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For the degree of Master of Science

Is approved by the final examining committee:

Anne Smith

Christine Weber-Fox

Howard Zelaznik

Anu Subramanian

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NEW EVIDENCE THAT BIMANUAL MOTOR TIMING PERFORMANCE IS NOT A SIGNIFICANT FACTOR IN DEVELOPMENTAL STUTTERING

A Thesis

Submitted to the Faculty

of

Purdue University

by

Allison Ilice Hilger

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

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Purdue University

West Lafayette, Indiana

In loving memory of my father Dr. William N. Hilger, who fueled my curiosity for research and inspired me to continually ask questions.

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ABSTRACT

Allison Hilger, M.S., Purdue University, August 2015. New evidence that bimanual motor timing performance is not a significant factor in developmental stuttering. Major Professor: Anne Smith.

Stuttering is a disorder that involves a breakdown in the speech-motor system, resulting in disfluencies such as part- and whole-word repetitions, prolongations, and blocks. This study addresses the question regarding whether this motor breakdown is specific to the speech-motor system, or more generalized across motor systems. As an expansion of Olander, Smith, and Zelaznik (2010), we measured bimanual motor timing performance in 115 children: 70 children who stutter (CWS) and 45 children who do not stutter (CWNS). The children were followed for five years of the study by completing a clapping task using a synchronization-continuation paradigm. Two analyses were completed. The first was a cross-sectional analysis of the data from the children in the initial year of the study (ages 4;0-5;11) comparing clapping performance between CWS and CWNS. In the second longitudinal analysis, the data were organized by the children's age to compare clapping performance across the developmental continuum, and compared by eventual persistence or recovery status of stuttering. The results of these analyses reveal that preschool CWS do not differ from their nonstuttering person rates of clapping, are not more variable than typically developing peers in performance of a bimanual rhythmic timing task. Additionally, bimanual motor timing differences are not a likely candidate as a contributing factor to the eventual persistence or recovery from stuttering. From these findings, we conclude that a bimanual motor timing deficit is not a core feature of persistent developmental stuttering.

INTRODUCTION

Stuttering is a speech production disorder characterized by disfluencies such as part- and whole-word repetitions, prolongations, and blocks. The etiology involves multiple factors, including motoric, linguistic, and psychosocial contributors (Conture, 1990; Smith, 1990; Starkweather, 1993; Van Riper, 1982; Wall & Myers, 1995). Stuttering onset generally occurs around two to four years of age with a 75% recovery rate for 3-year-olds who stutter (Ambrose & Yairi, 1999; Watkins, Yairi, & Ambrose, 1999; Yairi & Ambrose, 1999). Stutter-like disfluencies are believed to result from a disruption in the neural commands to the muscles necessary for fluent speech (Max et al., 2004).

Hypotheses for the source of these fluency breakdowns include (a) the central motor commands driving the speech motor systems to generate the acoustic output of speech are unstable, and that (b) disruptions in the speech output result from a heavy reliance on the afferent signals in the motor control system resulting in significant time lags in neuromuscular activations (Max et al., 2004). Specifically, people who stutter (PWS) exhibit decreased motor stability for lower lip movements, longer durations for devoicing intervals and voice onset time, atypical articulator velocities, deviant patterns in subglottal pressure build-up, asynchronous lip and jaw movements, and greater limb motor timing variability (Kleinow & Smith, 2000; Max & Gracco, 2005; McClean & Runyan, 2000; Peters & Boves, 1988; Ward, 1997; and Zimmermann, 1980). Smith and

Kleinow (2000) reported that the speech motor stability in PWS is significantly affected by linguistic complexity, such that increasingly complex stimuli are associated with greater variability in speech motor system, in contrast to adults who do not stutter (AWNS) who do not show this effect. A different trend has been observed for children who stutter (CWS). When repeating sentences of increasing length and complexity, CWS exhibit reduced speech motor stability across the board, including when speaking simple sentences (MacPherson & Smith, 2013; Walsh & Smith, manuscript in preparation). In comparison, children who do not stutter (CWNS) show greater stability when speaking simple sentences, and become less stable as the sentence length and complexity increase. CWS show this overall higher variability in oral motor coordination when repeating nonwords as well, suggesting that these children may lag their normally fluent peers in maturation of speech motor control processes (Smith, Goffman, Sasisekaran, & Weber-Fox, 2012).

The question arises as to whether this disruption in the speech motor system in stuttering is specific to speech or is observable in other motor behaviors. It is hypothesized that some aspects of the motor systems are connected by a shared underlying neural substrate; therefore a deficit in one system (speech motor system) should logically have an effect on other systems (such as, limb motor system) to a certain extent. Two contrasting points of view on neural control of movement include brain modularity and task-specific models of motor control (Fodor, 1983). The brain modularity model posits that cognitive, perceptual, and motor tasks are performed by a collection of mental processes rather than isolated neural areas performing each task independently (Fodor, 1983). With this model, neural resources are shared across motor systems. If neural areas were solely task-specific, i.e. speech movements should be distinctly represented from limb movements, timing movements among similar movements of different effectors (i.e. jaw opening vs. finger tapping) would not be correlated. In other words, the movement patterns among various effectors would be dissimilar due to the separate activations for each specific timing and coordination mechanism. However, measures of speech timing, vocal articulation, finger tapping, and foot tapping are positively correlated among similar movements of different effectors across individuals (i.e. speech articulators vs. finger movements), suggesting some degree of shared neural resources across motor systems (Cooper & Allen, 1977; Ivry & Richardson, 2002; Keele & Hawkins, 1982; Klapp, 1981).

Franz, Zelaznik, and Smith (1992) compared speech and nonspeech movements in 39 adults. The participants performed four limb, speech, and nonspeech oral tasks: finger-tapping and forearm tapping (i.e. the lateral side of the right wrist) on a microswitch lever, repeating the syllable */pa/*, and opening and closing the jaw in repetitive movements without vocalization. They compared the variability in intertap intervals for all task pairs: for example, arm-jaw, finger-arm, and speech-jaw, and found positive and significant correlations, suggesting the utilization of common timing processes for the timing of movements across various effectors. These processes mature together throughout development, as improvement in timing control for speech movements shows similar course of maturation as limb movements. Tingly and Allen (1975) measured temporal variability in 20 children across four age groups (5, 7, 9, and

11 years) with tasks that included phrase repetitions and finger tapping on a force gauge. The results showed that timing variability in finger tapping and speech improved in similar growth curves across the age groups, supporting a common timing-control mechanism that matures with development.

Timing and coordination are necessary processes for skilled motor control (Zelaznik, Smith, & Franz, 1994). These processes allow for fluidity and accuracy of movements by executing the correct sequence of muscle contractions to achieve a temporal target (i.e. moving the feet while walking). Coordination among various effectors arises from a common neural substrate in order to generate the highest efficiency and accuracy among interlimb movements (Smith, McFarland, & Weber, 1986). This includes the movement sequences for speech and other movements that are generated through common strategies in the central nervous system for this efficiency and accuracy (Smith & Zelaznik, 1990). This is exemplified in studies of force control, in which Keele, Ivry, & Pokorny (1987) suggest is an important factor in coordination. They compared force control across motor systems by measuring the consistency by which force is applied to a strain gauge by the finger, forearm, and foot. The subjects who showed lower variability in reproducing force in one effector, the finger, tended to show lower variability in reproducing force in the two other effectors as well, demonstrating the utilization of common strategies for coordination across the body.

Overall, behavioral investigations of shared coordinative processes across motor systems for particular movements suggest that a deficit in one area could have a potential effect on other areas as well, which would support a generalized motor deficit hypothesis in stuttering. Further support for this hypothesis is found in the overlapping neural activation for both speech and nonspeech movements. Broca's area is involved with premotor planning essential for movements in speech and is also active for complex hand movements, demonstrating a shared control mechanism among oral and limb movements (Binkofski & Buccino, 2004; Rizzolatti et al., 1996). In an fMRI study, seven adults performed speech and nonspeech (i.e. index finger) rhythmic sequencing tasks in order to examine effector-independent aspects of voluntary motor timing (Bengtsson, Henrik, Hans, & Fredrik, 2005). Within-subject analysis revealed that subjects consistently maintained a temporal pattern across the different effectors. Overlapping brain activation was found across effectors, demonstrating the sharing of neural resources among independent effectors.

In stuttering, atypical patterns of neural activation have been observed for both speech and nonspeech movements. Adults who stutter exhibit decreased activation in frontal and temporoparietal regions for perception and planning for speech and nonspeech movements, in addition to reduced activation in left superior temporal gyrus and left premotor area for producing motor sequences across systems (Chang, Kenney, Loucks, & Ludlow, 2009). Forster and Webster (2001) compared neural activation for a crank-turning coordination task in 4 AWS who persisted in stuttering (AWSp), 4 AWS who recovered from stuttering (AWSr), and 4 AWNS. The AWSp exhibited right hemisphere overactivation, indicating potential compensatory behavior. Although the AWSr performed similarly to the AWNS on the behavioral task (i.e. more stable coordination patterns compared to AWSp), they more closely resembled the AWSp in abnormal neural lateralization (i.e., right hemisphere overactivation). Functional and structural differences in brain connectivity for PWS are also found in the corticocortical network for speech and nonspeech oral motor tasks, as well as the thalamocortical pathway for motor execution tasks across motor systems (Chang et al., 2011). Transcortical magnetic stimulation (TMS) over the left and right motor cortices produced reduced left hemisphere activation for nonspeech movements in PWS (Busan et al., 2013). CWS also showed neural differences with reduced functional anisotropy in the left white matter tracts responsible for facial and laryngeal movements, as well as reduced gray matter volume in speech-relevant regions (Chang et al., 2008; Sommer et al., 2002). In total, motor systems share localized neural activation to allow for efficiency and consistency in timing and coordination across movement effectors, and PWS often exhibit neural and behavioral differences for speech and nonspeech motor movements (Archibald & De Nil, 1999; Chang et al., 2008; Chang et al., 2009; Chang et al., 2011; Forster & Webster, 2001; Webster, 1986).

Stuttering has also been associated with differences in the basal ganglia, a neural area responsible for internal timing and the execution of motor sequences. Adults who stutter show atypical activation in the basal ganglia-thalamocoritcal loop (Jiang et al., 2012; Watkins, Smith, Davis, & Howell, 2008), as well as output differences from the basal ganglia to the supplemental motor area (Lu et al., 2010), possibly reflecting a difficulty in updating timing and sequencing of movements. CWS have also demonstrated anatomical differences in the basal ganglia, including reduced grey matter in the left putamen (Beal et al., 2013), decreased volume in the right caudate nucleus compared to CWNS (Foundas et al., 2013), as well as reduced levels of connectivity from the putamen to the supplementary motor area (Chang & Zhu, 2013). The basal ganglia are believed to be responsible for the timing and initiation of self-paced movements, so a neural deficit in this area may be a contributing factor in the onset and persistence of stuttering (Alm, 2004; Etchell, Johnson, & Sowman, 2014). Furthermore, Ingham, Grafton, Bothe, and Ingham (2012) demonstrated that AWS show differences in basal ganglia activation not only during speech conditions, but also during rest conditions. If functional differences in neural activity of the basal ganglia are occurring in the absence of speech, then behaviorally, people who stutter should show timing differences in non-speech conditions.

Unfortunately, the behavioral data on non-speech motor performance in stuttering have been inconclusive. The goal of the present investigation is to further understand the potential role of a generalized motor deficit in stuttering and how such a deficit contributes to the onset and development of stuttering. Multiple studies in AWS have addressed this issue with conflicting results, which may reflect differences in experimental tasks as well as the small numbers of subjects used across studies. Task complexity is a critical variable in evaluating motor performance. A task that is too simple may fail to reveal any potential deficit. However, a task can also be too difficult if it is not developmentally appropriate to the age group of the people being studied. Two studies of AWS using the same groups of subjects (Zelaznik et al., (1994) and Zelaznik et al., (1997)) exemplify how task parameters can have a dramatic effect on experimental outcomes. The former study involved simple finger movements of flexing and extending the right index finger and no differences in timing and force-production performance were found between the AWS and the ANWS. The latter study incorporated bimanual finger movement synchronization by requiring the subjects perform similar flexion and extension movements with each index finger in synchrony to a metronome. They compared performance between AWS and AWNS and found that AWS moved with reduced amplitude and peak velocity, and exhibited greater relative phase variability than the AWNS. The bimanual task in Zelaznik et al. (1997) apparently had the complexity to elicit the deficit seen in many of the AWS, while the simple finger flexion task did not. Overall, motor differences are more likely to be observed when the task involves multi-level and multi-effector coordinative processes.

Motor differences between AWS and AWNS have been observed in many studies. Investigators who report a general timing deficit in stuttering have found that PWS demonstrate poor timing on a variety of paced and unpaced speaking, jaw movement, and finger tapping tasks in which timing skills are measured by either the ability to synchronize with a beat, or the ability to accurately repeat a rhythm (Boutsen, Brutten, & Watts, 2000; Brown, Zimmermann, Linville, & Hegman, 1990; Cooper & Allen, 1977; Forster & Webster, 2001; Kent, 1983; Ward, 1997). In a TMS study of the dorsolateral premotor cortex (PMd) in which subjects synchronized the index finger to a metronome, Neef et al. (2011) reported timing difficulties in 14 AWS after stimulation over the right PMd, whereas AWNS exhibited timing difficulty with the TMS over the left PMd, suggesting atypical connectivity for timing of nonspeech movements in AWS. A general coordination deficit in stuttering is shown in AWS by greater variability in multi-movement sequencing of lip, jaw, and finger movements using tasks such as accuracy in turning a crank, velocity of flexion movements, and accuracy of finger tapping sequences (Caruso, Abbs, & Gracco, 1988; Forster & Webster, 2001; Max, Caruso, & Gracco, 2003; Webster, 1986; Zelaznik, Smith, Franz, & Ho, 1997). A subgroup of AWS demonstrate reduced coordination ability for both the oral opening movements of jaw displacement, and the limb movements for finger tapping sequences (Archibald & De Nil, 1999; Webster, 1986). Max, Caruso, and Gracco (2003) examined speech and nonspeech motor abilities in 10 AWS compared with 10 AWNS on a variety of tasks, including producing words of increasing syllable length, creating a "popping" sound through a bilabial closing and opening movement, and touching the index finger to the thumb through successive flexion and extension of the index finger. They found that the AWS showed significantly greater movement duration and latency to peak velocity during finger flexion and jaw closing movements, and concluded that motor differences in AWS are not confined to speech.

Investigators also have failed to find differences in general timing and coordination processes in AWS compared to AWNS. Max & Yudman (2003) found that PWS showed similar timing abilities to the fluent controls across speech, orofacial nonspeech, and finger movements. They used a rhythmic timing synchronization-continuation paradigm in which 10 AWS and 10 AWNS matched their movements to a beat and then continued the rhythm in three conditions: repeating the syllable */pa/* to measure bilabial movement, assessing oral opening and closing without the speech component, and successively moving the index finger to contact the thumb. Overall, timing accuracy and variability did not differ between AWS and AWNS for all three motor tasks, suggesting that these AWS demonstrated normal timing ability. Additional studies using finger tapping in which no significant differences were observed between PWS and PWNS have supported this finding (Hulstijn, Summer, van Lieshout, & Peters, 1992; Webster, 1985). Studies of other tasks involving the coordination of finger flexion movements and isometric force matching have shown similar abilities between the two groups (De Nil & Abbs, 1991; Zelaznik, Smith, & Franz, 1994). These findings highlight that AWS can demonstrate normal coordination and timing abilities, and suggest that there may be subgroups of AWS who exhibit a generalized motor deficit.

Examining motor abilities in children is a particularly important issue in relation to specifying potential factors that contribute to the onset and persistence of stuttering. Few studies have looked at nonspeech motor skills in CWS, and the picture remains unclear as to whether a generalized motor disorder exists at a young age. In the first study to examine this, Westphal (1933) found that CWS 9 to 17 years of age scored lower than the age-matched children who did not stutter (CWNS) on a number of motor tasks, including tossing beads and writing while blindfolded. Riley and Riley (1980) completed a factor analysis of 19 variables in 76 CWS aged 5 to 12 years. They found a few statistically useful factors out of the 19 studied as potential underlying components of stuttering: linguistic, oral motor, and auditory processing abilities. In a study by Howell, Au-Yeung, & Rustin (1997), CWS (9-10 years) performed as well as CWNS on a sinusoidal lip tracking task for timing accuracy, but more poorly for motor control, suggesting a motor control deficit in stuttering. Most recently, Falk, Muller, & Dalla

Bella (2014) looked at motor timing in 20 CWS in two age groups, 10 children 8-11 years and 10 children 12-16 years, compared with 43 CWNS (22 younger children and 21 older children). They assessed the children's ability to synchronize finger tapping to an external beat. While the older CWNS demonstrated better timing abilities than the younger CWNS, the older CWS did not perform better than the younger CWS, and overall, these children performed worse than their fluent age-matched peers. Olander, Smith, & Zelaznik (2010) used the synchronization-continuation task with clapping, comparing motor timing performance between 17 CWS and 13 CWNS ages 4-6. The children clapped to a beat for 12 beats (i.e. synchronization) and then continued the rhythm on their own for 32 beats (i.e. continuation). The children's performance in the continuation phase to continue the beat with a consistent clapping pattern was analyzed. A subgroup of 60% of CWS demonstrated timing variability that was greater than the poorest performing child who did not stutter. However, the remaining CWS performed normally as compared with their peers.

As an expansion of the bimanual clapping study by Olander et al. (2010), we assessed the clapping abilities of CWS across the developmental continuum. Olander et al. (2010) assessed a sample of 17 CWS and 13 controls in the initial year of a larger longitudinal project. In this investigation, we utilize data from a study completed in 2012 that assessed a larger sample of 70 CWS and 45 CWNS that were followed over five years, from near onset at 3-5 years of age. Currently, no study has measured nonspeech motor ability longitudinally and comparatively between children who persist in stuttering and children who recover. A longitudinal analysis with a larger sample will allow us to determine whether a potential motor deficit is influential in relation to stuttering in development and its potential contribution to persistence.

The experimental task and dependent variables are identical to those reported by Olander et al., (2010). A bimanual clapping task with a synchronization-continuation paradigm was utilized in this study during a previously-completed longitudinal study. Clapping was chosen due its appropriateness for children as young as four years. With maturation, children become less variable in their clapping patterns with better motor coordination reflecting the development of interlimb coordination (Fitzpatrick, Schmidt, & Carello, 1996; Getchell & Whitall, 2003; Getchell, 2006; Roberston, 2001). Overall, children are poorer timers than adults and are more variable in rhythmic timing tasks. This variability demonstrates the developing coordination processes (Lagrasse, 2013; McAuley, Jones, Holub, & Johnston, 2006; Yu, Russel, & Sternad, 2003). Timing ability improves with maturation as the mental motor plan needed to execute movements becomes more stable and efficient (Getchell, 2006). The synchronization-continuation paradigm requires the child to match a temporal pattern during a pacing session and then to continue the beat without external cueing in a continuation session by utilizing a mental representation of the target interval (Fitzpatrick et al., 1996). This requires the child to store a temporal plan and execute the specific pattern of muscle commands (Michon, 1967).

The question arises as to whether a bimanual task is a valid measure of general non-speech motor ability, or whether hand gesture is inherently linguistic and therefore associated with the language processing system. The latter argument stems from an unsupported theory that language emerged from gesture, and that an evolutionary linguistic element is linked with both meaningful and meaningless hand movements (Komeilipoor, Vicario, Daffertshofer, & Paolo Cesari, 2014). If this were true, hand movements would activate similar neural networks to speech; however neuroimaging suggests otherwise. Mottonen, Farmer, & Watkins (2011) measured excitability in the left and right primary motor cortex (M1) of non-signing participants viewing signs in British Sign Language both before and after the knowledge of sign meaning. When excitability between the left and right M1 was compared, the left hemisphere M1 showed significantly greater excitability after the participants were familiar with sign meaning, suggesting that hand movements only activate language networks when meaning is associated with the movement. Komeilipoor et al. (2014) also measured motor excitability in the M1, but focused on the tongue and hand areas specifically in the left hemisphere while participants viewed bimanual hand movements both associated with nouns and not associated with nouns. Higher motor excitability in the tongue area was found during the observation of meaningful gestures as opposed to meaningless gestures. Excitability in the hand area did not significantly change with the presence or absence of meaning. Thus, hand movements activate language processing networks when meaning is associated with the movement, but that movements devoid of meaning do not show this effect. Therefore, the bimanual clapping task in our study is a valid measure for general non-speech motor timing ability due to the linguistically meaningless nature of clapping.

Our clapping task, more specifically the synchronization-continuation paradigm, is useful for evaluating the central time keeping mechanism in the brain that is necessary for timing in motor control (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). Inability to synchronize to a beat may be indicative of inadequate auditory-motor mapping, and failure to successfully continue the beat may highlight an inability to build a stable interval representation during the initial pacing session (Fitzpatrick et al., 1996; Michon, 1967; Sowinski & Dalla Bella, 2013). This continuation phase places high demand on temporal processing in the absence of an external cue, requiring greater neural resource to adapt to the timing and motor constraints (Serrien, 2008). The ability to match and continue a rhythm improves throughout development (McAuley, Jones, Holub, & Johnston, 2006). Multiple studies have utilized this paradigm for assessing nonspeech motor control in stuttering. Max & Yudman (2003) failed to find a difference for finger tapping abilities between AWS and AWNS in a synchronization-continuation task, whereas Falk, Muller, & Dalla Bella (2014) found a difference between CWS and CWNS with a similar task.

The findings from the present investigation are also potentially important for determining risk for persistence in stuttering. Stuttering is a multifactorial disorder such that the contributing factors are weighted differently in each individual (Smith & Kelly, 1997). The factors cumulatively result in the development of stuttering, although each particular factor may affect each person to a different extent. This study will help to determine whether a generalized motor deficit is an influential factor in contributing to stuttering persistence. Based on the multifactorial model of stuttering and the previous results from Olander et al. (2010), we predict that a generalized motor deficit will characterize a subset of CWS. Finally, because earlier investigations have reported differences in subgroups of children on speech and other motor abilities related to the following factors: sex (Smith & Zelaznik, 2004), presence of language impairment (Brumbach & Goffman, 2014), and/or presence and phonological impairment (Ramus, Pidgeon, & Frith, 2003), we analyze clapping abilities of subgroups of children sorted on these variables.

METHODS

This is an extension of a study (Olander et al., 2010) which examined data from sub-samples of the total number of participants in the current study. We report analyses of additional participants later recruited into the longitudinal study and analyses of subsequent years of testing for all participants who were successfully followed. The procedures summarized here are identical to those of Olander et al. (2010). Two analyses were performed: the first was an extension of Olander et al. (2010), a cross-sectional analysis of the data from children in the initial year of the study (ages 4;0-5;11), comparing clapping performance between children who stutter (CWS) and children who do not stutter (CWNS). In the second analysis, children were placed into six age groups and compared clapping performance longitudinally for the children who stutter who eventually persisted (CWSp), children who stutter who eventually recovered (CWSr), and children who never stuttered (CWNS). Data from the same children were used in both analyses, if criteria were met for each analysis.

Participants:

One hundred and fifteen children participated in the study[1], 70 children who stutter (CWS), and 45 children who did not stutter (CWNS) (see Appendix for full

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[1] Identical testing procedures were performed at two locations, Purdue University and the University of Iowa. The data presented is a subset of a larger longitudinal study looking at multiple factors in stuttering. The current study focuses on limb motor coordination for a bimanual clapping task, however other tasks included language processing and production tasks, nonword repetition tasks, and conversational speech samples.

description of participants). A diagnosis of stuttering was determined according to the criteria of Yairi and Ambrose (1999), which included a parent report, examiner report, and analysis of two speech samples. Children diagnosed as stuttering exhibited three or more stuttering-like disfluencies (SLD) (i.e. syllable repetition, part-word repetition, and dysrythmic phonation) per 100 syllables during two spontaneous speech samples (one with the parent and one with the examiner). The SLDs were coded according to the methods of Yairi and Ambrose (1999). Recovery from stuttering was defined as two consecutive years in which the child did not meet the criteria listed previously for a diagnosis of stuttering. Of the CWS, 30 children recovered and 29 children persisted in stuttering. Persistence/recovery status was not available for 11 children.

Cross-sectional analysis of initial year data Children were included in the first analysis if they were between the ages 4;0 and 5;11 when first tested on the clapping paradigm. Twenty-three children were outside this range and were excluded, resulting in groups of 47 CWS and 37 CWNS (see Table 1). The mean age was 4;6 for the CWS, and 4;9 for the CWNS. There was a male to female ratio of 33:14 for CWS and 24:13 for CWNS. A Handedness Inventory (subset of five tests adapted from Oldfield, 1971) indicated of the CWS, 41 children were right-handed and 6 children were left-handed, and for CWNS, 32 children were right-handed and 5 children were left handed. At the time of the study, 22 CWS were receiving fluency and/or speech-language therapy.

Table 1: Description of participants in cross-sectional year analysis between for children who stutter (CWS) and children who do not stutter (CWNS)

Initial Year	**CWS**	**CWNS**	**Total**
n	47	37	84
Average Age (months [mean, median]	(55, 55)	(57, 57)	(56, 56)
Male:Female	33:14	24:13	57:27

Longitudinal Analysis For the longitudinal analysis of clapping performance, children were grouped into six age groups: 3;5-4;5 (n=27), 4;6-5;5 (n=67), 5;6-6;5 (n=78), 6;6-7;5 (n=67), 7;6-8;5 (n=52), and 8;6-9;5 (n=23). Overall, a total of 115 subjects were included in the longitudinal analysis, comprising 70 CWS and 45 CWNS. Table 2 includes the breakdowns for each age group for children who stutter who eventually persisted (CWSp), children who stutter who eventually recovered (CWSr), and children never stuttered (CWNS), in addition to the gender ratios for children who stutter (CWS) and children who do not stutter (CWNS).

Table 2: Description of participants in longitudinal analysis for children who stutter who persisted (CWSp), children who stutter who recovered (CWSr), and children who never stuttered (CWNS).

Across Years	**3;5-4;5**	**4;6-5;5**	**5;6-6;5**	**6;6-7;5**	**7;6-8;5**	**8;6-9;5**
n	27[1]	67[2]	78[4]	67[4]	52	23[4]
CWSp	6	15	17	18	10	5
CWSr	9	21	23	21	17	8
CWNS	9	30	38	28	25	10
Male:Female CWS	11:7	27:12	28:13	28:11	2:1	10:3
Male:Female CWNS	7:2	9:5[3]	22:13[5]	19:9	14:11	1:1

[1] Persistence/recovery status was not included for 3 subjects.
[2] Persistence/recovery status was not included for 2 subjects.
[3] Gender information was not included for 2 subjects.
[4] Persistence/recovery status was not included for one subject.
[5] Gender information was not included for 3 subjects.

Screening/Testing Procedures completed at Initial Recruitment:

All of the children spoke American English as their first language. A pure tone hearing screening (20 dB HL at 400, 1000, 2000, and 4000 Hz) indicated normal hearing for all participants. No motor delays, neurological problems, or serious illnesses were reported. The CWS and CWNS were matched on socio-economic status, as determined by the mother's highest year of education (4 being high school, 5 as partial college, 6 as college grad, and 7 as post-grad work) (Hollingshead, 1975). The mean education score for each group was 6.

A set of standardized tests were administered to determine the children's abilities on a number of variables. The Bankson Bernthal Test of Phonology was administered for phonology (Bankson & Bernthal, 1990). For language, the Test of Auditory Comprehension of Language, 3rd edition, and the Structure Photographic Expressive Language Test, 3rd edition, were given (Carrow-Woolfolk, 1999; Dawson, Stout, & Eyer, 2003). Finally, oral-motor and cognitive abilities were assessed through the administration of an oral-motor mechanism exam, the Columbia Mental Maturity Scale, and the Auditory Number and Word Memory subtests of the Test of Auditory-Perceptual Skills (Burgemeister, Blum, & Lorge, 1972; Gardner, 1996; Robbins & Klee, 1987). When compared to same-age peers, the CWNS scored within one SD for all tests. The CWS scored within one SD below the mean for the tests, with the exception of 30 who scored within 2 SDs for phonology and 13 who scored within 2 SDs for language abilities. We included these children due to the high rates of comorbid speech and language disorders in children who stutter (Arndt & Healey, 2001). The appendix lists the characteristics of the participants, along with the age of onset and stuttering severity. Stuttering severity was determined based on the average number of disfluencies per 100 syllables.

Apparatus:

A Northern Digital Optotrak 3020 system was used to record hand movements during the clapping task. The system consisted of three fixed cameras that tracked the motion of two infrared light emitting diodes (IRED's) attached to the children's hands. The IRED's were connected to a small splint that was taped onto the distal end of each middle finger. The splint allowed the diodes to remain in view of the camera for the entire clapping motion. To avoid interference with clapping, wires were taped to the children’s hands. Each IRED was sampled at 250 samples/second, with the medial-lateral dimension analyzed.

Procedure

Refer to Olander et al. (2010) for more detailed information. When the children were situated in front of the cameras with the IREDs attached, they were instructed to clap to a beat. The metronome beat consisted of a computer generated piano tone with an interbeat interval of 600 ms. After the synchronization phase of 12 beats, the metronome stopped and the children were instructed to continue clapping as if the metronome were still on. The unpaced phase continued for 32 claps until the children were instructed to stop. Each participant was given up to the three practice trials to ensure they understood the task. During these practice trials, the child clapped with the examiner. Data collection began when the child completed two practice trials independently. Prompts (e.g., “Keep clapping when the beat goes off”) were provided during data collection when needed.

To maintain view of the IRED’s, the children were instructed to point their fingers at “Ernie,” a doll sitting on top of the cameras. If the IRED’s went out of view, the children were reminded to point their fingers at “Ernie.” Further prompting included cueing the children to make “softer” claps if they clapped outside the camera range. Each participant was encouraged to complete at least six trials.

Data Analysis

Signal conditioning and data analysis were completed in a Matlab signal processing program. The displacement records were low-pass filtered forward and backward with a cutoff at 8 Hz using a fifth-order Butterworth filter.

The motion of each hand was measured. Velocity was computed by using a three-point difference technique. The starting point of the clap was defined as the point in which the velocity of the hand slowed to 3% of peak velocity while moving toward the midline. This 3% velocity criterion was automatically computed for each clap for each hand through a Matlab algorithm. The algorithm was checked by the experimenter looking over the graphical display of hand placements with the automatically defined claps. If the algorithm was mistaken, i.e. picking an erroneous starting point or missing a point entirely, the starting point was corrected by using a mouse-driven cursor to manually move or create a point in the proper location. Good reliability of 90% was maintained between two individuals by comparing each individual's scoring check of randomly selected trials. This technique has been verified as being accurate for measuring rhythmic movements (Robertson et al., 1999; Zelaznik et al., 1997).

Trials were excluded when the child ceased clapping for more than two seconds. Clapping was defined as requiring both hands to reach the midline, and analysis confirmed that each trial contained the equal number of claps for both hands. Only the continuation (32 claps) phase was analyzed for timing variability due to the lack of sufficient number of usable trials in the 12 beat synchronization phase. The synchronization phase taps the children's ability to synchronize a motor activity to an external beat, whereas the continuation phase allows us to measure their ability to maintain the motor activity independent of the beat. Ideally, the continuation phase contained at least 28 claps, with the first two claps and the final clap excluded from analysis.

The displacement traces were analyzed to compute average clap cycle duration, the variation of the cycle, and the coefficient of variation of interclap interval across the trials for each child's left and right hand. To account for any possible influences of drift on average clapping rate, detrended variance was calculated, and its square root was used to calculate the coefficient of variation in percent [CV= (Detrended standard deviation/mean interclap interval) x 100].

Statistical Analyses

For the cross-sectional experiment, a repeated measures (right and left mean duration of clap) ANOVA was computed to compare the rate of clapping for CWS and CWNS. Separate repeated measures ANOVAs were computed on the CV of the interclap interval (repeated factor, right and left hand CV) for Group (CWS vs. CWNS), Sex and Group, Language status (CWS+LI vs. CWS-LI and CWNS), and Phonological status (CWS+PI vs. CWS-PI and CWNS). For the longitudinal experiment, as noted above, children were grouped by stuttering status (CWSp, CWSr, CWNS) for each of the six ages. Repeated measures ANOVAs on the right and left CVs of clapping were computed for the three groups for each year to determine if timing performance is related to recovery status.

RESULTS

Cross-Sectional Analysis: CWS vs. CWNS

Results are reported for 47 CWS and 37 CWNS who produced at least two useable clapping trials. The range of useable trials per child was 2-11 trials, with a median of 6 useable trials per child for both groups. Olander et al. (2010) addressed the statistical concern that clapping variability may be affected by the number of useable trials for a subject by computing the correlation between the number of useable trials and the coefficient of variation of the interclap interval. The correlation was almost zero (-.075), thus mitigating this concern.

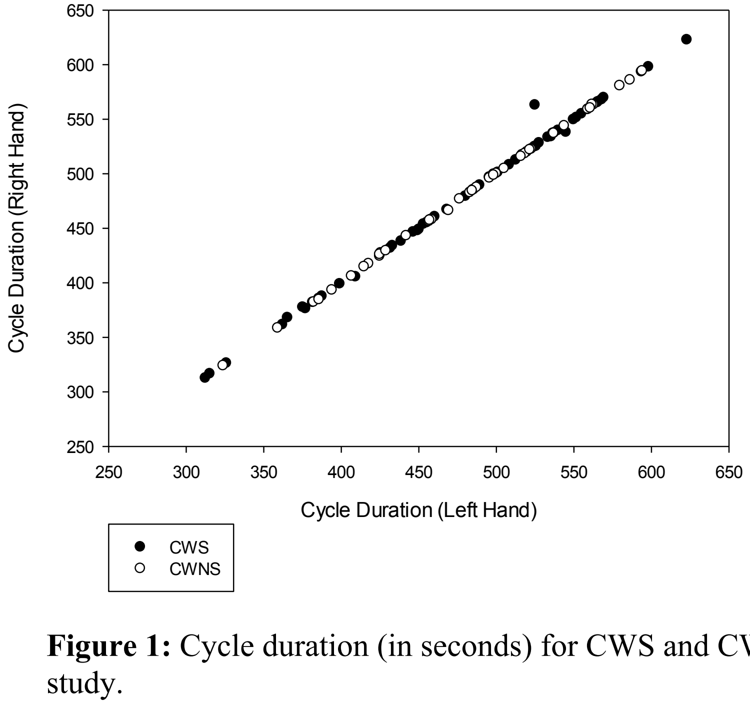

Figure 1: Cycle duration (in seconds) for CWS and CWNS in the initial year of the study.

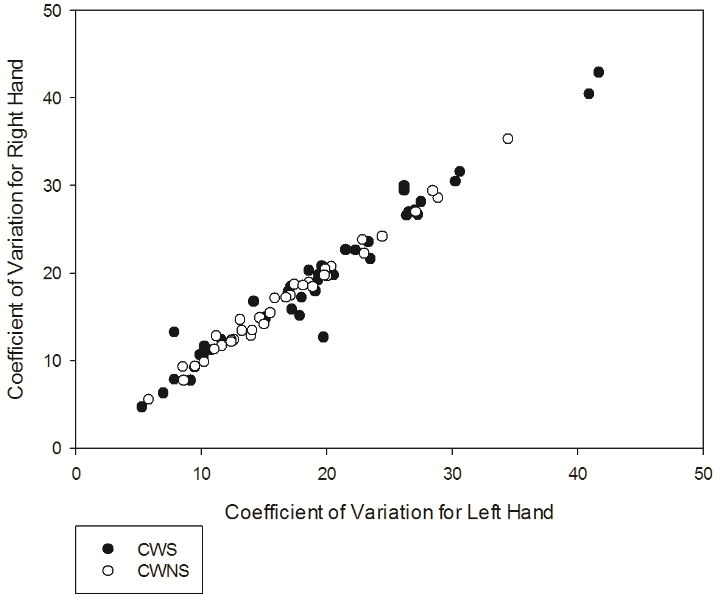

Figure 2: Coefficient of variation of interclap intervals for CWS vs. CWNS in the initial year of the study.

Figure 1 shows the right and left hand mean clapping interval for each child. As suggested by this plot, no group differences were found for average clap duration, *F*(1, 85) <1 (mean and SD for each group: CWS 480.6 seconds, 75.25; CWNS 482.0 seconds, 66.14). Figure 2 contains scatter plots of the coefficient of variation of the interclap intervals for the right and left hands for each participant. From the plot, it is apparent that the distributions of the children's mean coefficient of variation are overlapping for the two groups of participants. A repeated measures analysis of variance (with two levels for hand, L and R) revealed no significant difference between coefficient of variation for interclap intervals for children who stutter and children who do not stutter, *F*(1, 83) = 1.28, $p = 0.26$. Sex did not have an effect on interclap interval variability (*F*(1, 77) <1), and there was not a significant interaction between the factors, sex and group, *F*(1, 77) <1 (see Table 3). CWS with language impairment and CWS with phonological impairment (those who scored below 1 SD below the mean on a standardized language or phonological assessment) were analyzed separately to examine whether a deficit in one of these areas could have an effect on clapping abilities. A repeated measures ANOVA revealed no significant effect for language impairment on clapping performance (CWS + LI vs. CWNS – LI vs. + CWNS) ($F(2, 81) = 1.03$, $p = 0.36$), as well as no significant effect for phonological (speech sound) status (CWS + PI vs. CWS – PI vs. CWNS) ($F(2, 81) = 1.74$, $p = 0.18$) (see Table 4). These results indicate that CWS, regardless of language or phonological status, and CWNS demonstrated similar bimanual timing performance in the clapping task. Finally, we note that the range of both average clap duration and the coefficient of variation values for all participants in the present study, duration range and CV range, respectively, were 323-623 seconds and 5- 35% comparable to that in Olander et al. (2010) of duration range (320-575 seconds), CV range (3-32%). Unlike the results observed in our earlier study in which 60 % of CWS fell outside the normal CV range for clapping, in the present study CWS were among the best at keeping the beat and among those with the most variable performance.

Figure 3 is a plot of the same initial year CV data shown in Figure 2, but in this case the stuttering participants have been classified according to stuttering status, recovered or persisted, which was determined in later years of the project. This plot helps to answer the question of whether the CWS who would ultimately persist in stuttering (CWSp) were among the most variable in clapping timing performance when they were preschoolers. Clearly, the clapping variability of the CWSp is distributed along the entire continuum from the “best” timers to the “worst” timers. In fact, there is a significant cluster of CWSp with extremely consistent (CVs in the 10% or lower range) clapping performance.

Table 3: Average detrended coefficient of variation by sex and group

Sex	***CWS Male (n=35)***		***CWS Female (n=14)***		***CWNS Male (n=24)***		***CWNS Female (n=13)***	
Detrended CV Left and Right Hands	18.87	19.54	18.53	18.02	17.14	17.24	16.92	17.34

Table 4: Average detrended coefficient of variation by language impairment and group (top) and phonological impairment and group (bottom).

Language	***CWS + LI (n=8)***		***CWS – LI (n=35)***		***CWNS (n=37)***	
Detrended CV Left and Right Hands	20.6	21.63	18.41	18.7	16.9	17.07
Phonology	***CWS + PI (n=24)***		***CWS – PI (n=22)***		***CWNS (n=37)***	
Detrended CV Left and Right Hands	20.28	20.72	17.1	17.56	16.9	17.07

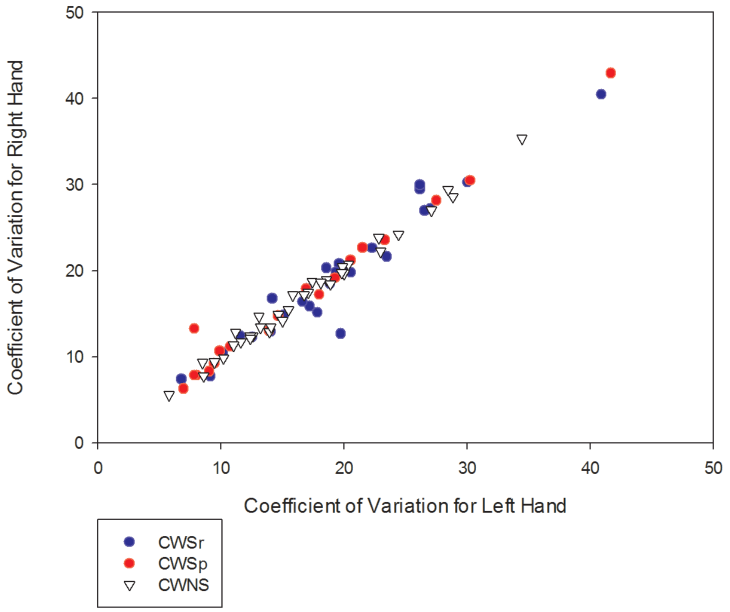

Figure 3: Clapping performance of 4-5 year old preschool children who eventually recover from stuttering (CWSr in blue), children who eventually persist (CWSp in red), and children who do not stutter (CWNS, open triangle).The poorest performing children include children from all three groups.

Longitudinal Analysis

Results are reported for 115 subjects grouped into CWSp, CWSr, and CWNS. Data from children followed for up to five years were organized into six ages. The children began and completed the study at varying ages depending on stuttering onset and study referral, accounting for the differences in sample size across the age groups. Figure 4 contains a plot showing the means and standard error of measurement for detrended coefficient of variation for each group at each age. Figure 5 contains the plots showing individual data values for each subject in each group across the years (5A, 5B, 5C). Plot 4 confirms that the groups follow a similar trajectory in improvement in bimanual timing control through the developmental progression. The individual data in plots 5A, 5B, and

5C further exemplify the similarities in developmental profiles between CWSp, CWSr, and CWNS. A repeated measures analyses of variance computed for the groups for each year (again, with two levels of hand) revealed no significant differences among average coefficient of variation among the three groups for any year: 3;5-4;5 [*F*(2, 23) <1], 4;6-5;5 [*F*(2, 62) <1], 5;6-6;5 [*F*(2, 76) = <1], 6;6-7;5 [*F*(2, 65) = <1], 7;6-8;5 [*F*(2, 52) = 1.76, *p* = 0.18], 8;6-9;5 [*F*(2, 23) = 2.67, *p* = 0.09]. Thus, the group of children who ultimately persisted in stuttering were not more variable in their clapping performance at any age; albeit there is a trend for the CWSp at the oldest age examined to be more variable in their clapping performance compared to CWNS and CWSr.

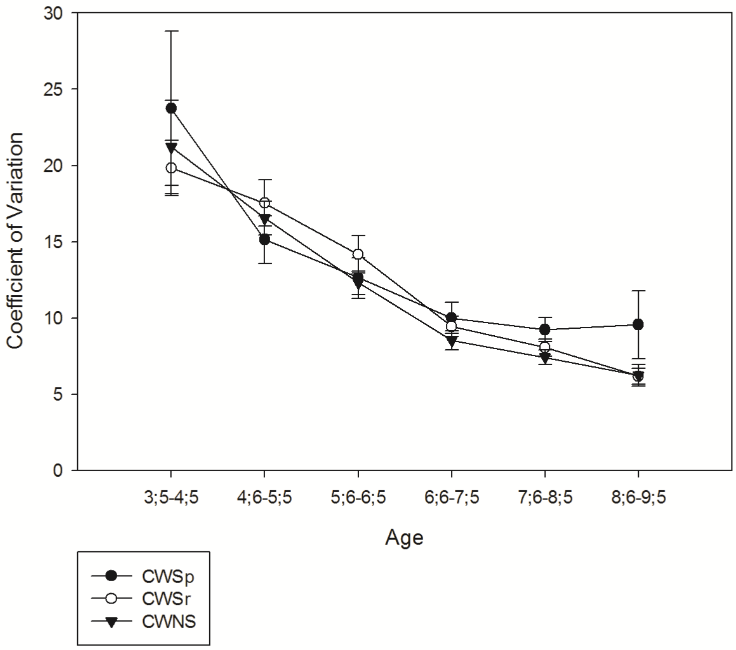

Figure 4: Coefficient of variation for right and left hand interclap intervals as a function of age for children who stutter who eventually persisted (CWSp), children who eventual recovered (CWSr), and children who never stuttered (CWNS) across 6 ages.

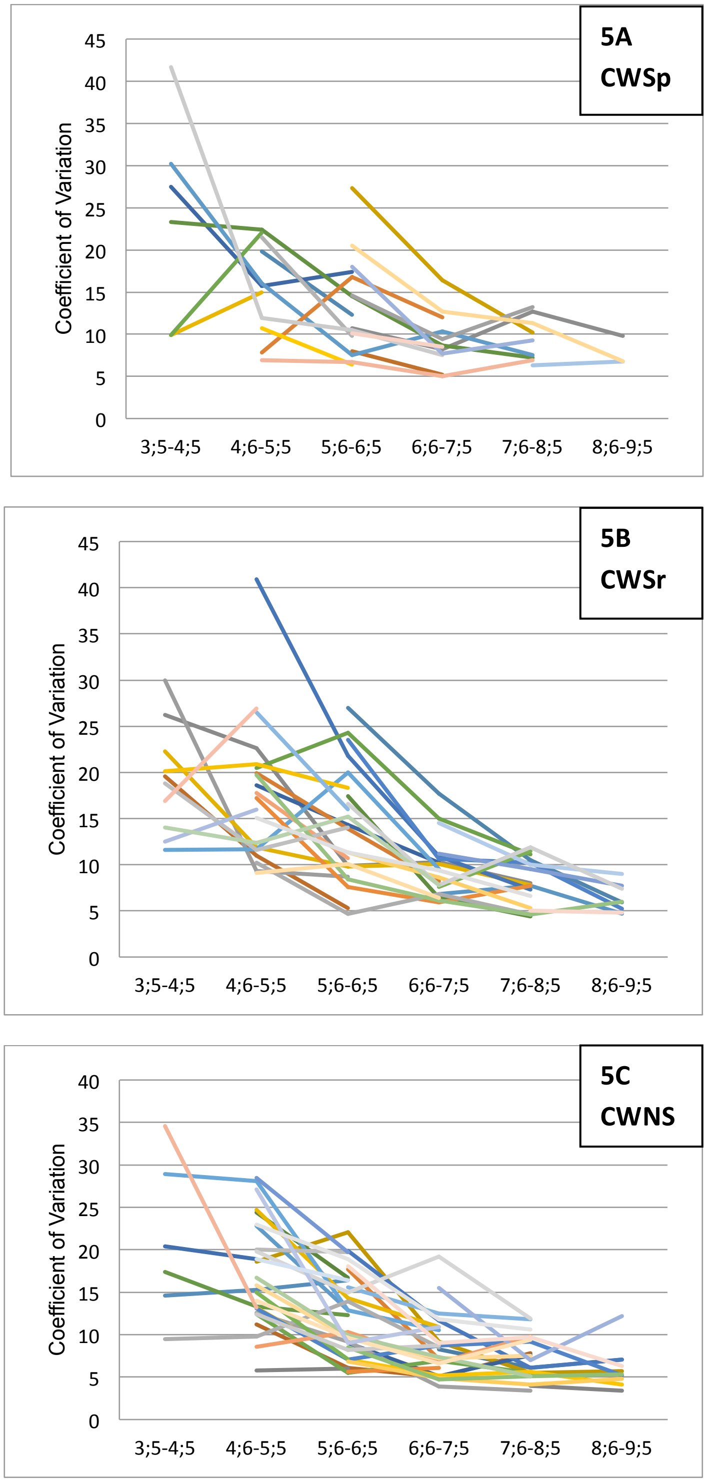

Figure 5: Individual data for clapping performance in persisted (CWSp) **(5A)**, recovered (CWSr) **(5B)**, and children who never stuttered (CWNS) **(5C)**. Each subject is represented by a different color line.

DISCUSSION

In this study, the bimanual motor timing control in preschool children who stutter was examined. As an extension of Olander et al. (2010), we utilize a bimanual clapping task in a synchronization-continuation paradigm to measure motor timing performance in a larger sample of children that included subjects later recruited into the longitudinal study. Studying children closer to the onset of stuttering is crucial for identifying whether a potential generalized motor timing deficit is an influential factor in the onset and persistence in stuttering. Two analyses were performed to answer these questions. First, in a cross-sectional analysis we compared CWS and CWNS in the initial year that the child performed the clapping task. This analysis addressed the question: do children who stutter between 4 and 5 years of age demonstrate differences in bimanual motor timing performance compared to their nonstuttering peers? In Olander et al. (2010), a subgroup of 60% of seventeen CWS 4-5 years of age had poorer clapping performance than the poorest performing child who did not stutter. In the present analysis, we examined overall clapping performance of larger groups CWS and CWNS at age 4-5 years, and we also observed whether a subgroup of poor-clapping CWS were the children who eventually persisted in stuttering. For the second question, we took two approaches. The children in the cross sectional study were retrospectively grouped according to their ultimate stuttering status, and their data were replotted to determine if those children who would ultimately persist tended to have poorer timing ability on first testing. We also assessed clapping variability as the children performed the task once a year for five years (age range 3;5 to 9;5 years). These analyses addressed the question: Is a bimanual motor timing deficit predictive of persistence or recovery in stuttering? Taken together, these analyses examine a potential general motor timing deficit in CWS as an influential factor for the onset and persistence of stuttering.

In the cross-sectional analysis for the first year large dataset, there were no differences in bimanual motor timing performance, either for clapping rate or clapping variability, between CWS and CWNS. Timing consistency was measured using the detrended coefficient of variation for inter-clap interval, thus normalizing each participant's variation measures to their mean rate of clapping. Compared to the earlier, smaller *n* study from our lab (Olander et al.), we found a much smaller percentage subgroup of poor clapping timing performance in CWS, with 4% of the CWS (i.e. two out of 47 children) performing more poorly than the poorest performing CWNS. This is in marked contrast to the subgroup 60% of CWS seen in Olander et al. (2010). With the larger sample sizes in the current analysis, the CWS and CWNS overlapped along the range of performance with no significant group differences between the two. Since we utilized an expanded sample from Olander et al. (2010), the same poor-clapping CWS were detected in our new analysis, but with considerable overlap with the CWNS (see Figure 2). Variability in clapping performance was observed for both groups, with performance ranging from poor to excellent distributed throughout the continuum for CWS and CWNS.

Additionally, the more variable clapping CWS at age 4-5 years were not the children who eventually persisted in stuttering (see Figure 3). Rather, this group of poor clappers consisted of a mix of both the persisting and recovered children. In fact, many of the children who would eventually persist exhibited the lowest timing variability. One of the goals of work in our laboratory is to develop a battery of tests that can be used to predict the likelihood of persistence or recovery of stuttering in preschoolers. This would allow targeted treatment for those children at the highest risk for persistent stuttering. Thus, the present finding of a lack of predictive power for basic timing variability, as measured from the simple task of clapping, suggests that clapping measures will not be a useful part of such a battery.

On the other hand, our findings regarding the absence of a basic timing deficit in clapping for stuttering children, coupled with Walsh & Smith (manuscript in preparation), provide interesting insight into overall motor control characteristics in preschool children who stutter. Walsh & Smith measured speech motor coordination consistency during fluent productions of simple sentences in an overlapping sample of children from the same project between 4-5 years of age. In this study, the children produced simple sentences (e.g. “Buy Bobby a puppy”) while the motions of the upper lip, lower lip, and jaw were tracked using the same Optotrak motion capture system used in the current study. When basic movement parameters and coordination consistency were measured, the boys who stutter, but not the girls, exhibited reduced displacement and velocity dynamic ranges, as well as greater coordination variability in the production of simple sentences. These combined results suggest that the stuttering etiology in children, particularly boys who stutter, may lie in deficits or lags in motor control specific to the speech motor system rather than in a generalized motor timing deficit. However, a speech motor deficit is not a defining characteristic of all children who stutter, as no significant differences in speech motor coordination consistency were found for the girls who stutter.

In the longitudinal analysis, children’s clapping performance was followed across five years with an age range of 3;5 to 9;5 years of age. Longitudinal developmental profiles were compared among the children who stutter who eventually persisted (CWSp), children who stutter who eventually recovered (CWSr), and children who never stuttered (CWNS). No differences were found among the group developmental profiles: All three groups improved in parallel across the years. These findings suggest the unsurprising fact that all of the children generally improve in bimanual motor timing control throughout development. The individual longitudinal profiles (Figure 5) further demonstrate a similar range in performance across the profiles, with poor clappers and excellent clappers all improving as a function of age without regard to stuttering status.

Language and phonological status at the initial year of testing were assessed to examine a potential interaction with clapping performance. A language deficit and/or a phonological deficit in CWS did not influence variability in clapping performance, and these children performed comparably to children with normal language and phonology. This is an interesting finding in light of previous studies of children with SLI and phonological impairments who demonstrate motor deficits (Brumbach & Goffman, 2014; Ramus, Pidgeon, & Frith, 2003). A possible reason may be due to task complexity; a more challenging task involving rhythmic sequencing of movements may better reveal potential deficits.

Overall, the current findings offer a new perspective to the disparity seen in earlier studies of non-speech motor timing and coordination in stuttering, demonstrating that a general timing deficit is not observed in a simple bimanual clapping task in preschool children who stutter, but may be present in adults who stutter. Multiple confounding factors may be contributing to the conflicting results of the earlier studies. Sampling error is one factor that presents a particular challenge in investigating heterogeneous disorders such as stuttering. Representative sampling is crucial to acquiring results reflecting the entire population. Many of the studies that reported poor timing ability in stuttering also utilized relatively small sample sizes that may have resulted in sampling error. Sample error is exemplified in the dramatically different results in Olander et al. (2010) and the present study. The sample size was enlarged from 17 CWS in Olander et al. (2010) to 47 CWS in the present study, and 13 CWNS to 37 CWNS. With this addition, the subgroup of 60% poor clapping CWS (i.e. 10 out of 17 children) found in Olander et al. (2010) overlapped with many of the CWNS in the present analysis. Moreover, the subgroup of poor-performing CWS that scored worse than the poorest performing CWNS was reduced to 4% of CWS (i.e. 2 out of 47 children). Unlike the earlier study from our lab (i.e. Olander et al., 2010) using identical data collection and analysis techniques, we found no significant group differences.

Task complexity also may play a role in these conflicting results. The tasks utilized across studies of non-speech motor ability in stuttering range from very simple to highly complex. More complex tasks have greater potential for revealing timing differences. As described earlier, this phenomenon was observed in Zelaznik et al. (1994) and Zelaznik et al. (1997) when task difficulty was increased from a simple unimanual finger tapping to a more difficult bimanual finger synchronization-continuation task. This modification unveiled significantly poorer timing ability in the AWS that were not previously observed. Task complexity is a challenge in the current study; it is necessary to find a task that is complex enough to elicit a potential deficit, but not too difficult for children at three to four years of age. Clapping is a developmentally appropriate task that the children at all ages in our study were able to successfully complete; however a more complex rhythm continuation or sequencing activity may have increased the potential for observing differences. Yet, as observed in Figure 2, variability in clapping performance was distributed across a wide range for the CWS and CWNS, suggesting a varying level of difficulty for the children.

An important question for stuttering concerns the neural bases of this neurodevelopmental disorder. As described earlier, atypical neural activation for non-speech behavior has been observed in both adults and children who stutter. In particular, the basal ganglia, a region involved in internal timing of movement, have been implicated for these differences in stuttering (Beal et al., 2013; Chang & Zhu, 2013; Foundas et al., 2013). Deficits in the basal ganglia should show behavioral differences in motor timing for speech and non-speech movements. However, the findings in the current study do not support this, showing that CWS do not demonstrate a deficit in bimanual timing control. Etchell et al. (2014) offer an explanation for these paradoxical findings of neuroimaging and behavioral data, arguing that the absence of behavioral differences does not imply the absence of differences at a neural level. Another possibility is that behavioral tasks recruit more neural areas and complex networks that may be compensating for a timing deficit.

Overall, this study provides critical insight into the lack of influence of bimanual timing performance to the onset and persistence in stuttering. Bimanual timing performance in preschool children shows no differences between CWS and CWNS, nor is it predictive of eventual persistence or recovery of stuttering. This is demonstrated in the similarities of the developmental profiles among the groups whose stuttering persisted and recovered and, and typical developing children. All of the children appear to improve in bimanual motor timing control with maturation.

Conclusion

The results of the present study using a larger sample of CWS studied to date in a motor timing task reveal that preschool children who stutter do not differ from their nonstuttering peers on rates of clapping and are not more variable than typically developing peers in performance of a bimanual rhythmic timing task. Additionally, bimanual motor timing differences are not a likely candidate as a contributing factor to the eventual persistence or recovery from stuttering. From these findings, we conclude that a bimanual motor timing deficit is not a core feature of persistent developmental stuttering.

REFERENCES

REFERENCES

Alm, P.A. (2007). The dual premotor model of cluttering and stuttering: A neurological framework. In P*roceedings of the First World Conference on Cluttering, Katarino, Bulgaria*. (pp. 207-210)

Ambrose, N. G., & Yairi, E. (1999). Normative disfluency data for early childhood stuttering. *Journal of Speech, Language, and Hearing Research, 42*(4), 895-909.

Archibald, L., & De Nil, L. F. (1999). The relationship between stuttering severity and kinesthetic acuity for jaw movements in adults who stutter. *Journal of Fluency Disorders, 24*(1), 25-42.

Arndt, J., & Healey, E. C. (2001). Concomitant disorders in school-age children who stutter. *Language Speech and Hearing Services in Schools, 32*(2), 68-78.

Bankson, N. W., & Bernthal, J. E. (1990). *Bankson-Bernthal test of phonology*: Applied Symbolix.

Beal, D. S., Gracco, V. L., Brettschneider, J., Kroll, R. M., & De Nil, L. F. (2013). A voxel-based morphometry (VBM) analysis of regional grey and white matter volume abnormalities within the speech production network of children who stutter. *cortex, 49*(8), 2151-2161.

Bengtsson, S. L., Ehrsson, H. H., Forssberg, H., & Ullén, F. (2005). Effector-independent voluntary timing: behavioural and neuroimaging evidence. *European Journal of Neuroscience, 22*(12), 3255-3265.

Binkofski, F., & Buccino, G. (2004). Motor functions of the Broca's region. *Brain Lang., 89*(2), 362-369.

Boutsen, F. R., Brutten, G. J., & Watts, C. R. (2000). Timing and intensity variability in the metronomic speech of stuttering and nonstuttering speakers. *Journal of Speech Language and Hearing Research, 43*(2), 513-520.

Brown, C. J., Zimmermann, G. N., Linville, R. N., & Hegmann, J. P. (1990). Variations in self-paced behaviors in stutterers and nonstutterers. *Journal of Speech and Hearing Research, 33*(2), 317-323.

Brumbach, A. C. D., & Goffman, L. (2014). Interaction of language processing and motor skill in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *57*(1), 158-171.

Burgemeister, B. B., Blum, L. H., & Lorge, I. (1972). *Columbia mental maturity scale*: Harcourt, Brace Jovanovich.

Busan, P., D'Ausilio, A., Borelli, M., Monti, F., Pelamatti, G., Pizzolato, G., et al. (2013). Motor excitability evaluation in developmental stuttering: A transcranial magnetic stimulation study. *Cortex, 49*(3), 781-792.

Carrow-Woolfolk, E. (1999). *Test for Auditory Comprehension of Language: TACL-3*: Pro-Ed.

Caruso, A. J., Abbs, J. H., & Gracco, V. L. (1988). Kinematic analysis of multiple movement coordination during speech in stutterers. *Brain, 111*(2), 439-455.

Chang, S.-E., Erickson, K. I., Ambrose, N. G., Hasegawa-Johnson, M. A., & Ludlow, C. L. (2008). Brain anatomy differences in childhood stuttering. *Neuroimage, 39*(3), 1333-1344.

Chang, S.-E., & Zhu, D. C. (2013). Neural network connectivity differences in children who stutter. *Brain*, *136*(12). 3709-3726.

Chang, S. E., Horwitz, B., Ostuni, J., Reynolds, R., & Ludlow, C. L. (2011). Evidence of left inferior frontal-premotor structural and functional connectivity deficits in adults who stutter. *Cerebral Cortex, 21*(11), 2507-2518.

Chang, S. E., Kenney, M. K., Loucks, T. M. J., & Ludlow, C. L. (2009). Brain activation abnormalities during speech and non-speech in stuttering speakers. *Neuroimage, 46*(1), 201-212.

Conture, E. G. (1990). *Stuttering*: Prentice Hall Englewood Cliffs, NJ:.

Cooper, M. H., & Allen, G. D. (1977). Timing control accuracy in normal speakers and stutterers. *Journal of Speech, Language, and Hearing Research, 20*(1), 55-71.

Dawson, J. I., Stout, C. E., & Eyer, J. A. (2003). *SPELT-3: Structured Photographic Expressive Language Test*: Janelle Publications.

De Nil, L. F., & Abbs, J. H. (1991). Kinaesthetic acuity of stutterers and non-stutterers for oral and non-oral movements. *Brain, 114*(5), 2145-2158.

Etchell, A. C., Johnson, B. W., & Sowman, P. F. (2014). Behavioral and multimodal neuroimaging evidence for a deficit in brain timing networks in stuttering: hypothesis and theory. *Frontiers in human neuroscience, 8,* 467.

Falk, S., Müller, T., & Bella, S. D. (2014). Sensorimotor synchronization in stuttering children and adolescents. *Procedia-Social and Behavioral Sciences, 126*, 206-207.

Fitzpatrick, P., Schmidt, R., & Carello, C. (1996). Dynamical patterns in clapping behavior. *Journal of Experimental Psychology: Human Perception and Performance, 22*(3), 707-724.

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*: MIT press.

Forster, D. C., & Webster, W. G. (2001). Speech-motor control and interhemispheric relations in recovered and persistent stuttering. *Developmental neuropsychology, 19*(2), 125-145.

Foundas, A., Mock, J., Cindass Jr, R., & Corey, D. (2013). Atypical caudate anatomy in children who stutter. *Perceptual and motor skills, 116*(2), 528-543.

Franz, E. A., Zelaznik, H. N., & Smith, A. (1992). Evidence of common timing processes in the control of manual, orofacial, and speech movements. *Journal of Motor Behavior, 24*(3), 281-287.

Gardner, M. F. (1996). *TAPS-R: Test of Auditory-perceptual Skills-revised*: Psychological and Educational Publications.

Getchell, N. (2006). Age and task-related differences in timing stability, consistency, and natural frequency of children's rhythmic, motor coordination. *Developmental psychobiology, 48*(8), 675-685.

Getchell, N., & Whitall, J. (2003). How do children coordinate simultaneous upper and lower extremity tasks? The development of dual motor task coordination. *Journal of experimental child psychology, 85*(2), 120-140.

Henry, F. M. (1968). Specificity vs. generality in learning motor skill. *Classical studies on physical activity*, 328-331.

Hollingshead, A. B. (1975). Four factor index of social status.

Howell, P., Au-Yeung, J., & Rustin, L. (1997). Clock and motor variances in lip-tracking: A comparison between children who stutter and those who do not. In W. Hulstijn, H. F. M. Peters & P. H. H. vanLieshout (Eds.), *Speech Production: Motor Control, Brain Research and Fluency Disorders* (Vol. 1146, pp. 573-578).

Hulstijn, W., Summers, J. J., Vanlieshout, P. H. M., & Peters, H. F. M. (1992). Timing in finger tapping and speech - a comparison between stutterers and fluent speakers. *Human Movement Science, 11*(1-2), 113-124.

Ingham, R. J., Grafton, S. T., Bothe, A. K., & Ingham, J. C. (2012). Brain activity in adults who stutter: Similarities across speaking tasks and correlations with stuttering frequency and speaking rate. *Brain and language, 122*(1), 11-24.

Ivry, R. B., & Richardson, T. C. (2002). Temporal control and coordination: the multiple timer model. *Brain and Cognition, 48*(1), 117-132.

Keele, S. W., & Hawkins, H. L. (1982). Explorations of individual differences relevant to high level skill. *Journal of Motor Behavior*, *14*(1), 3-23.

Keele, S. W., Ivry, R. I., & Pokorny, R. A. (1987). Force control and its relation to timing. *Journal of Motor Behavior, 19*(1), 96-114.

Keele, S. W., Pokorny, R. A., Corcos, D. M., & Ivry, R. (1985). Do perception and motor production share common timing mechanisms: A correlational analysis. *Acta psychologica, 60*(2), 173-191.

Kent, R. D. (1983). The segmental organization of speech. *The production of speech* (pp. 57-89): Springer.

Klapp, S. T. (1981). Temporal compatibility in dual motor tasks II: Simultaneous articulation and hand movements. *Memory & Cognition, 9*(4), 398-401.

Kleinow, J., & Smith, A. (2000). Influences of length and syntactic complexity on the speech motor stability of the fluent speech of adults who stutter. *Journal of Speech, Language, and Hearing Research, 43*(2), 548-559.

Komeilipoor, N., Vicario, C. M., Daffertshofer, A., & Cesari, P. (2014). Talking hands: tongue motor excitability during observation of hand gestures associated with words. *Frontiers in Human Neuroscience*, *8*, 767.

LaGasse, A. B. (2013). Influence of an external rhythm on oral motor control in children and adults. *Journal of music therapy, 50*(1), 6-24.

Ludlow, C. L., & Loucks, T. (2004). Stuttering: a dynamic motor control disorder. *Journal of fluency disorders, 28*(4), 273-295.

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.

Max, L., Caruso, A. J., & Gracco, V. L. (2003). Kinematic analyses of speech, orofacial nonspeech, and finger movements in stuttering and nonstuttering adults. *Journal of Speech Language and Hearing Research, 46*(1), 215-232.

Max, L., & Gracco, V. L. (2005). Coordination of oral and laryngeal movements in the perceptually fluent speech of adults who stutter. *Journal of Speech, Language & Hearing Research, 48*(3), 524-542.

Max, L., Guenther, F. H., Gracco, V. L., Ghosh, S. S., & Wallace, M. E. (2004). Unstable or insufficiently activated internal models and feedback-biased motor control as sources of dysfluency: A theoretical model of stuttering. *Contemporary issues in communication science and disorders, 31*, 105-122.

Max, L., & Yudman, E. M. (2003). Accuracy and variability of isochronous rhythmic timing across motor systems in stuttering versus nonstuttering individuals. *Journal of Speech, Language and Hearing Research, 46*(1), 146-163.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: life span development of timing and event tracking. *Journal of Experimental Psychology: General, 135*(3), 348-367.

McClean, M. D., & Runyan, C. M. (2000). Variations in the relative speeds of orofacial structures with stuttering severity. *Journal of Speech, Language, and Hearing Research, 43*(6), 1524-1531.

Michon, J. A., & Instituut voor Zintuigfysiologie RVO-TNO (Soesterberg, P.-B.) (1967). *Timing in temporal tracking.* Institute for Perception RVO-TNO, Soesterberg, The Netherlands.

Möttönen, R., Farmer, H., & Watkins, K. E. (2010). Lateralization of motor excitability during observation of bimanual signs. *Neuropsychologia*, *48*(10), 3173-3177.

Neef, N. E., Jung, K., Rothkegel, H., Pollok, B., von Gudenberg, A. W., Paulus, W., et al. (2011). Right-shift for non-speech motor processing in adults who stutter. *Cortex, 47*(8), 945-954.

Olander, L., Smith, A., & Zelaznik, H. N. (2010). Evidence that a motor timing deficit is a factor in the development of stuttering. *Journal of Speech, Language and Hearing Research, 53*(4), 876-886.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the edinburgh inventory. *Neuropsychologia, 9*(1), 97-113.

Paden, E. P., Yairi, E., & Ambrose, N. G. (1999). Early childhood stuttering II: Initial status of phonological abilities. *Journal of Speech Language and Hearing Research, 42*(5), 1113-1124.

Peters, H. F., & Boves, L. (1988). Coordination of aerodynamic and phonatory processes in fluent speech utterances of stutterers. *Journal of Speech, Language, and Hearing Research, 31*(3), 352-361.

Ramus, F., Pidgeon, E., & Frith, U. (2003). The relationship between motor control and phonology in dyslexic children*. Journal of Child Psychology and Psychiatry*, 44(5), 712-722.

Riley, G. D., & Riley, J. (1980). Motoric and linguistic variables among children who stutter - a factor-analysis. *Journal of Speech and Hearing Disorders, 45*(4), 504-514.

Rizzolatti, G., Fadiga, L., Matelli, M., Bettinardi, V., Paulesu, E., Perani, D., et al. (1996). Localization of grasp representations in humans by PET .1. Observation versus execution. *Experimental Brain Research, 111*(2), 246-252.

Robbins, J., & Klee, T. (1987). Clinical assessment of oropharyngeal motor development in young children. *Journal of Speech and Hearing Disorders, 52*(3), 271-277.

Robertson, S. D. (2001). Development of bimanual skill: The search for stable patterns of coordination. *Journal of motor behavior, 33*(2), 114-126.

Serrien, D. J. (2008). The neural dynamics of timed motor tasks: Evidence from a synchronization–continuation paradigm. *European Journal of Neuroscience, 27*(6), 1553-1560.

Siegel, S., & Castellan Jr, N. J. (1988). *Nonparametrics statistics for the behavioral sciences.* 2^{nd} ed. New York, NY McGraw-Hill.

Smith, A. (1990). Factors in the etiology of stuttering. *ASHA Reports, 18*, 39-47.

Smith, A. (1990). Toward a comprehensive theory of stuttering - a commentary. *Journal of Speech and Hearing Disorders, 55*(3), 398-401.

Smith, A. (1999). Stuttering: A unified approach to a multifactorial, dynamic disorder. *Stuttering research and practice: Bridging the gap*, 27-44.

Smith, A., Goffman, L., Sasisekaran, J., & Weber-Fox, C. (2012a). 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., & Kelly, E. (1997a). Stuttering: A dynamic, multifactorial model. *Nature and treatment of stuttering: New directions, 2*, 204-217.

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

Smith, A., Luschei, E., Denny, M., Wood, J., Hirano, M., & Badylak, S. (1993). Spectral analyses of activity of laryngeal and orofacial muscles in stutterers. *Journal of Neurology, Neurosurgery & Psychiatry, 56*(12), 1303-1311.

Smith, A., McFarland, D. H., & Weber, C. M. (1986). Interactions between speech and finger movements - an exploration of the dynamic pattern perspective. *Journal of Speech and Hearing Research, 29*(4), 471-480.

Smith, A., & Zelaznik, H. (1990). Comparative investigations of speech and other neuromotor systems. *Advances in Psychology, 70*, 575-594.

Smits-Bandstra, S., De Nil, L., & Rochon, E. (2006). The transition to increased automaticity during finger sequence learning in adult males who stutter. *Journal of fluency disorders, 31*(1), 22-42.

Smits-Bandstra, S., De Nil, L. F., & Saint-Cyr, J. A. (2006). Speech and nonspeech sequence skill learning in adults who stutter. *Journal of Fluency Disorders, 31*(2), 116-136.

Sommer, M., Koch, M. A., Paulus, W., Weiller, C., & Büchel, C. (2002). Disconnection of speech-relevant brain areas in persistent developmental stuttering. *The Lancet*, *360*(9330), 380-383.

Sowiński, J., & Dalla Bella, S. (2013). Poor synchronization to the beat may result from deficient auditory-motor mapping. *Neuropsychologia, 51*(10), 1952-1963.

Spencer, R. M., Zelaznik, H. N., Diedrichsen, J., & Ivry, R. B. (2003). Disrupted timing of discontinuous but not continuous movements by cerebellar lesions. *Science, 300*(5624), 1437-1439.

Starkweather, C. W. (1993). Issues in the efficacy of treatment for fluency disorders. *Journal of Fluency Disorders, 18*(2), 151-168.

Tingley, B. M., & Allen, G. D. (1975). Development of speech timing control in children. *Child Development*, 186-194.

Van Riper, C. The nature of stuttering, 1982: Prentice-Hall, Englewood Cliffs, NJ.

Wall, M. J., & Myers, F. L. (1995). *Clinical management of childhood stuttering*: Pro-ed Austin, TX.

Walsh, B., & Smith, A. (manuscript in preparation). Atypical speech motor development in early childhood stuttering.

Walsh, B., & Smith, A. (2013). Oral electromyography activation patterns for speech are similar in preschoolers who do and do not stutter. *Journal of Speech, Language, and Hearing Research*, *56*(5), 1441-1454.

Ward, D. (1997). Intrinsic and extrinsic timing in stutterers' speech: Data and implications. *Language and Speech, 40*(3), 289-310.

Watkins, K. E., Smith, S. M., Davis, S., & Howell, P. (2008). Structural and functional abnormalities of the motor system in developmental stuttering. *Brain, 131*(1), 50-59.

Watkins, R. V., Yairi, E., & Ambrose, N. G. (1999). Early childhood stuttering initial Status of Expressive Language Abilities. *Journal of Speech, Language, and Hearing Research, 42*(5), 1125-1135.

Webster, W. G. (1985). Neuropsychological models of stuttering—I. Representation of sequential response mechanisms. *Neuropsychologia, 23*(2), 263-267.

Webster, W. G. (1986). Response sequence organization and reproduction by stutterers. *Neuropsychologia, 24*(6), 813-821.

Westphal, G. (1933). An experimental study of certain motor abilities of stutterers. *Child Development, 4*(3), 214-221.

Wing, A. M., & Kristofferson, A. (1973). The timing of interresponse intervals. *Perception & Psychophysics, 13*(3), 455-460.

Wing, A. M., & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses. *Perception & Psychophysics, 14*(1), 5-12.

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

Yu, H., Russell, D. M., & Stenard, D. (2003). Task-effector asymmetries in a rhythmic continuation task. *Journal of Experimental Psychology: Human Perception and Performance, 29*(3), 616-630.

Zelaznik, H. N., Smith, A., & Franz, E. A. (1994). Motor-performance of stutterers and nonstutterers on timing and force control tasks. *Journal of Motor Behavior, 26*(4), 340-347.

Zelaznik, H. N., Smith, A., Franz, E. A., & Ho, M. (1997). Differences in bimanual coordination associated with stuttering. *Acta Psychologica, 96*(3), 229-243.

Zimmermann, G. (1980). Articulatory dynamics of fluent utterances of stutterers and nonstutterers. *Journal of Speech and Hearing Research, 23*(1), 95-107.

APPENDIX

Table of individual subject information. “S” refers to a child who stutters, and “C” referS to a child who did not stutter.

Participant	Gender	Age at first visit (year; month)	Hand	Age of onset (months)	SLD's per 100 syllables	Pass speech?	Pass language?	In therapy?	Recover or persist?	Mother's Ed
S1	M	4;0	R	30	2.85	N	Y	Y	unkn.	5
S2	M	5;6	R	30	3.81	Y	Y	Y	R	7
S3	M	6;3	R	48	5.92	Y	Y	Y	P	4
S4	M	5;7	R	30	7.83	N	Y	Y	P	4
S5	F	4;1	L	24	7.71	N	N	Y	R	6
S6	M	4;1	R	36	9.57	Y	Y	Y	P	6
S7	M	4;1	R	36	7.73	N	Y	N	P	6
S8	M	4;0	R	36	6.98	N	N	Y (L)	R	7
S9	M	4;2	R	36	6.10	Y	Y	N	unkn.	5
S10	M	4;7	R	42	7.87	Y	Y	N	R	6
S11	M	4;0	R	36	3.18	N	N	N	R	4
S12	F	6;11	R	36	4.46	Y	Y	Y	R	6
S13	M	4;0	R	24	9.39	Y	Y	N	P	6
S14	M	5;1	L	48	16.29	N	Y	N	R	6
S15	F	4;1	R	42	24.66	N	Y	Y	P	4
S16	M	3;9	R	30	5.99	Y	Y	Y	R	6
S17	M	4;10	R	36	18.93	Y	Y	Y	P	4
S18	M	6;5	R	54	10.27	Y	Y	N	P	6
S19	F	4;1	R	30	39.82	N	N	Y	R	4
S20	M	4;2	R	42	6.82	Y	Y	Y (L)	P	5
S21	M	6;9	R	42	7.95	N	N	Y	P	2
S22	M	4;1	L	37	10.28	Y	Y	Y	P	6
S23	M	4;6	R	24	6.00	Y	Y	N	R	6
S24	M	5;0	R	unkn.	5.75	N	Y	N	unkn.	6
S25	M	4;9	R	36	2.21	Y	Y	N	R	6
S26	M	5;11	R	36	4.80	N	N	Y	unkn.	4
S27	M	4;9	R	unkn.	11.02	N	Y	N	P	6
S28	F	4;2	R	24	7.83	Y	Y	N	R	7
S29	M	4;5	R	24	4.07	N	Y	N	R	5
S30	F	4;7	R	unkn.	4.42	N	Y	N	unkn.	4

Participant	Gender	Age at first visit (year; month)	Hand	Age of onset (months)	SLD's per 100 syllables	Pass speech?	Pass language?	In therapy?	Recover or persist?	Mother's Ed
S31	F	4;6	R	36	5.36	N	Y	N	R	5
S32	M	4;0	R	24	3.65	Y	Y	N	P	6
S33	M	5;10	R	42	2.60	Y	Y	N	P	5
S34	M	5;8	L	30	4.04	Y	Y	N	R	7
S35	M	4;8	L	24	16.89	Y	Y	N	R	7
S36	M	5;1	R	48	15.13	N	N	Y	P	6
S37	M	4;6	R	36	3.38	N	Y	Y	R	7
S38	F	4;11	R	36	2.79	Y	Y	N	R	6
S39	F	4;4	R	24	6.58	Y	Y	N	P	6
S40	F	3;11	R	36	13.15	Y	Y	N	R	7
S41	F	4;0	R	33	3.89	Y	Y	Y	R	7
S42	M	4;9	R	46	10.8	N	Y	Y	R	6
S43	unkn.	unkn.	unkn.	unkn.	15.16	Y	N	unkn.	P	unkn.
S44	M	6;7	R	52	25.69	Y	Y	Y	P	4
S45	F	4;10	R	46	2.65	Y	Y	N	R	7
S46	F	4;10	R	48	5.55	Y	Y	N	R	4
S47	M	6;5	L	66	11.31	N	N	Y	P	7
S48	M	unkn.	unkn.	unkn.	unkn.	N	Y	unkn.	unkn.	unkn.
S49	F	unkn.	unkn.	unkn.	10.54	N	N	unkn.	unkn.	unkn.
S50	M	3;5	R	36	4.7	N	Y	Y (L)	R	7
S51	F	4;11	R	36	7.83	Y	Y	Y	P	7
S52	M	6;0	R	36	5.36	Y	N	Y	R	6
S53	M	4;7	R	22	3.16	Y	Y	Y	R	6
S54	M	4;0	R	unkn.	2.89	Y	Y	N	R	7
S55	M	4;0	R	24	18.06	N	Y	Y	P	6
S56	M	6;0	R	30	4.78	Y	Y	N	P	7
S57	M	3;11	R	24	10.93	Y	Y	N	R	7

Participant	Gender	Age at first visit (year; month)	Hand	Age of onset (months)	SLD's per 100 syllables	Pass speech?	Pass language?	In therapy?	Recover or persist?	Mother's Ed
S58	M	5;8	R	36	28.93	N	Y	Y	P	5
S59	F	6;11	R	36	4.11	Y	Y	Y	P	7
S60	M	5;1	R	42	3.87	N	Y	N	R	5
S61	M	5;3	R	48	2.3	N	Y	Y (P)	P	6
S62	M	6;10	R	80	7.58	N	Y	Y	R	6
S63	F	4;10	R	36	5.75	N	Y	Y	P	4
S64	M	4;8	R	unkn.	1.33	unkn.	N	N	P	6
S65	M	4;8	R	unkn.	6.97	N	N	N	P	6
S66	M	4;0	L	unkn.	5.26	Y	N	N	unkn.	5
S67	M	6;1	R	unkn.	7.74	Y	Y	Y	unkn.	5
S68	M	5;0	R	unkn.	9.67	N	Y	Y	unkn.	6
S69	F	3;9	R	unkn.	9.58	unkn.	unkn.	Y	unkn.	7
S70	F	4;4	R	unkn.	4.41	N	Y	N	P	6
C1	M	5;0	R	n/a	3.61	Y	Y	N	n/a	7
C2	M	5;5	R	n/a	n/a	Y	Y	N	n/a	6
C3	F	5;5	R	n/a	n/a	Y	Y	N	n/a	7
C4	F	4;6	R	n/a	n/a	Y	Y	N	n/a	6
C5	F	4;0	R	n/a	n/a	Y	Y	N	n/a	5
C6	F	4;8	R	n/a	n/a	Y	Y	N	n/a	7
C7	M	4;0	R	n/a	n/a	Y	Y	N	n/a	7
C8	M	4;5	R	n/a	n/a	Y	Y	N	n/a	4
C9	M	5;10	L	n/a	n/a	Y	Y	N	n/a	7
C10	F	4;8	R	n/a	n/a	Y	Y	N	n/a	3
C11	M	4;5	R	n/a	n/a	Y	Y	N	n/a	4
C12	F	4;0	R	n/a	n/a	Y	Y	N	n/a	7
C13	F	4;10	R	n/a	n/a	Y	Y	N	n/a	7
C14	M	3;11	L	n/a	n/a	Y	Y	N	n/a	7
C15	M	4;10	L	n/a	n/a	Y	Y	N	n/a	7
C16	M	4;1	R	n/a	n/a	Y	Y	N	n/a	7
C17	M	5;10	R	n/a	n/a	Y	Y	N	n/a	6
C18	M	4;11	R	n/a	n/a	Y	Y	N	n/a	7
C19	M	4;2	R	n/a	n/a	Y	Y	N	n/a	7
C20	M	4;3	R	n/a	n/a	Y	Y	N	n/a	7
C21	M	4;2	R	n/a	n/a	Y	Y	N	n/a	6
C22	F	4;9	R	n/a	n/a	Y	Y	N	n/a	7
C23	M	4;9	R	n/a	n/a	Y	Y	N	n/a	7
C24	unkn.	unkn.	unkn.	n/a	n/a	Y	Y	N	n/a	unkn.

Participant	Gender	Age at first visit (year; month)	Hand	Age of onset (months)	SLD's per 100 syllables	Pass speech?	Pass language?	In therapy?	Recover or persist?	Mother's Ed
C25	M	4;2	L	n/a	n/a	Y	Y	N	n/a	6
C26	M	4;8	L	n/a	n/a	Y	Y	N	n/a	6
C27	M	6;2	R	n/a	n/a	Y	Y	N	n/a	6
C28	M	5;3	R	n/a	n/a	Y	Y	N	n/a	5
C29	M	5;1	R	n/a	n/a	Y	Y	N	n/a	6
C30	F	5;7	R	n/a	n/a	Y	Y	N	n/a	7
C31	F	6;3	R	n/a	n/a	Y	Y	N	n/a	6
C32	M	3;6	R	n/a	n/a	Y	Y	N	n/a	7
C33	M	4;11	L	n/a	n/a	Y	Y	N	n/a	5
C34	F	4;8	R	n/a	n/a	Y	Y	N	n/a	7
C35	F	6;11	R	n/a	n/a	Y	Y	N	n/a	5
C36	F	4;11	R	n/a	n/a	Y	Y	N	n/a	5
C37	F	4;4	R	n/a	n/a	Y	Y	N	n/a	6
C38	M	5;4	R	n/a	n/a	Y	Y	N	n/a	6
C39	M	4;11	R	n/a	n/a	Y	Y	N	n/a	7
C40	F	5;4	R	n/a	n/a	Y	Y	N	n/a	5
C41	M	4;11	R	n/a	n/a	Y	Y	N	n/a	5
C42	unkn.	unkn.	unkn.	n/a	n/a	Y	Y	N	n/a	unkn.
C43	unkn.	unkn.	unkn.	n/a	n/a	Y	Y	N	n/a	unkn.
C44	M	5;6	R	n/a	n/a	Y	Y	N	n/a	6
C45	M	4;7	R	n/a	n/a	Y	Y	N	n/a	7