planning and production. Findings from nonword repetition *vs*. reading highlight the need for careful consideration of nonword properties.

Keywords

Stuttering; nonword repetition; nonword reading; speech accuracy movement variability

1. Introduction

Stuttering is a fluency disorder characterized by disruptions in the smooth flow of speech. A few theories have been proposed to account for stuttering within a motoric framework with a speculated core deficit in speech motor planning and/or production (e.g., Webster, 1990;

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Zimmerman; 1980; Neilson & Neilson, 1991). Evidence for such theories is available from studies of speech and limb motor performance in persons who stutter, primarily adults, that have reported delayed initiation and slower productions, higher movement variability, poor timing and coordination of intra- and inter-gestural synergies, delayed acquisition and poor retention of skilled movement sequences (Brown, Zimmermann, Linville, & Hegmann, 1990; Cross & Luper, 1979; Kleinow & Smith, 2000; Loucks, De Nil, & Sasisekaran, 2007; Max & Gracco, 2005; Namasivayam & Van Lieshout, 2008; Smits-Bandstra, De Nil, & Rochon, 2006; Zelaznik, Smith, & Franz, 1994). Furthermore, the interactions between speech motor and other processes, including stages of linguistic processing, and their implications for stuttering have resulted in explanations of stuttering within a multidimensional framework. For instance, Smith and colleagues (*Multifactorial model*; Smith; 1999; Smith & Kelly, 1997) identified stuttering as an emerging, dynamic motor disorder with complex interactions between multiple systems (including linguistic, cognitive, and emotional) that eventually destabilize the speech motor system. In the present study, a nonword repetition task and a nonword reading task were used to investigate the underlying processes in adults who stutter (AWS) with specific focus on the functioning of the speech motor system and its response to increased task complexity.

1.1 Nonword Repetition *vs*. Reading: Underlying Processes

The ability to repeat novel phonetic sequences is a critical skill underlying word learning. Gathercole's (2006) framework of nonword repetition involves various stages, including auditory processing (when the nonwords are presented aurally), phonological analysis, phonological storage and retrieval, speech motor planning and execution. In the present study, in addition to the traditional nonword repetition task, a nonword reading task was employed. Presumably, nonword reading involves some of the same underlying processes involved in nonword repetition, including phonological storage and retrieval, speech motor planning and execution. However, this task also eliminates some of the steps involved in the nonword repetition task while introducing a few additional steps. For instance, in contrast to the focus on auditory processing of the input in nonword repetition, nonword reading involves deciphering the orthographic code. Furthermore, the reading task shifts the focus from phonological working memory to other stages, including encoding the phonemic units from orthography and speech motor planning and execution. This task also offers an opportunity to study underlying speech motor output processes as well as the plasticity at the motor level with progressive acquisition of novel phonetic strings. Measures of speech kinematics provide a sensitive index of speech formulation and implementation (e..g, Goffman & Smith, 1999), and supplement the information provided by speech errors and/or reaction time data. Therefore, the investigation of speech kinematics associated with nonword reading performance in speech disorders, such as stuttering, will provide critical insights into the role of the speech planning and production processes involved in its causation and maintenance.

1.2 Nonword Repetition Skills in AdultsWho Stutter

Several studies have employed nonwords to investigate cognitive - linguistic and motoric processing in AWS. Some of these studies have reported behavioral measures (Byrd, Vallely, Anderson, & Sussman, 2012; Ludlow, Siren, & Zikria, 1997), while some others have reported kinematic measures of task performance (e.g., Namasivayam & van Lieshout, 2008; Smith, Sadagopan, Walsh, & Weber-Fox, 2010).

1.2.1 Behavioral studies of nonword repetition in adults—Ludlow et al. (1997) tested the speech learning abilities of adults who stutter (AWS) in a nonword repetition task. Five AWS and five typically fluent speakers repeated two lengthy nonwords multiple times. Both groups improved in production accuracy with repeated nonword production thereby showing a practice effect. However, AWS did not appear to benefit much from practice as their percentage of consonants correct was still lower than that of control participants after repeated production of the two novel words. The authors interpreted the difference in practice effect to support the assumption that AWS have phonological encoding deficits. Despite limited sample size, the Ludlow et al. study was the earliest to report of difficulties in nonword repetition in AWS.

Byrd et al. (2012) explored the phonological working memory of AWS through the use of a nonword repetition and a phoneme elision task. Participants were 14 AWS and 14 age and gender matched control participants. For the nonword repetition task, the participants had to repeat a set of 12 nonwords across four syllable lengths (2, 3, 4, and 7 syllables). For the phoneme elision task, the participants repeated the same set of nonwords at each syllable length, but with a designated target phoneme eliminated. AWS were significantly less accurate than adults who do not stutter in their initial attempts to produce the longest nonwords (i.e., 7 syllables). The groups were comparable in nonword repetition performance across the other syllable lengths. AWS also required a significantly higher mean number of attempts to accurately produce 7-syllable nonwords than adults who do not stutter. For the phoneme elision task, there was no significant interaction between group and syllable length. The authors interpreted the group differences in repeating the 7-syllable nonwords to suggest phonological working memory deficits in AWS.

1.2.2 Kinematic studies of nonword repetition in adults—Namasivayam and van Lieshout (2008) investigated the spatial and temporal variability of cyclic patterns of upper lip, lower lip, and jaw trajectories associated with multiple repetitions of two simple bisyllablic nonwords—*/bapi/* and */bipa/*—in three sessions spanning several days in five AWS and five typically fluent speakers. The aim of the study was to investigate speech motor learning and practice effects in AWS. They reported that the AWS showed reduced practice effects evident as higher movement variability and a trend for reduced strength of inter-gestural coupling between bilabial closure and tongue body gestures across days compared to control participants.

Smith, Sadagopan, Walsh, and Weber-Fox (2010) tested nonword repetition skills in 17 AWS and an equal number of fluent speakers matched in age, education, and sex. Five nonwords varying in length (1 to 5 syllables) and phonemic complexity were presented in quasi-random blocks and both behavioral (% correct) and kinematic data (speech duration and lip aperture variability index, a measure of inter-articulator coordination and stability of the upper lip, lower lip, and jaw) were reported. The groups were comparable in behavioral accuracy at each length/complexity level, but AWS exhibited higher inter-articulator coordination variability and longer speech duration compared to normally fluent adults. The group differences were larger with increasing nonword length and complexity. Furthermore, a practice effect was observed in AWS as a significant increase in the consistency of articulatory movements, and reduction in speech duration, which occurred within a session. The normally fluent adults showed an increase in speech rate on the later trials, but no changes in the consistency of inter-articulator (lower lip -upper lip - jaw) coordination. The findings were interpreted to suggest a fragile speech motor system in AWS reactive to increasing utterance length and complexity. However, based on the findings from Byrd et al. (2012), it could be argued that comparable accuracy rates in the Smith et al. (2010) study may be because the nonword stimuli were not sufficiently challenging to identify potential difficulties in AWS.

1.3 Purposes of the Present Study

Past studies have investigated nonword repetition skills in AWS and the findings have been mixed (e.g., Byrd et al., 2012; Ludlow et al., 1997; Smith et al., 2010). In the present study, in addition to testing behavioral responses to a nonword repetition task, participants were also tested for behavioral and kinematic responses to a nonword reading task. The use of the nonword reading task offers several advantages. First, by modifying the task the focus can be shifted to specific underlying sub-processes. For instance, using a nonword *reading task* is likely to reduce the dependence on phonological working memory, which is ascribed a critical role in nonword repetition. (e.g., Byrd et al., 2012). It is of potential interest to identify if AWS continue to perform poorly under conditions of reduced reliance on working memory. Second, by varying the properties of the nonwords along different dimensions the effects on task performance can be better elucidated. For instance, nonword length can potentially influence behavioral accuracy and movement kinematics in both groups. Furthermore, increasing nonword length (i.e., number of syllables) and complexity (i.e., syllable-internal phonemic composition) has been shown to have adverse effects on speech motor stability in a nonword repetition task in AWS (e.g., Smith et al., 2010). To test these assumptions, in the present study nonwords of two different lengths (6 *vs*. 11 syllables) were employed in the nonword reading task. These lengths were chosen based on earlier reports that AWS are comparable to control participants in producing nonwords up to 5 syllable length (e.g., Smith et al., 2010); any potential differences are likely to emerge in nonwords that are 7 or more syllables (Byrd et al., 2012). The 11 syllable, longer nonwords, which carry more phonemes and complex phonemic combinations, may compound any difficulties experienced by AWS. Third, studying kinematic performance in addition to behavioral responses allows the investigation of the downstream, speech motor planning and execution processes associated with task performance in both the groups. Fourth, past studies of nonword repetition have identified reduced speech motor practice and learning effects in AWS (e.g., Namasivayam & van Lieshout, 2008; Smith et al., 2010). An aim of this study was to test whether similar effects are observed in AWS in a nonword reading task.

The following research questions were addressed in the present study:

Nonword repetition:

1. Behavioral: Does the AWS group differ from the control group in the percent correct productions in a nonword repetition task?

   Kinematic measures were not obtained from the repetition task as the nonwords were not specifically designed to enable consistent identification of the start and end points required for analyzing the kinematic signal (see Section 2.2 for further details).

Nonword reading:

1. Behavioral: Does the AWS group differ from the control group in the percent correct productions in a nonword reading task?
2. Kinematic:
   - **a.** Does the AWS group differ from the control group in speech movement stability (as measured by lip aperture variability index) and movement duration (in sec) in a nonword reading task?
   - **b.** Does the AWS group differ from the control group in the extent of influence of nonword length on the behavioral and kinematic measures?
   - **c.** Does the AWS group differ from the control group in practice effects on nonword reading performance?

2. Methods

2.1 Participants

Participants were 9 AWS (8 males, *Mean* age = 32.2 years, *SD* = 14.7; *Median* age = 26.6 years; *Age range* = 20 to 65 years) and 9 age- and gender-matched non-stuttering individuals (*Mean* age = 31.8 years, *Median* age = 22.2 years, *Age range* = 20 to 65 years, *SD* = 14.6). Data from two AWS from the initial subject pool were excluded as these participants could not produce stutter-free speech during task performance. All participants were monolingual native speakers of American English. Participants were recruited through the National Stuttering Association, Minnesota chapter, and from the Julia Davis Speech and Hearing clinic at the Department of Speech-Language-Hearing Sciences, University of Minnesota. The experimental protocol was approved by the Institutional Review Board, University of Minnesota.

Participant selection was based on responses to a screening form used to rule out positive history of language, hearing, and/or neurological deficits, and current usage of drugs likely to affect the outcome of the experiment (e.g. drugs for ADHD and anti-anxiety drugs). All participants passed a binaural hearing screening at 20 dB HL at .5, 1, 2, 4, and 8 KHz. Normal articulatory structures and movements in both groups were confirmed using the *Oral Speech Mechanism Screening Evaluation-Revised* (OSMSE-R; St. Louis & Ruscello, 1987).

All participants in the AWS group had a positive treatment history. Two of the AWS had undergone treatment a year before the study was conducted. Three AWS were undergoing treatment once a week during the time the study was conducted. Reading and speech samples collected from individuals in the AWS group were used to calculate stuttering severity using the Stuttering Severity Instrument – 3 (SSI – 3; Riley, 1994). A trained research assistant coded the stuttered disfluencies (sound and syllable repetitions, monosyllabic word repetitions, prolongations, and blocks) in the samples. Accordingly, there were 5 individuals with very mild stuttering severity, one mild, and three moderate stuttering severity scores. Table 1 shows the percent disfluencies for reading and conversation and the SSI scores of participants in the stuttering group.

2.1.1 Stuttering severity reliability rating—Inter-judge reliability for the disfluency analysis was obtained between a trained research assistant and the principal investigator for four of the nine AWS participants. Interjudge syllable-by-syllable reliability rating as indexed by Cohen's Kappa (Cohen, 1960) was. 0.94.

2.1.2 Digit Span—Short-term memory was tested using the forward and backward digit span subtest of the Weschler's Intelligence test (Wechsler, 1997). Participants were presented with a series of digits in a specified order with the length of each series increasing progressively. They were required to recall the digits in each series in the pre-specified order. For the forward digit span subtest participants were required to recall the series in the forward order and for the backward digit span in the reverse order. Table 1 presents individual scores and group means for the forward and backward digit span tasks. Independent samples t-test revealed the AWS and control groups to be comparable in the forward, $t(16) = -0.13$, $p = 0.44$, and the backwards digit span tasks, $t(16) = -0.46$, $p = 0.32$.

2.2 Stimuli

2.2 1 Nonword repetition—All participants were administered the Nonword Repetition test (NRT; Dollaghan & Campbell, 1998). This test was administered as a baseline measure of the ability to perceive and repeat nonwords. The test consisted of a total of 16 nonwords varying in length (1 – 4 syllables) with the nonwords themselves containing tense vowels and consonants acquired early in development (Dollaghan & Campbell, 1998).

2.2 2 Nonword reading—Four 6-syllable nonwords and four 11-syllable nonwords formed the target stimuli. All nonwords started with /mæb/ and ended in a /bV/ syllable. This strategy was used to select consistent start and end points for the extraction of oral movement trajectories on the basis of lower lip peak opening velocities for the kinematic analysis. The 6-syllable nonwords were */mæbbeIbabʊbibo/*, */mæbtabomatiba/*, */mæbfrʊglabrʊpliba/*, and */mæbgrafroplʊkriba/*. The 11-syllable nonwords were constructed by combining the 6-syllable nonwords and included, */mæbbeIbabʊbIbotabomatiba/*, */mæbbeIbabʊbIbografroplʊkriba/*, */mæbfrʊglabrʊplibatabomatiba/*, and */mæbfrʊglabrʊplibagrafroplʊkriba/*. All nonwords carried an alternating strong - weak stress pattern. These nonwords were initially constructed to vary in complexity, for instance, */mæbbeIbabʊbibo/* is the least complex nonword while */mæbgrafroplʊkriba/* is the most complex nonword within the 6-syllable length category as these nonwords contained the least and most complex speech sound combinations. However, the complexity variation within the nonwords was not taken into consideration for analysis purposes.

2.3 Apparatus

2.3.1 Kinematic protocol—Participants were seated in front of an Optotrak Certus camera (Northern Digital, Waterloo, Ontario). This system allows tracking of movements in 3D with an accuracy better than 0.1 mm. Eight small (7 mm) infra-red light emitting diodes (IREDs) were attached to the participant's face to track articulatory movements of the upper lip, lower lip, and jaw. Four of the IREDs were mounted on a set of goggles that participants were required to wear during the experimental session. One IRED was placed in the center of the forehead. Together, these five IREDs were used to calculate the 3D head coordinate system (Smith, Johnson, McGillem, & Goffman, 2000), which allowed head movement artifact to be eliminated. The remaining three IREDs were placed one on the vermilion border of the upper lip, one on the center of the lower lip (this marker represents combined actions of the lower lip and jaw), and one on a splint taped to the jaw. The IREDs were fixed to the subject and facing the Optotrak camera such that the movements could be tracked. The IRED motions were sampled at a rate of 250 Hz. A wireless condenser microphone was placed approximately 8 cms away from the participant's mouth and a microphone receiver was used to record the acoustic speech signal. This acoustic signal was digitized on an A/D channel of the Optotrak system and was thus synchronized with the movement data. The acoustic signal was digitized at the rate of 16,000 Hz.

2.4 Procedure

2.4 1 Nonword repetition—During this task, the nonwords spoken by a native English speaker were pre-recorded and presented over loudspeakers. A trained research assistant presented the stimuli and participants were required to repeat each nonword as accurately as possible. The nonwords repeated by the participants were recorded and analyzed offline to obtain the percent of correct phonemes across the four syllable lengths.

2.4 2 Nonword reading—The research assistant and the PI monitored subjects' performance throughout this task. Participants were instructed that they would be provided with eight nonwords printed on a sheet of paper and they were required to read the nonwords at comfortable loudness upon hearing a number corresponding to each nonword. Participants in the AWS group were instructed not to use any of the fluency inducing strategies taught in treatment while reading the nonwords. Following instructions, participants were provided practice trials. During practice the eight nonwords were read by the participant twice in a block of eight each. Productions during practice were monitored and corrected for pronunciation and stress errors. Participants were instructed to use the pronunciations used during practice throughout the rest of the session. The data indicated that a majority of participants were able to achieve a minimum of one correct production within the two practice blocks. Following practice, participants were instructed that the experimenter would call out a number between one and eight and they were required to read the nonword corresponding to each number. They were asked to try and be as accurate as possible in the nonword reading task.

A total of 18 blocks were presented to all participants. Each block consisted of the eight test nonwords read out aloud once in random order. A number (between one and eight) corresponding to each nonword was presented and participants were required to read out the nonword corresponding to the number. A 10 second gap was presented between each nonword production. Within each block the order of the eight nonwords was randomized. Participant's response during each trial was recorded in order to ensure a minimum 10 correct productions of nonwords at each nonword length as these numbers of trials were minimally required for the kinematic analysis. In instances where additional blocks were required in each category, up to three additional blocks were presented such that all participants were able to obtain the required 10 correct productions of each nonword. A total of 10 correct productions was used as the minimum number of required trials as earlier studies of movement variability using LA VAR have used at least five early and five later (total 10) trials for investigating practice effects (e.g., Kleinow & Smith, 2000; Sasisekaran, Smith, Sadagopan, Weber-Fox, 2010; Walsh, Smith, Weber-Fox, 2006). In instances where more than ten correct productions were available, only the first ten trials were included in the analysis.

The procedure required both the experimenters to record the participant errors and disfluencies online during the experiment. Post-experiment, one of the experimenters listened independently to the recordings and provided offline scores of correct and error productions as well as disfluencies for the behavioral and kinematic analysis. The online coding was later compared to offline analysis of the recorded productions for inter-judge reliability. Only those productions that both raters (offline and online) agreed upon as being correct and fluent were included in the kinematic analysis.

2.5 Data Analysis

2.5.1 Behavioral analysis, nonword repetition—Nonwords produced with consonant and/or vowel errors were coded offline. Errors included substitions, omissions, additions, and distortions. Disfluenct productions, if produced correctly, were coded as correct responses. Reliability rating was obtained between the PI and the research assistant who scored the productions offline. Three participants in each group (N = 6) were re-scored for reliability purposes. A 100% agreement score was obtained in the reliability scoring. Table 1 shows the individual scores and group means (and SD) from the nonword repetition task.

2.5.2 Behavioral analysis, nonword reading—Nonwords produced with consonant and/or vowel errors were coded offline. This analysis resulted in a behavioral measure of the percent correct productions for each nonword length for both the groups. Stress errors were not coded although observation revealed that a majority of participants were able to maintain the rhythm of production as the strong syllables in each nonword were underlined in print to encourage consistent stress placement during reading. Disfluencies, including interjections, hesitations, sound or syllable repetitions, prolongations, and blocks, were included in the behavioral analysis as correct responses if participants did read the nonwords correctly, but were disfluent. Interjudge reliability ratings were computed between the online coding obtained from one of the experimenters and offline coding of the productions by a trained research assistant. For the AWS group, coding of 3.5% (N = 44) of the trials were disagreements and excluded from the behavioral and kinematic analysis. For the control group, 3.1% (N = 39) of the trials were disagreements and excluded from analysis. A total of 9.0 % (SD = 7.0) of the 6-syllable nonwords and 11.0 % of the 11-syllable nonwords (SD = 11.5) were coded as disfluencies in the AWS group. Similarly, 1.8 % (SD = 1.9) of the 6-syllable nonwords and 3.0 % (SD = 3.3) of the 11-syllable nonwords were coded as disfluencies in the control group. Disfluent trials were excluded from the kinematic analysis as these would potentially contribute to movement variability. Table 2 shows the percent correct productions and disfluencies in the nonword reading task for each subject in both groups.

2.5.3 Kinematic analysis—A detailed description of this analysis can be obtained from Smith et al. (2000) and Smith and Zelaznik (2004). The MATLAB digital signal processing software was used to simultaneously load and analyze the acoustic and kinematic data from the nonword reading task. The lip displacement signals (both upper and lower lip) were low pass filtered (cut-off 10 Hz) in both forward and backward directions using a Butterworth filter. Following this, the velocity signal was computed from the lower lip displacement signal using a three-point difference method. Following this, the lower lip displacement trajectories associated with 10 correct productions of each nonword at the two lengths were obtained by identifying the correct productions from the 18 blocks and segmenting the corresponding displacement file for each correct production. The velocity signal was used to obtain the start and end point of the lower lip displacement trajectory of each correct production. The start point for each segment was the point of peak velocity of the lower lip opening gesture for */m/* (in the first syllable */mæb/)* and the end point was the point of peak velocity of the lower lip opening gesture for */b/* (in the last syllable). The peak velocity regions were easily located by the experimenter, and a MATLAB algorithm selects the peak opening velocity within a user-defined window. Each trim corresponding to a correct production selected in the above-described manner was then reassessed for fluency and accuracy of extraction by listening to the associated audio recording.

Following extraction of the lip displacement trajectories for a set of 10 correct productions corresponding to each nonword, a multi-step analysis was performed using a custom MATLAB program. First, the lip aperture (LA) signal was obtained by a sample-by-sample subtraction of the upper lip from the lower lip superior - inferior displacement signal. This analysis was carried out to obtain the difference between the upper and lower lip IRED markers as a function of time. Second, the 10 LA trajectories for each nonword were amplitude normalized, which involved subtracting the mean and dividing by the standard deviation. Third, using interpolation, the LA trajectories were time normalized to a fixed record length of 1000 points. Fourth, standard deviation values were calculated at 50 point intervals (2% intervals in relative time) of the normalized waveform. The cumulative sum of the 50 standard deviations was computed to obtain a cumulative spatial and temporal coordinate index called lip aperture variability index (LA VAR; Smith & Zelaznik, 2004). The LA VAR is a measure of the trial-to-trial spatial and temporal variability associated with the lip aperture (LA) trajectory. This index reflects the degree of spatial and temporal variability in coordinate patterns among the upper lip, lower lip, and jaw trajectories for each nonword production. A higher LA VAR index suggests a greater degree of trial to trial variability in inter-articulatory coordination for nonword production, and vice versa. In addition to LA VAR, the speech duration in real time was computed as the total duration of the LA signal for each target production and was obtained by measuring the duration of each movement trajectory of a nonword from start to end point. Figure 1 illustrates the comparison of movement trajectories for a 6-syllable and 11-syllable nonword from an adult who stutters. In the left panel, amplitude and time normalized lip aperture trajectories for the first 5 trials of the nonwords */mæbbeIbabʊbibo/* and */mæbbeIbabʊbIbotabomatiba/* are plotted and the trajectories for the later 5 trials are plotted in the right panel. Notice the higher LA VAR score for the 11-syllable nonword compared to the 6-syllable nonword.

2.6 Statistical Analysis

Four repeated measures analyses of variance (ANOVA) were run on the data set. The aim of the first analysis was to investigate group differences between the AWS and control groups in the percent of correct productions in the nonword repetition task. For this analysis, Group (AWS, Control) was the between-subject variable while Nonword length (1 – 4 syllables) was the within-subject variable. The aim of the second analysis was to investigate group differences between the AWS and control groups in the percent of correct productions in the nonword reading task. For this analysis, Group was the between-subjects factor while Nonword length (6, 11 syllable) was the within-subjects factors. The aim of the third analysis was to investigate: a) if the groups differed in the movement variability of the nonword trajectories, and b) to investigate the effect of practice on movement variability by comparing the first 5 with the next 5 correct and fluent productions across the groups in the nonword reading task. For this analysis, Group was the between-subjects factor while Nonword length (6 *vs.* 11 syllables) and Trial (first *vs.* next 5) were the within-subjects factors. LA VAR was the dependent variable in this analysis. The aim of the fourth analysis was to investigate: a) if the groups differed in the speech duration of the nonword trajectories, and b) to investigate the effect of practice on speech duration by comparing the first 5 with the next 5 productions across the groups in the nonword reading task. For this analysis, Group was the between-subjects factor while Nonword length and Trial were the within-subjects factors. Speech duration (in s) was the dependent variable in this analysis. *Huynh-Feldt p* values are reported for all analyses (Max & Onghena, 1999). Finally, correlations were computed between average disfluencies (percent syllables stuttered) obtained from the reading and conversation samples of each participant and the three dependent measures (percent accuracy, movement variability, and speech duration) from the nonword reading task. Correlations were also computed between percent disfluencies and the magnitude (in percent) of practice-induced changes in movement variability (LA VAR from first 5 trials – LA VAR from next 5 trials/LA VAR from first 5 trials) and duration in the nonword reading task.

3. Results

3.1 Behavioral Data

3.1.1 Nonword repetition—The percent phonemes correct for the four syllable lengths in AWS and control groups are shown in Table 1. The repeated measures ANOVA revealed a non-significant Group effect, $F(1, 15) = 2.4$, $p = 0.14$. A significant main effect of Nonword length was observed, $F(3, 45) = 6.2$, $p = 0.003$, *partial eta squared* (η_p^2) = 0.29. Post-hoc comparisons (*Fisher's Least Significant Difference, LSD*) revealed a significantly lower percent of correct phonemes at the 4-syllable level compared to the 2- (p = 0.0009) and 3-syllable (p = 0.001) levels. A non-significant Group × Nonword length interaction was obtained, $F(3, 45) = 0.15$, $p = 0.89$.

3.1.2 Nonword reading—A trend toward a Group effect was observed with the AWS group (Mean = 82.6, SD = 14.2) scoring a lower percent of correct productions than the control group (Mean = 92.1, SD = 6.9), $F(1, 16) = 3.7$, p = 0.07, $\eta_p^2 = 0.19$. Figure 2 shows the data from the AWS and control groups. A significant main effect of length revealed a higher percent of correct productions for the 6-syllable nonwords compared to the 11-syllable nonwords, $F(1, 16) = 15.4$, p = 0.001, $\eta_p^2 = 0.49$. A non-significant Group × Nonword length interaction was obtained, $F(1, 16) = 2.2$, p = 0.15, $\eta_p^2 = 0.12$.

3.1.3 Mean number of blocks—Three AWS subjects received an additional one to three blocks (two AWS received 3 additional blocks and one AWS received one additional block) beyond the 18 blocks. One control subject received an additional block. Comparison of the mean number of blocks presented to participants in both groups revealed a trend for the AWS group (*Mean* = 18.8, *SD* = 1.3) to have received a higher number of blocks than the control group (*Mean* = 18.1, *SD* = 0.3), $t(16) = 1.66$, $p = 0.055$.

3.2 Kinematic Data

3.2.1 Movement variability—Table 3 and Figure 3 illustrate the differences between AWS and control groups in LA VAR scores. A significant Group effect indicated that the AWS group showed higher LA VAR scores than the control group, $F(1, 16) = 7.7$, $p = 0.01$, $\eta_p^2 = 0.32$. A significant Trial effect was observed with lower LA VAR scores for the later 5 trials compared to the early 5 trials, $F(1, 16) = 32.2$, $p < 0.001$, $\eta_p^2 = 0.67$. A significant Length effect, $F(1, 16) = 167.4$, $p < 0.001$, $\eta_p^2 = 0.91$, indicated higher LA VAR scores for the 11-syllable compared to the 6-syllable nonwords. A trend toward significance was observed in the Group × Length effect, $F(1, 16) = 4.3$, $p = 0.052$. Descriptive analysis revealed that the control group exhibited larger differences in LA VAR scores between the 6- and 11-syllable nonwords; the differences between the two syllable lengths were reduced in AWS. All other interactions were non-significant; Group × Trial, $F(1, 16) = 1.15$, $p = 0.29$; Trial × Length, $F(1, 16) = 0.0004$, $p = 0.98$; Group × Length × Trial, $F(1, 16) = 1.16$, $p = 0.29$.

3.2.2 Speech duration—The duration of the lip aperture trajectory of each nonword was also measured. Table 3 and Figure 4 illustrate the differences between AWS and control groups in speech duration. A significant Group effect indicated that the AWS group had longer speech durations than the control group, $F(1, 16) = 3.7$, $p = 0.02$, $\eta_p^2 = 0.27$. A significant Trial effect showed that the later 5 trials were shorter in duration than the early 5 trials, $F(1, 16) = 7.8$, $p = 0.01$, $\eta_p^2 = 0.32$. A significant Length effect indicated longer durations of the 11-syllable compared to the 6-syllable nonwords, $F(1, 16) = 147.4$, $p < 0.001$, $\eta_p^2 = 0.90$. A significant Group × Length interaction, $F(1, 16) = 6.6$, $p = 0.02$, $\eta_p^2 = 0.29$, and subsequent post-hoc analysis (*Fisher's LSD*) indicated that the AWS showed significantly longer speech durations than the control group for the 11-syllable nonwords ($p = 0.004$), but not for the 6-syllable nonwords ($p = 0.16$). A trend for Group × Trial interaction was observed. The control group showed a larger reduction in speech duration from the early to the later 5 trails (*Mean* difference = 0.34 ms) than the AWS group (*Mean* difference = 0.08), $F(1, 16) = 3.1$, $p = 0.09$. A trend toward significance was observed for the Length × Trial effect, $F(1, 16) = 3.1$, $p = 0.09$, where a larger reduction in speech duration was seen from the first 5 to the later 5 trials for the 11-syllable (*Mean* difference = 0.31 ms) compared to the 6-syllable nonwords (Mean difference = 0.12 ms). The Length × Trial × Group interaction was non-significant, $F(1, 16) = 3.03$, $p = 0.100$.

3.2.3 Correlations—Correlations between average disfluencies (in percent) obtained from the reading and conversation samples and the three dependent measures revealed significant positive correlations ($p < .05$) between percent disfluencies and movement duration for the 6-(*Pearson* $r = 0.70$) and 11-syllable nonwords (*Pearson* $r = 0.74$). None of the other correlations were significant. Also, a significant negative correlation was obtained between percent disfluencies and magnitude of change in LA VAR from the first 5 to the next 5 trials (*Pearson* $r = -0.71$).

4. Discussion

Earlier studies of nonword repetition have reported mixed results, particularly in the behavioral domain (e.g., Byrd et al., 2012; Ludlow et al., 1997; Smith et al., 2010), although a potential speculation based on the findings from such studies is that AWS are likely to experience greater difficulties with lengthier and complex nonwords. In the present study, participants were compared in behavioral responses (speech accuracy) to a nonword repetition and a nonword reading task where the two tasks differed in the length of the nonwords. The repetition task consisted of nonwords that were one to four syllables long while the nonwords in the reading task were six or 11-syllables long. Furthermore, the effects of the length manipulation on kinematic (movement variability and speech duration) profiles of both groups were studied in the nonword reading task. In addition, the effects of practice (repeated production) on speech kinematics were also investigated in the reading task by comparing the early 5 correct and fluent productions to the later 5 productions in both the groups.

In response to the questions raised earlier in the introduction, the findings from the present study demonstrated that: a) the groups were comparable in the percent phonemic errors in the nonword repetition task; b) the AWS showed a trend toward a difference in the percent of accurate productions in the nonword reading task; c) the fluent and correct productions of AWS showed higher movement variability and longer speech durations than the control group in the nonword reading task; and d) group differences in practice effects on movement variability were not obtained although some preliminary evidence for such effects was seen in the AWS as a negative correlation between percent disfluencies and the magnitude of change in movement variability with practice thereby suggesting the need to consider individual differences. A trend toward a group difference in practice effect on movement duration was observed. The findings are interpreted based on the different sub-processes underlying nonword repetition and reading.

4.1 Behavioral Performance

4.1.1 Nonword repetition—In the present study the groups were compared in percent accuracy in both nonword reading and nonword repetition tasks. While the repetition task included nonwords that were one to four syllables long, the nonword reading task included 6-and 11-syllable nonwords. Findings from nonword repetition revealed the groups to be comparable in the percent correct phonemes. Earlier studies of nonword repetition in adults and children who stutter (e.g., Anderson, Wagovich, & Hall, 2006; Byrd et al., 2012; Hakim & Bernstein Ratner, 2004) have attributed the observed group differences to phonological working memory deficits. Interpretation of the findings from nonword repetition in this study would suggest that at least for simpler nonwords pre-existing phonological working memory deficits, if any, may not interfere with task performance. Comparable performance of AWS and control participants in nonword repetition corroborates earlier findings from Smith et al. (2010), who used nonwords of similar length as those in this study. Perhaps significant differences are likely to emerge with lengthier nonwords. For instance, Byrd et al. (2012) observed significant differences between AWS and control participants in the repetition of nonwords that were seven-syllables long, but not of nonwords that were two to four syllables long.

4.1.2 Nonword reading—Findings from the nonword reading task revealed a trend for the AWS to show a lower percent of accurate nonword productions compared to the control group. Although nonword reading has not been investigated in AWS before, the finding of a trend toward a group difference in nonword reading performance corroborates earlier reports of a higher percent of phonemic errors in nonword repetition in AWS (e.g., Byrd et al. 2012;

Ludlow et al., 1997), while being contrary to comparable error rates between groups reported in other studies (e.g., Smith et al. 2010). Again, the differences in the findings from such studies attest to the due consideration needed in choosing the nonword stimuli. Furthermore, the findings of comparable performance in nonword repetition, but a trend toward group differences in nonword reading alludes to potential difficulties experienced by AWS in downstream processes involved in nonword reading, including phonemic/phonetic encoding and speech motor execution, while making it less likely for such differences to be attributable to phonological working memory deficits. However, the design employed in this study does not allow the distinction of phonemic encoding vs. speech motor planning and execution difficulties as the source of the observed group differences. Therefore, further investigations are required to understand and differentiate the nature of the underlying processes that may contribute group differences in noword reading performance. For instance, fine-grained analysis of the phonemic and syllabic level errors may offer clues to the differentiation of abstract linguistic-phonemic from motoric contributions.

4.2 Kinematic performance

4.2.1 Movement variability—The study of speech kinematics of nonword reading was undertaken to investigate the speech motor processes and the effects of task complexity on speech motor performance in AWS. The significant length effect indicated that the length manipulation used in this study did have an effect on movement variability. However, the interpretation of this effect is confounded by the fact that the 6- vs. 11-syllable nonwords also differed in the stress of the final syllable. The 11-syllable nonwords ended with a syllable that carried strong stress while the 6-syllable nonwords ended with a syllable that carried weak stress. This difference in stress pattern may be a potential contributing factor to the observed differences in movement variability between the two nonword lengths.

The findings indicated that the AWS showed higher movement variability than the control participants in the nonword reading task. Reduced coordinative consistency in the AWS group supports the assertions of a fragile speech motor system (e.g., Smith & Kelly, 1997). A similar finding of higher speech movement variability in AWS, although with nonword repetition, has been reported even for relatively short nonwords (e.g., Namasivayam & van Lieshout, 2008; Smith et al., 2010). Furthermore, in the present study a trend for Group × Nonword length effect indicated smaller between-group differences in movement variability for the 11-syllable nonwords with the AWS group becoming more similar to the control group for the longer nonwords. Findings of higher movement variability of the upper and lower lip trajectories in typically fluent speakers have also been reported in other studies at fast rates and are interpreted to suggest the loss of basic pattern stability when participants move away from habitual rates (Namasivayam & van Lieshout, 2008; Smith et al., 1995). A similar interpretation would suggest that the 11-syllable nonwords used in this study, which are longer than real words, resulted in the loss of movement stability in both AWS and control participants.

4.2.2 Speech duration—The findings revealed that the stuttering group was significantly slower in speech durations compared to the control group. In addition, a significant Group × Length effect indicated that increasing utterance length results in longer speech duration in AWS compared to the control group. Both these findings are interpreted to support the earlier argument that the fragile speech motor system in AWS is less efficient in dealing with task complexity. Slower speech duration with increasing length and complexity in AWS has also been reported in other studies (e.g., Smith et al., 2010). However, caution is warranted in interpreting this finding as an outcome of speech motor planning or execution difficulties as other variables, including treatment effects, could be potential contributing factors.

4.2.3 Practice effect—In the present study the effect of practice on movement kinematics was investigated by comparing the LA VAR scores and speech duration of the first vs. the next 5 trials. Varying versions of a reduced practice effect in AWS has been reported. For instance, Byrd et al., (2012) showed that AWS require higher mean number of attempts to accurately produce 7-syllable nonwords. Similarly, in the present study a higher mean number of stimuli blocks were presented to the AWS to elicit the required number of correct responses. Smith et al. (2010) reported that AWS did exhibit a significant short-term reduction in movement variability from the early to the later 5 trials within a session. However, the control group performed at ceiling throughout the experiment and therefore, did not show such within-session changes. Findings from the present study, while showing an overall trial effect, failed to show group differences in short-term gains in movement stability with practice. However, a significant negative correlation was obtained between percent disfluencies in reading and conversation and the magnitude of change in movement variability with practice. This later finding offers preliminary evidence that participants with more severe stuttering show a smaller practice effect. Bauerly & De Nil (2011) reported comparable practice effects for accuracy, response anticipation time, and sequence duration between AWS and control groups in repeating a single nonsense syllable sequence. However, larger within-group differences in practice effects were also evident in the AWS group. The finding from this study suggests that stuttering severity may be a factor influencing such within-group differences in practice effects.

Findings from the analysis of speech duration also offered preliminary evidence for a reduced practice effect in AWS. Seen as a trend, the Group × Trial effect indicated that the control group exhibited a greater reduction in speech duration from the early to the later 5 trials compared to the AWS group. Smits-Bandstra, De Nil, and Saint-Cyr (2006) also reported a similar trend toward group differences in early *vs*. later trials in repeating a nonsense syllable sequence. The authors compared the groups on the first trial and found group differences (the AWS were slower by 400 ms), which they attributed to additional task demands associated with syllable reading that may have differentiated the groups initially and resulted in the observed trend.

4.3 Conclusions, Limitations, and Future Directions

In conclusion, evidence from the present study suggests that AWS differ in both behavioral and kinematic profiles compared to adults who do not stutter. In addition to higher movement variability and longer speech duration, a trend for lower accuracy in nonword reading was observed in the AWS group. Keeping in mind the findings from earlier studies of nonword repetition and the present findings from nonword repetition and reading: a) behavioral differences in nonword repetition and reading performances in AWS seem more likely to emerge when the nonwords are sufficiently challenging (e.g., longer nonwords) and multiple processes may be implicated under such circumstances; and b) group differences in movement variability and speech duration are evident even for the shorter nonwords suggesting that an unstable speech motor system may be a default characteristic in AWS. Yet another conclusion is that the speech kinematic measures are much more sensitive indices of nonword performance differences in AWS.

A few potential limitations of the present study should be considered in designing future studies. First, what is the extent of generalizability of the present findings to other stimuli? For instance, the 11-syllable nonwords are not similar to words encountered in real life situations. Therefore, it could be argued that the response to such nonwords do not mirror the way the speech motor system reacts to typical speech stimuli in AWS. While the generalization of the present findings to words seems limited, it is not uncommon to produce 11-syllable sentences. Therefore, future studies will benefit from comparing differences in

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the production of nonwords vs. sentences matched in length. Second, contrary to earlier reports (e.g., Namasivayam & van Lieshout, 2008; Smith et al., 2010), present findings offer limited support for reduced practice effects in AWS. However, findings from the correlation analysis suggested the need to examine individual differences in practice effects and the variables, such as stuttering severity, contributing to within-group differences. Third, the measure of movement variability (LA VAR) used in this study is primarily limited to the upper lip, lower lip, and jaw, and does not involve other major speech articulators. Future studies need to investigate if other major articulators, such as, the tongue show similar kinematic patterns in AWS. Furthermore, the linear analysis used in the computation of LA VAR represents the combined variation of spatial and temporal control. Further non-linear analysis may be required to identify the individual contributions of spatial and temporal variability to any observed group differences.

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- Nonword repetition and reading were investigated in 9 adults who stutter (AWS) and age, sex matched adults who do not stutter.
- Groups were compared in speech accuracy in both tasks and in speech kinematics of nonword reading performance.
- Groups were comparable in percent accuracy in nonword repetition; AWS showed a trend toward a higher percent of errors in nonword reading.
- Higher movement variability and longer speech duration were also observed in the AWS in the reading task.
- Findings shed light on differences between AWS and control in processes underlying nonword reading and repetition.

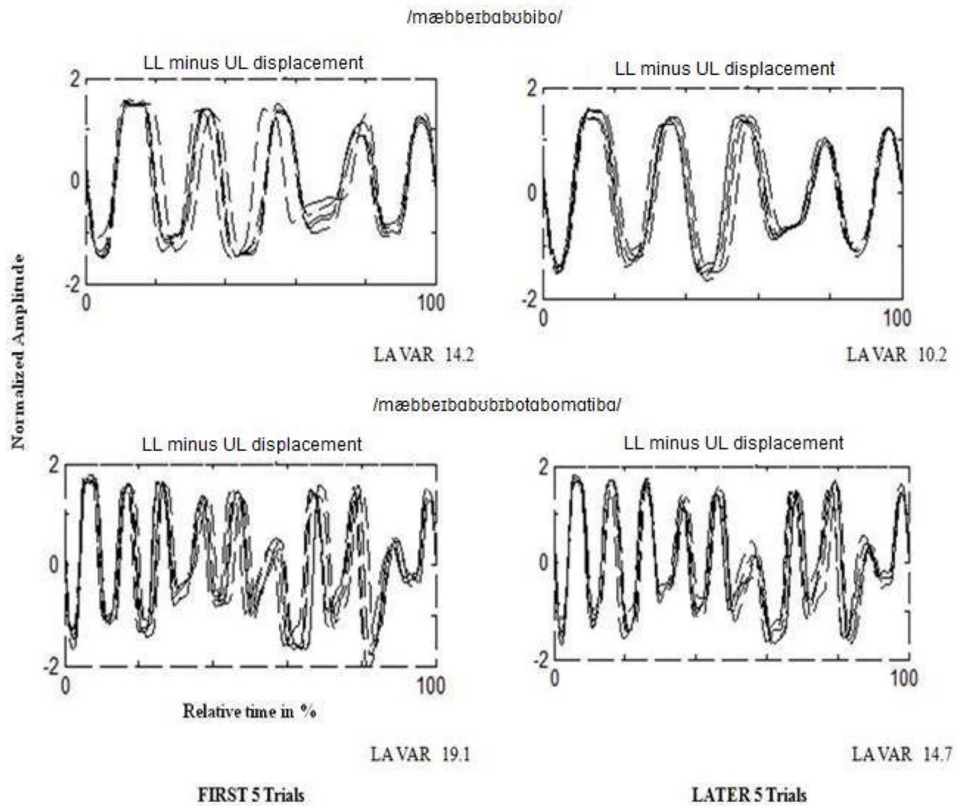

Figure 1.

Amplitude and time normalized lip aperture trajectories for the first 5 and later 5 trials of the nonwords */mæbbeIbabƱbibo/* and */mæbbeIbabƱbIbotabomatiba/*.

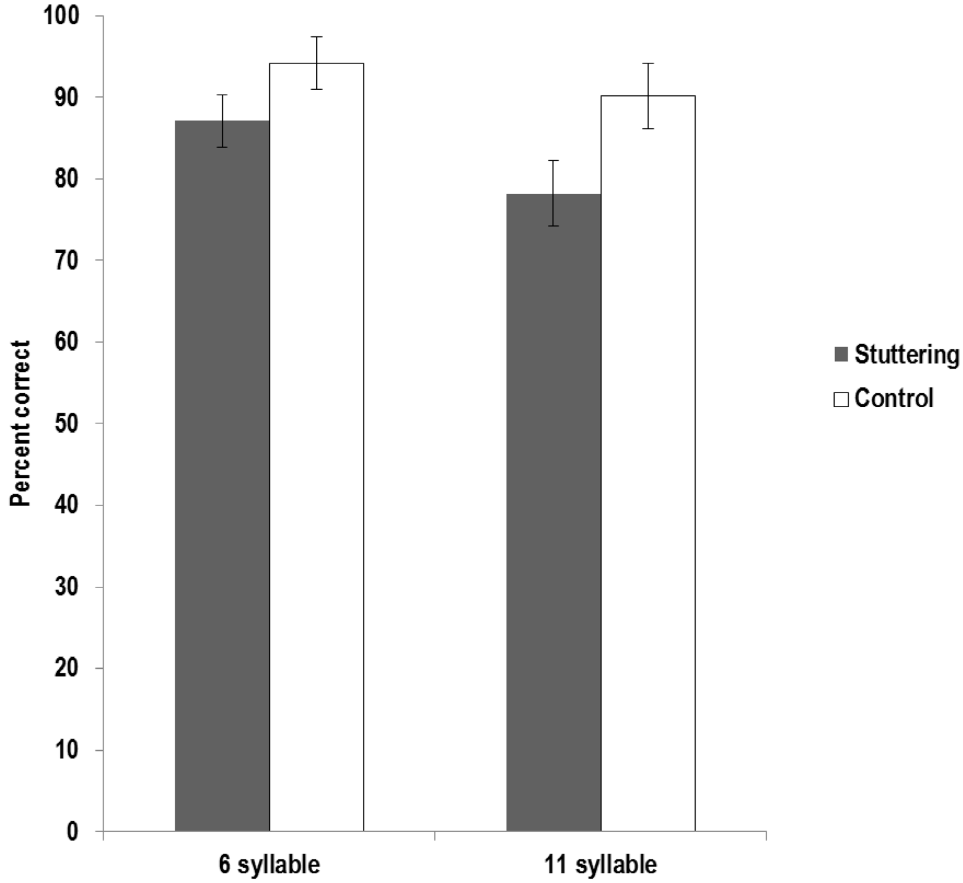

Figure 2.
Percent correct productions (and SE) of the 6– and 11-syllable nonwords by group in nonword reading.

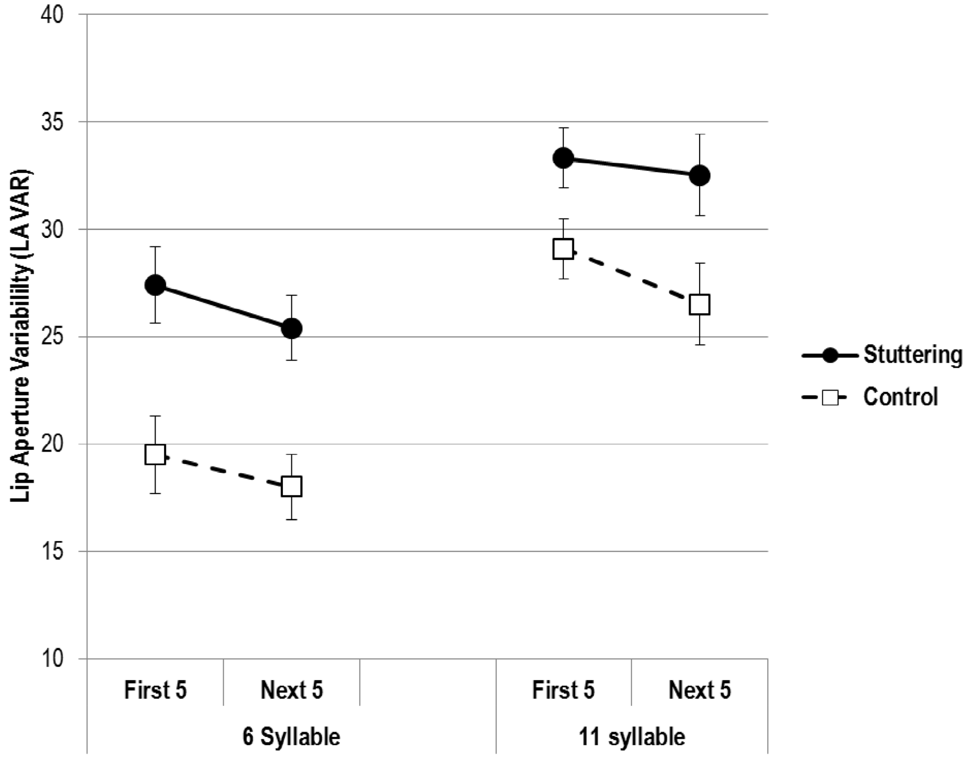

Figure 3.

Mean and SE of LA VAR scores for the first and next 5 trials by group in nonword reading.

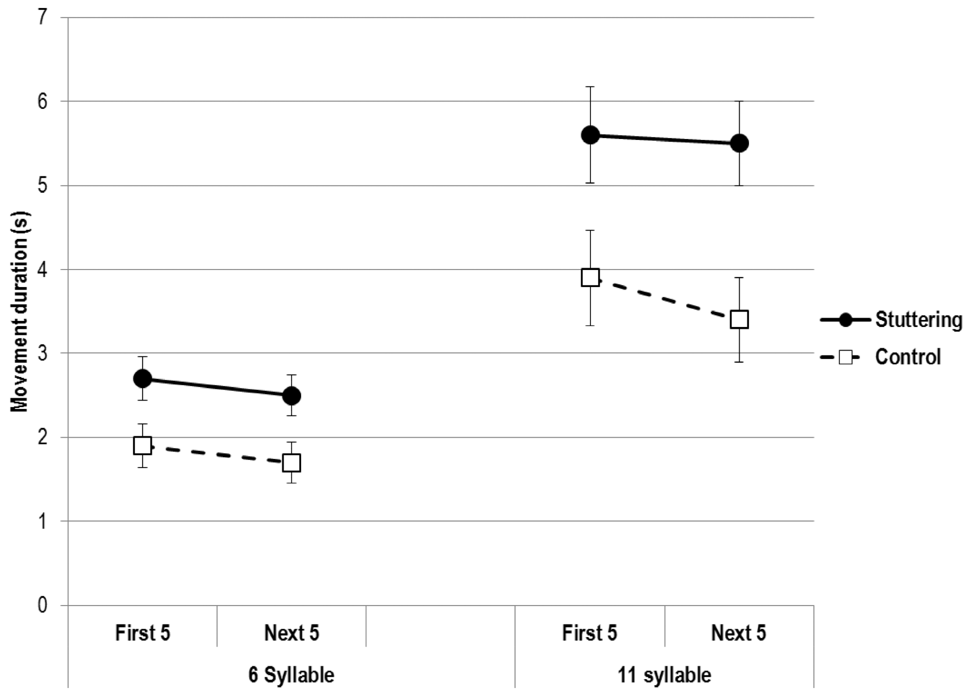

Figure 4.

Mean duration and SE of target nonwords for AWS and control groups in nonword reading.

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Table 1

Percent syllables stuttered (% SS), SSI scores, digit span, and nonword repetition (1-4 syllables) scores for the AWS and control groups.

					Digit Span		Nonword Repetition Test % phonemes correct			
Group	**% SS Read ing**	**% SS Conversation**	**SSI Score**	**Stuttering Severity**	**Forward (Total = 16)**	**Backward (Total = 14)**	**1-**	**2-**	**3-**	**4-**
AWS 1	23.4	7.2	30	Moderate	10	5	92	100	96	81
AWS 2	1.7	8	14	Very mild	12	8	83	95	100	86
AWS 3	3.1	7.1	27	Moderate	10	5	83	95	100	100
AWS 4	1.6	0	18	Mild	15	8	92	100	100	100
AWS 5	0	3.5	11	Very mild	13	12	83	90	100	97
AWS 6	0.3	1.5	10	Very mild	10	4	100	100	100	94
AWS 7	0	3.6	10	Very mild	12	7	100	95	89	86
AWS 8	1.8	2.6	16	Very mild	12	11	100	100	96	81
AWS 9	5.7	5.8	31	Moderate	8	4	92	100	93	84
Average					11.3	7.1	91.7	97.2	97.1	89.9
SD					2.1	2.9	7.4	3.6	4.0	7.9
C 1					11	5	100	100	100	86
C 2					11	7	100	100	100	100
C 3					12	9	83	100	100	86
C 4					10	7	100	100	100	94
C 5					14	7	100	100	100	94
C 6					13	9		Missing Data		
C 7					12	12	100	100	100	100
C 8					9	7	92	94	100	86
C 9					11	6	86	94	90	96
Average					11.4	7.7	95.1	98.5	98.8	92.8
SD					1.51	2.1	7.2	2.8	3.5	6.0

Table 2

Percent correct trials and percent disfluent trials for the 6- and 11-syllable nonwords by group in nonword reading.

	Percent correct		**Percent disfluencies**	
Group	**6-syllable**	**11-syllable**	**6-syllable**	**11-syllable**
AWS 1	91.7	79.2	23.6	37.5
AWS 2	72.9	52.2	8.3	6.9
AWS 3	93.1	89.7	16.7	15.3
AWS 4	95.8	88.9	1.4	0.0
AWS 5	94.4	88.9	2.8	1.4
AWS 6	86.1	90.3	2.8	2.8
AWS 7	58.3	55.6	4.2	4.2
AWS 8	93.1	79.2	11.1	8.3
AWS 9	98.6	80.6	9.7	22.2
Average	87.1	78.3	9.0	11.0
SD	12.4	13.8	7.0	11.5
C 1	95.8	94.5	0.0	4.4
C 2	90.2	88.9	0.0	2.9
C 3	98.6	94.4	2.9	1.5
C 4	94.4	91.7	1.5	4.4
C 5	87.5	70.9	0.0	1.5
C 6	97.2	98.6	2.9	2.9
C 7	95.7	97.1	4.4	1.5
C 8	98.6	94.4	0.0	0.0
C 9	89.5	81.6	4.4	10.3
Average	94.2	90.2	1.8	3.3
SD	4.1	8.8	1.9	3.0

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Table 3

Mean (and SD) LA VAR scores in units of millimeters (mm) of displacement and speech duration (in sec) for 6- and 11-syllable nonwords in AWS and control groups.

		LA VAR scores			
		6-syllable		**11-syllable**	
		First 5	**Next 5**	**First 5**	**Next 5**
AWS	*Mean*	27.4	25.4	33.3	32.5
	SD	6.5	5.4	5.1	6.9
Control	*Mean*	19.5	18.1	29.1	26.5
	SD	4.6	3.8	3.7	4.2
		Speech Duration			
		6-syllable		11-syllable	
		First 5	Next 5	First 5	Next 5
AWS	*Mean*	2.7	2.6	5.6	5.5
	SD	0.9	0.9	1.9	1.9
Control	*Mean*	1.9	1.7	3.9	3.4
	SD	0.6	0.5	1.5	1.0