Evidence That a Motor Timing Deficit Is a Factor in the Development of Stuttering

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Purpose: To determine whether young children who stutter have a basic motor timing and/or a coordination deficit.
Method: Between-hands coordination and variability of rhythmic motor timing were assessed in 17 children who stutter (4–6 years of age) and 13 age-matched controls. Children clapped in rhythm with a metronome with a 600-ms interbeat interval and then attempted to continue to match this target rate for 32 unpaced claps.
Results: Children who stutter did not significantly differ from children who were typically developing on mean clapping rate or number of usable trials produced; however, they produced remarkably higher variability levels of interclap interval. Of particular interest was the bimodal distribution of the stuttering children on clapping variability. One subgroup of children who stutter clustered within the normal range, but 60% of the children who stutter exhibited timing variability that was greater than the poorest performing nonstuttering child. Children who stutter were not more variable in measures of coordination between the 2 hands (mean and median phase difference between hands).
Conclusion: We infer that there is a subgroup of young stuttering children who exhibit a nonspeech motor timing deficit, and we discuss this result as it pertains to recovery or persistence of stuttering.

KEY WORDS: stuttering, motor timing, development of stuttering, bimanual motor control, nonspeech task

Stuttering is a disorder involving breakdowns in the speech motor system. Most theories of the causes of stuttering postulate that many factors are involved in producing these motor breakdowns, including genetic, linguistic, and psychosocial contributors (e.g., Conture, 1990; Smith, 1990, 1999; Starkweather, Gottwald, & Halfond, 1993; Van Riper, 1982; Wall & Myers, 1995). Despite the complex interaction of underlying factors in accounts of the onset and development of stuttering, it is clear that abnormal speech motor output is an essential component of stuttering. During the disfluencies that characterize stuttering, the speech motor system fails to generate and/or send the motor commands to muscles that are necessary for fluent speech to continue. Thus, disfluent intervals of speech in children and adults who stutter are clearly associated with breakdowns in the precise spatial and temporal control of movement necessary for fluent speech production. Also striking are findings that people who stutter often differ from controls in terms of the variability, speed, and relative timing of their articulatory movements when producing perceptually fluent speech (Kleinow & Smith, 2000; Max & Gracco, 2005; McClean & Runyan, 2000; McClean, Tasko, & Runyan, 2004; Zimmermann, 1980). These studies provide evidence for persistent motor timing and coordination deficits that are present in the speech motor control systems of people who stutter, even when there are no perceptible stuttering behaviors in their speech.

Many investigators have hypothesized that people who stutter have a general motor deficit (Max, Caruso, & Gracco, 2003; Webster, 1985; Zelaznik, Smith, Franz, & Ho, 1997) or, in some accounts, more specifically, a timing deficit (Boutsen, Brutten, & Watts, 2000; Kent, 1983) that contributes to the development and maintenance of the disorder. The underlying premise of this hypothesis is that motor control processes for speech, nonspeech oral, and limb movement share underlying neural substrates. Many neuroimaging studies have provided evidence for this overlap by identifying regions of the brain that are activated during speech and other motor behavior. Binkofski and Buccino (2004) observed activation in Broca's area during speech production and complex hand movements. Similarly, increased blood flow to Broca's area has been observed during performance of grasping gestures (Rizzolatti et al., 1996). Regions near Broca's area have also been identified as active during both rhythmic oral and limb movement (Bengtsson, Ehrsson, Forssberg, & Ullen, 2005).

Studies of speech and limb movements produced by normally fluent speakers have provided evidence of common characteristics and/or entrainment. For example, Smith, McFarland, and Weber (1986) found that when normally fluent participants spoke and tapped a finger at the same time, the pace and amplitude of the two activities spontaneously became coordinated. In addition, several studies of normally fluent participants have provided evidence that intrasubject timing, variability, and accuracy are similar for speech and nonspeech rhythmic movements (Bengtsson et al., 2005; Franz, Zelaznik, & Smith, 1992; Tingley & Allen, 1975), suggesting that individuals have common timing mechanisms that are utilized in performance of many different rhythmic motor tasks. Evidence of timing similarities across limb and speech tasks also has been observed in individuals who stutter. Cooper and Allen (1977) found that participants who were good timers in comparison with other participants for finger tapping were also good timers for sentence repetition and that this correlation was stronger in participants who stutter than in nonstuttering controls.

Given these arguments, a generalized motor deficit in stuttering hypothetically would affect nonspeech oral movements as well as limb movements. However, studies comparing timing and coordination variability in oral motor behaviors (e.g., open/close oral movements, syllable repetition) and limb motor performance of individuals who stutter with that of individuals who do not stutter have produced equivocal results. In considering these mixed results, it is notable that many different kinds of motor behaviors have been studied, from those involving processes postulated in the general motor control literature to recruit intrinsic (or emergent) timing processes to others, presumably involving extrinsic (or event) timing mechanisms (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). Some studies have reported no differences between individuals who stutter and controls in timing or coordination variability (e.g., Hulstijn, Summers, van Lieshout, & Peters, 1992; Max & Yudman, 2003; Zelaznik, Smith, & Franz, 1994). Others have reported that participants who stutter were more variable in timing and/or coordination measures (Boutsen et al., 2000; Cooper & Allen, 1977; Ward, 1997; Zelaznik et al., 1997), and one investigation of self-paced oral and finger movements demonstrated that adults who stutter were less variable timers than the control group (Brown, Zimmerman, Hegmann, & Linville, 1990). In discussions of these mixed results, the issue of task complexity is often raised (Max & Yudman, 2003; Zelaznik et al., 1997). It is possible that differences in nonspeech motor coordination and timing as well as differences in speech movement variability (Kleinow & Smith, 2000) are more obvious in people who stutter when the task is more demanding. In fact, many studies of more complex tasks have revealed differences in the nonspeech motor timing of adults who stutter. For example, when a finger sequencing task was used, people who stutter produced slower response initiations, made more errors (Webster, 1986), and were more variable than controls (Smits-Bandstra, De Nil, & Rochon, 2006).

Increasing task difficulty by requiring participants to produce bimanual, rather than unimanual, movements also has resulted in observations of greater variability in performance in people who stutter. Differences in relative phase variability (a measure of intereffector coordination that captures the relative timing of two effectors on repeated cycles of a rhythmic behavior) between adults who stutter and controls have been found with a bimanual finger-waving task (Zelaznik et al., 1997) and a bimanual hand-tapping task (Hulstijn et al., 1992). Hulstijn et al. (1992) also found greater variability in adults who stuttered than in normally fluent controls when they performed a dual task of simultaneously synchronizing speech and hand movement to a metronome. These differences were not found when the same participants completed less complex timing tasks.

If a more generalized motor coordination and/or a timing deficit contributes to the onset and development of stuttering, we should observe differences in performance of a nonspeech motor task in young children who stutter compared with their normally fluent peers. Therefore, in the present study, we examined performance of 4–6-year-old children who stutter on a clapping task, which required bimanual control. We chose this task because it has ecological validity, that is, young children clap their hands spontaneously and would be able to do the task. Furthermore, this task requires bimanual coordination, which on the basis of earlier studies of adults, should increase the probability of observing differences between stuttering and nonstuttering groups. We also elected to use a classic paradigm from the motor behavior literature (Wing & Kristofferson, 1973), requiring the children to produce a series of paced claps in time to a metronome, followed by a continuation phase of unpaced claps.

We are aware of three earlier studies of the nonspeech motor timing or coordination abilities of children who stutter. Westphal (1933) assessed 26 boys diagnosed as stuttering and 26 matched control participants (8–18 years of age) on a battery of motor tests. She included grip strength, eye-hand coordination, hand writing while blindfolded, and hand steadiness while balancing a plate. She found no differences in the boys who stuttered compared with the nonstuttering boys on any of these measures. Riley and Riley (1980) administered tests of motor and psycholinguistic abilities and stuttering severity in 76 children 5–12 years of age who stuttered. They completed a factor analysis of 19 variables that yielded four statistically useful factors implicating linguistic, oral motor, and auditory processing abilities as significant underlying components in stuttering. Finally, Howell, Au-Yeung, and Rustin (1997) reported a pilot investigation of children 9–10 years of age who stuttered and controls on a sinusoidal lip tracking task. For the children who could complete the task, they decomposed lip tracking variance into central clock and implementation variance according to Wing and Kristofferson's (1973) model. They found that the children who stuttered performed the task as well as the nonstuttering children on timing accuracy (equal clock variances) but that there was a trend for implementation variance to be higher in the stuttering group. Thus, there is scant evidence concerning the issue of whether differences in nonspeech motor performance are a characteristic of children who stutter.

The existence of an impairment in a motor process shareable by speech and nonspeech motor control systems in young children who stutter in comparison with children who do not stutter would be a critical piece of evidence needed to evaluate the hypothesis outlined above, that a generalized difference in motor capacities contributes to onset and development of stuttering in early childhood. Evidence of timing and/or coordination deficits seen in the clapping movements of young children near the onset of stuttering would also further support the hypothesized common substrates for the neural processes controlling speech and nonspeech motor behaviors.

Method

Participants

Participants were 17 children who stutter and 13 children who do not stutter. Consistent with methods used by Yairi and Ambrose (1999), a child was diagnosed as stuttering if he/she produced three or more stutter-like disfluencies (i.e., whole or part-word repetitions or disfluent phonations) per 100 syllables in two spontaneous language samples (one with a parent and one with an experimenter). Disfluencies were identified and coded using the methods described by Yairi and Ambrose. The group of stuttering children consisted of 13 boys and four girls between the ages of 4;0 (years;months) and 6;10 (M = 5;0). The nonstuttering children consisted of nine boys and four girls between the ages of 4;0 and 6;2 (M = 4;9). The Handedness Inventory (subset of five tests adapted from Oldfield, 1971) identified one child in each group as left handed. Of the children who stutter, eight were currently undergoing speech therapy targeting fluency, whereas one was in language therapy.

Screening/Testing Procedures

The children spoke standard American English as their first language and passed a pure tone hearing screening (20 dB HL at 500, 1000, 2000, and 4000 Hz). The parents of the children reported negative histories for motor delays, neurological problems, and serious illnesses. As an index of socioeconomic status, the mother's highest year of education was recorded (4 = high school, 5 = partial college, 6 = college graduate, 7 = postgraduate work; Hollingshead, 1975). The median educational score for each group was 6.

All participants underwent speech (Bankson–Bernthal Test of Phonology [Bankson & Bernthal, 1990]); language (Test for Auditory Comprehension of Language [3rd ed.; Carrow-Woolfolk, 1999] and Structured Photographic Expressive Language Test [3rd ed.; Dawson, Stout, & Eyer, 2003]); oral–motor (Robbins & Klee, 1987); and cognitive (Columbia Mental Maturity Scale [Burgemeister, Blum, & Lorge, 1972] and Test of Auditory–Perceptual Skills [Gardner, 1996; Auditory Number and Word Memory subtests only]) testing. All nonstuttering children scored no lower than 1 SD below the mean for same-age peers on all of the tests. Of the 17 children who stutter, three scored lower than 1 SD below the mean for same-age peers on speech testing, three scored <1 SD on language testing, and one scored <1 SD on both. These participants were included in the current study because the population of stuttering children exhibits high rates of co-occurrence of other speech and language disorders (Arndt & Healey, 2001). Characteristics of the participants, including age of onset and severity of stuttering for the children who stutter, are summarized in Table 1. The estimates of stuttering severity were based on a combination of the

Table 1. Description of participants.

Participant	Gender	Age at testing (years;months)	Hand	Age of onset (months)	Severity	Pass speech?	Pass language?	In therapy?
S1	M	5;6	R	30	Mild	Yes	Yes	Yes
S2	M	6;3	R	48	Moderate	Yes	Yes	Yes
S3	M	5;7	R	30	Moderate/severe	No	Yes	Yes
S4	F	4;1	L	24	Moderate	Yes	No	Yes
S5	M	4;1	R	36	Mild	No	Yes	No
S6	M	4;0	R	36	Mild	No	No	Yes
S7	M	4;2	R	36	Mild	Yes	Yes	No
S8	M	5;7	R	48	Moderate	Yes	No	Yes
S9	M	4;7	R	42	Mild	Yes	Yes	No
S10	F	6;11	R	36	Mild	Yes	Yes	Yes
S11	M	4;0	R	24	Moderate	Yes	Yes	No
S12	M	5;1	R	48	Moderate/severe	Yes	Yes	No
S13	M	4;9	R	46	Moderate	No	Yes	Yes
S14	M	4;11	R	30	Moderate/severe	Yes	No	Yes
S15	M	6;7	R	52	Severe	Yes	Yes	Yes
S16	F	4;10	R	46	Mild	Yes	Yes	No
S17	F	4;10	R	48	Mild	Yes	Yes	No
C1	M	5;1	R					
C2	M	5;0	R					
C3	M	5;5	R					
C4	F	5;5	R					
C5	F	4;6	R					
C6	F	4;8	R					
C7	M	4;0	R					
C8	M	4;5	R					
C9	F	4;9	R					
C10	M	4;9	R					
C11	M	5;4	R					
C12	M	4;8	L					
C13	M	6;2	R					

Note. M = male; F = female; R = right; L = left.

results of the parents' severity rating on a 0–7 scale, the project clinician's severity rating on the same scale, and the average number of disfluencies per 100 syllables in the child's speech.

Testing Locations

Two testing sites were used: Purdue University and the University of Iowa. Identical testing procedures were used at both sites. Participants also performed a number of other tasks as part of a larger study, including electroencephalographic and electromyographic recording sessions as well as sentence and word repetition tasks. These results are not reported in this article.

Apparatus

A Northern Digital Optotrak 3020 system was used to record hand movements during the clapping task. In the Optotrak system, the motion of infrared light emitting diodes (IREDs) is tracked by a set of three fixed cameras. Children sat in view of the cameras with IREDs attached to both middle fingers. IREDs were connected to a small splint that was taped to the distal end of each middle finger so that the diode could remain in view of the camera for the entire clapping motion. Wires extending from the IREDs were secured to the hands with tape to prevent them from interfering with clapping. Movements were analyzed in the medial-lateral dimension. The position of each IRED was sampled at 250 samples per second.

Procedure

The experimental protocol began after the IREDs were attached. A metronome (computer generated piano tone) with an interbeat interval of 600 ms was played, and the children were instructed to complete a clap coincident with the metronome beat. The children were instructed that when the metronome stopped (after 12 beats), they should keep clapping as though the metronome was still on (this phase is called continuation). Child-friendly language was used (e.g., "clap in time with the piano beat, when the beat goes off, keep clapping and try to keep the beat"). The continuation phase lasted long enough for 32 claps, after which the children were instructed to stop clapping. Up to three practice trials were given to ensure participants understood and could complete the task correctly. Children clapped along with the experimenter on the first practice trial and then were required to complete the task themselves before data collection began. Participants completed the task independently during the data-collection trials but, if necessary, were prompted to continue clapping when the beat stopped. To keep the IREDs in view, children were instructed to point their fingers toward "Ernie," a doll seated on top of the cameras. If they clapped so that the markers went out of view of the cameras, they were told to "make sure that they aimed at Ernie." In some cases, children produced such large claps that the IREDs went outside the camera view, and they were asked "not to clap so hard" or "to make softer claps." All participants were encouraged to complete at least six trials.

Data Analysis

All signal conditioning and data analysis were completed in the Matlab signal processing program. Displacement records were low pass filtered in both backward and forward directions with a cutoff of 8 Hz using a fifth-order Butterworth filter. The velocity of each clapping movement was calculated using a three-point difference technique. Motions of each hand were measured separately. The starting point for each clap was defined as the point at which the velocity of the hand slowed to 3% of the peak velocity while moving toward the midline. The 3% velocity toward the midline value corresponds almost exactly to the point in time when the hands first make contact. The starting point of each clapping cycle also served as the ending point of the previous clapping cycle. A Matlab algorithm automatically computed the starting point for each clap, for each hand, on the basis of this 3% velocity criterion. The displacement of both hands and the automatically defined claps were graphically displayed for each trial (see Figure 1). If the Matlab algorithm obviously picked an erroneous starting point, it was manually moved to the correct location using a mouse-driven cursor. Likewise, if a clap was missed by the algorithm, it was added in the correct location. Similar techniques have been shown to be accurate and reliable in previous studies in which rhythmic movements were measured (Robertson et al., 1999; Zelaznik et al., 1997). Trials were excluded if the child stopped clapping during the trial for 2 s or more. Trials were also analyzed to ensure that the same number of claps was recorded for each hand because a clap by definition requires that both hands reach midline. Of the 38 children tested on this protocol, eight participants (five children who stuttered and three who were normally fluent) were excluded from the present study because they did not produce at least two useable clapping trials. Thus, the task was clearly challenging for our young participants.

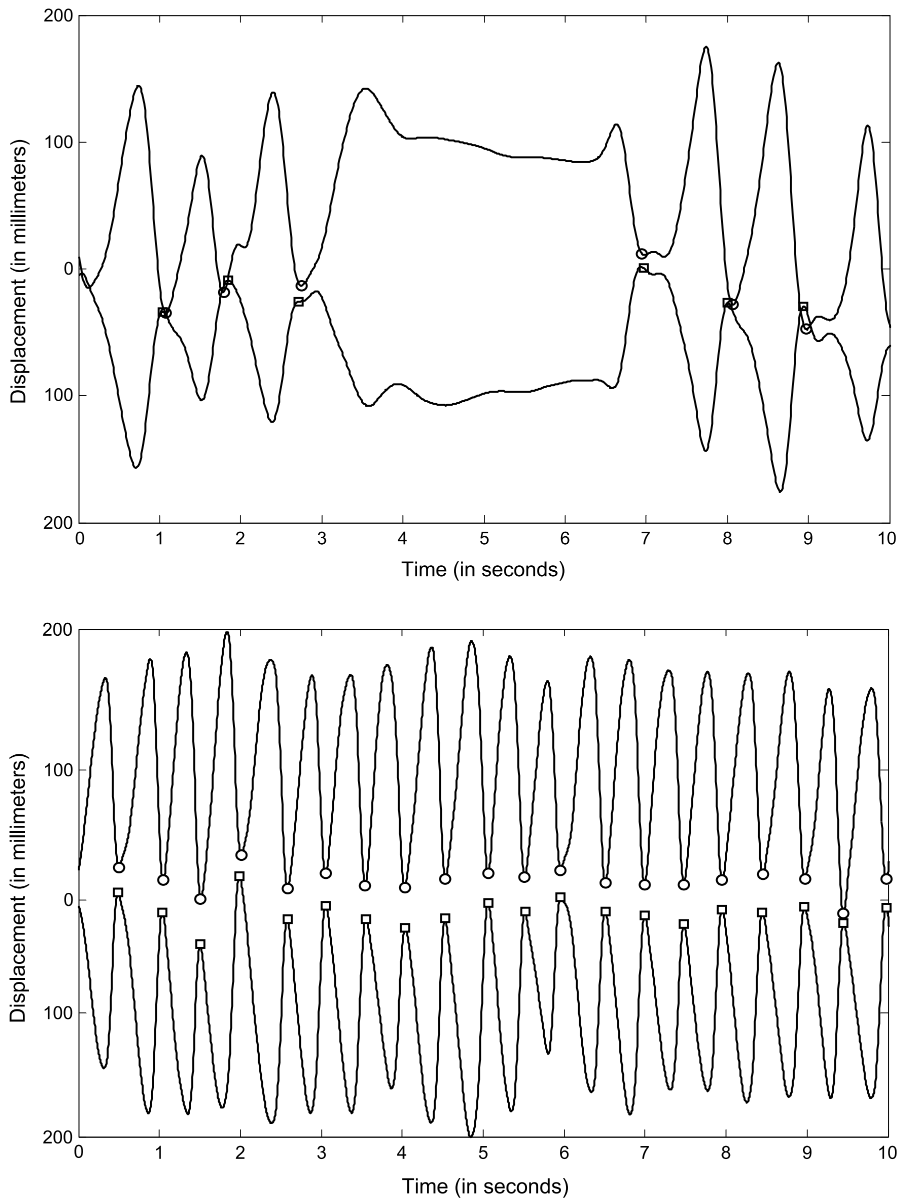
Only claps produced during the continuation phase of 32 claps (without metronome) were analyzed to determine timing variability. Although analysis of the paced claps would be of interest to compare the abilities of the two groups to synchronize a motor activity to an external beat, there were not enough pacing beats (only 12 per trial) to conduct a meaningful analysis. The first two claps and the final clap of the continuation phase were not included in the analysis. Each trial ideally included 28 claps. The average cycle duration, its variance, and the coefficient of variation of the interclap interval were computed and averaged across trials for each participant's left and right hand. These variables served as measures of timing variability for each hand. Detrended variance was calculated to remove the influence of any drift in average clapping rate on variability, and the square root of the detrended variance was used to calculate the coefficient of variation in percent [CV = (Detrended standard deviation/mean interclap interval) × 100]. Phase difference was calculated by finding the difference between the right and left hand in the onset of each clap and by dividing that difference by the duration of the following interclap interval of the right hand [(right hand onset – left hand onset)/following interclap interval for the right hand] (Zelaznik et al., 1997). A positive value indicated that the right hand reached midline before the left hand, whereas a negative value indicated that the left hand reached midline before the right hand. Mean and median phase differences, which served as measures of the coordination of timing between the hands, were determined and converted into degrees.

It was our plan to report clock and implementation variance for the unpaced clapping sequences following Wing and Kristofferson's (1973) methods, but the children's interclap interval data series violated the model's basic assumption of negative lag 1 covariance, and the model could not be applied. It is notable that in a study of stuttering adults performing similar rhythmic tasks, the adults' interresponse interval data series met the negative lag 1 covariance assumption, and the model was applied (Max & Yudman, 2003).

Results

Results are reported for 17 children who stutter and 13 normally fluent children who produced at least two useable clapping trials. The range of useable trials

Figure 1. Displacement of each hand from the midline during the clapping task. The top line represents the left hand, and the bottom line represents the right hand. The circles (for the left hand) and the squares (for the right hand) represent the starting/ending points of each clapping cycle. The top record was unusable because the child stopped for more than 2 s. The bottom record shows a trial that was usable.



per child was 2–5, with a median of 4 useable trials per child for both groups. To address the statistical concern that clapping variability would be greater in the children for whom fewer usable trials were completed, we computed the correlation between the number of usable trials and the coefficient of variability of the interclap interval. This correlation (number of trials vs. CV right hand) was zero (–.075), thus alleviating this concern. Table 2 contains means and standard deviations for the variables measured in this study for the two groups of participants.

Interclap Interval

Figure 2 contains scatter plots of interclap intervals (top plot) and the variability of the interclap intervals for all 30 children for whom clapping data were analyzable. From the interclap interval plot, it is apparent that the distribution of the children's mean clapping intervals is overlapping for the two groups of participants. A repeated measures analysis of variance revealed no significant difference between average interclap intervals of stuttering and nonstuttering children, $F(1, 28) = 2.05$,

Table 2. Dependent variable means and standard deviations for children who stutter and normally fluent controls.

Dependent variable	CWS		CNORM	
	M	*SD*	*M*	*SD*
Duration of interclap interval (milliseconds)	427	80	464	56
Detrended variance of interclap interval	4137	4135	1421	673
Right hand coefficient of variation (%) of interclap interval	13.4	6.3	7.6	2.4
Mean phase difference (degrees) between hands	–0.49	9.7	0.89	10.9
Median phase difference (degrees) between hands	–2.90	8.0	0.72	9.9
Standard deviation of phase	22.9	10.8	15.7	8.0

Note. CWS = children who stutter; CNORM = children who are typically developing.

$p = .16$, and no significant main effect of hand ($F < 1$) or interaction between hand and group ($F < 1$). These results indicate that the stuttering and nonstuttering children were clapping at the same rate, and both groups apparently clapped at a rate faster than the target 600-ms interbeat interval.

Variability of Interclap Intervals

In contrast to the plot of interclap intervals in the top panel of Figure 2, the plot of the coefficient of variation of the interclap intervals for the right and left hands (lower plot) for each participant reveals that the distributions of scores are not overlapping. A subgroup of children who stutter performed outside the range of variability observed in the normally fluent group. Specifically, 10 of the 17 stuttering children show clapping variability higher than that observed in the most variable nonstuttering child (a CV of about 12%). Given that the distribution of the CVs for the stuttering children does not approximate the normal distribution and that the variance of the stuttering group is clearly much larger than that of the normally fluent children, an analysis of variance could not be used to test for differences between groups. A nonparametric test (Siegel & Castellan, 1988) for differences between two independent samples was calculated for the CV of the interclap interval for the right and left hands. Children who stutter had higher CV for the interclap intervals for right (Mann–Whitney $U = 50, p = .01$) and left (Mann–Whitney $U = 46, p < .01$) hands.

Coordination Between Hands

Children who stutter did not significantly differ from the nonstuttering children in terms of mean, $t(28) = 0.37$, $p = .72$, or median, $t(28) = 1.1$, $p = .28$, phase difference between the hands, indicating that children who stutter, on average, did not show higher levels of dyssynchrony in coordinating the movements of the two hands toward the midline. The standard deviation of the phase difference was significantly different between the two groups, $t(28) = 2.02$, $p = .05$.

Potential Effects of Testing Site

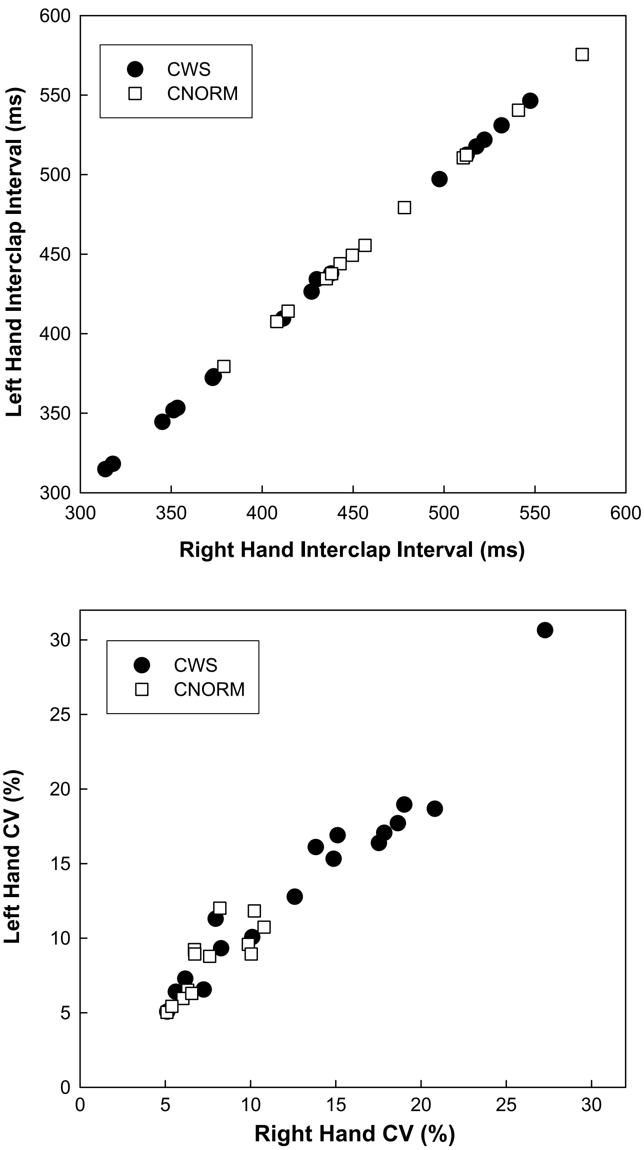
As indicated by t tests computed separately for each group, there was no effect of testing site (Purdue vs. Iowa) on any of the dependent variables. Although differences in performance among the stuttering children related to speech/language status, therapy history, and severity would be of potential interest, any subgrouping of the 17 stuttering participants would result in very small participant numbers; therefore, we did not pursue these issues with any statistical analyses.

Discussion

Rhythmic Timing Variability in Children Who Stutter

The present study is the first to investigate nonspeech motor timing and coordination in young children who stutter. Examining potential timing and coordination differences in children who stutter, near the age of stuttering onset, is a critical step toward providing evidence of an underlying neural overlap between speech and nonspeech motor control processes and understanding whether the motor differences often observed in adults who stutter are adaptive or causal in nature. The most striking finding of the present study is that timing variability during a clapping task significantly differed between children who stutter and age-matched typically developing children. The variance and coefficient of variation of the interclap interval were much higher in the children who stutter, despite the fact that both groups responded to the task similarly with no significant differences in average clapping rates or number of usable trials produced. This suggests that both groups of children matched the metronome rate with the same level of

Figure 2. Graphs of mean interclap interval for each child's right and left hand (top plot) and the coefficient of variation of the interclap interval computed for each child's right and left hand (lower plot). CWS = children who stutter; CNORM = children who are typically developing.



accuracy and completed the task with similar levels of success. However, the children who stutter clearly did not maintain a consistent rate of clapping as well as normally fluent children, even when the data were detrended to remove the influence of any steady rate change on variability levels. Furthermore, 10 of the 17 children who stuttered performed outside the normal range in clapping variability. These results provide clear evidence that in its early years, developmental stuttering is associated with a fundamental deficit in the child's ability to generate consistent, rhythmic motor behaviors. This suggests that children who stutter have atypical development of neural networks in the brain involved in the control of speech and other complex movements.

The results of the current study support the theory put forth by Max et al. (2003) and Zelaznik et al. (1997) that differences in the timing, coordination, and synchronization of the articulators of adults who stutter are influenced by an underlying motor timing deficit. The fact that timing differences were found during performance of a clapping task suggests that they are not specific to the speech motor system and that motor timing differences for speech and nonspeech movements may share a common neural substrate (Bengtsson et al., 2005; Binkofski & Buccino, 2004). Further support for this argument is provided by a recent neuroimaging study by Chang, Kenney, Loucks, and Ludlow (2009), who reported that the same atypical neural activations observed in adults who stuttered during speech tasks were also present when they performed nonspeech oral motor tasks. The presence of significantly increased timing variability in 4-, 5-, and 6-year-old children who stutter, in comparison with age-matched nonstuttering children, also provides evidence that these timing differences are present close to the onset of stuttering rather than developed over time as an adaptation to chronic stuttering, as hypothesized by McClean et al. (2004). Within the scope of a multifactorial model of stuttering (Smith, 1999), the present results lend strong support to the hypothesis that a general motor timing deficit is one of the factors contributing to the abnormal speech and nonspeech motor output observed in a significant portion of individuals who stutter.

Influence of Task

We used clapping to produce a target rhythm to assess timing differences in young children who stutter because rhythmic clapping is a difficult task for young children. It is, however, a task that can be understood and performed with limited amounts of practice. Furthermore, clapping is complex enough to reveal subtle differences in the motor timing abilities between groups. Normally developing 4-year-old children are able to perform rhythmic clapping but are more variable in timing than adults (Fitzpatrick, Schmidt, & Carello, 1996; Getchell, 2006) and older children (Getchell & Whitall, 2003). Children as old as 10 years have also been reported to be less accurate in rhythmic motor timing than adults (McAuley, Jones, Holub, Johnston, & Miller, 2006). Rhythmic clapping may be challenging because it is bimanual (Serrien, 2008) and requires the spatial control necessary to make the hands come together on each cycle. In previous studies examining articulatory movements in adults who stutter, variability differences were observed more often when speech tasks were linguistically more complex (Kleinow & Smith, 2000). Hence, the complexity of the clapping task used in this study was critical in preventing a ceiling effect in participant performance. The actual clapping rates produced by the children in this study, which missed the target rate typically by 15%–50%, clearly indicate the high difficulty level of the task. There were no differences between groups on mean clapping rates, and only nine of the 30 children clapped within 100 ms of the target rate produced by the metronome. Many of the tasks used in previous studies (Max & Yudman, 2003; Webster, 1985) with adults have likely not been challenging enough to elicit timing differences between adults who stuttered and controls.

With regard to relative phase, both groups of children produced the same mean and median phase differences between the two hands in the clapping task. We interpret this finding to suggest that the groups were equal in terms of the relative time at which the two hands arrived at midline. Between-hands coordination differences may not have been found in this study because clapping requires the hands to come together on each timing cycle, making it less likely for the hands to be out of phase. The children who stutter, however, were significantly more variable in maintaining a consistent phase relationship between the hands. This result is consistent with those of previous studies in which adults who stutter performed rhythmic tapping tasks with higher relative phase variability—a measure of consistency of between-fingers coordination—than controls (Hulstijn et al., 1992; Zelaznik et al., 1997).

Differences in Interclap Interval Variability Levels Among Children Who Stutter

An important finding is that 41% of the children who stutter exhibited interclap interval variability levels within the range produced by the group of normally fluent children, whereas 59% were so variable that they were outside the normal range. It is possible that only a proportion of children who stutter have a motor timing deficit in comparison with same-age peers. These two subgroups may still be present in adults who have persisted in stuttering. If this is the case, an additional explanation may be provided for the lack of differences in nonspeech motor timing found between adults who stutter and controls in some previous studies (e.g., Max & Yudman, 2003; Webster, 1985). These mixed results may simply reflect sampling differences in these studies with small sample sizes. It is also possible that some children who spontaneously recover from developmental stuttering continue to show subtle differences in motor timing. In fact, Chang, Erickson, Ambrose, Hasegawa-Johnson, and Ludlow (2008) reported that children between the ages of 9 and 12 years who had recovered from developmental stuttering continued to show less gray matter volume in Broca's area and in the supplementary motor area when compared with children who had never stuttered. This may explain why the current study revealed significant differences in variability between children who stuttered and controls, despite the fact that approximately half of the participants included will not persist in stuttering.

An intriguing speculation arising from the present work is that the presence of a general motor timing deficit in children who stutter may be an early indicator of persistent stuttering. In other words, children who stutter who do not show evidence of a general timing deficit might spontaneously recover, whereas those who do show abnormally high motor timing variability will persist. Currently there is no way to determine whether a child who stutters will continue to do so into adulthood. Findings of the Illinois Stuttering Project (Ambrose & Yairi, 1999; Paden, Yairi, & Ambrose, 1999; Watkins, Yairi, & Ambrose, 1999; Yairi & Ambrose, 1999)—a 4-year longitudinal study of children who stuttered—revealed a 75% spontaneous recovery rate for 3-year-olds who stuttered. Because the children in the current study were 4-, 5-, and 6-year-olds, and as a result had already been stuttering for 1–3 years, recovery rates for this group should be approximately 50%. The distribution of clapping variability levels produced by children who stutter in the present study (41% of the children who stuttered falling within the range produced by typically developing children, and 59% producing higher variability levels than children who stuttered) roughly matches expected recovery rates.

Although it is beyond the scope of the present study to strongly suggest that clapping variability is an early marker of stuttering persistence versus recovery, the bimodal-looking distribution in the coefficient of variation in the children who stuttered provides a promising possibility for the early identification of persistent stuttering and will continue to be investigated in future work in our laboratory. A procedure for the early detection of persistent stuttering would clearly be beneficial for speech language pathologists and families of children who stutter when deciding whether a young child who is stuttering should enter therapy.

Conclusion

The results of the present study reveal that a subgroup of children who stutter contained more variable timers than typically developing children during a bimanual rhythmic timing task. This provides evidence that speech and nonspeech motor timing may share a common neural substrate and that abnormalities in this shared brain region may lead to a generalized motor control deficit that is one of the factors contributing to the abnormal speech motor output observed in individuals who stutter. The fact that only a portion of children who stutter performed with higher interclap interval variability levels than controls also provides a possible early indicator of persistent stuttering that warrants further investigation.

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