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Oral and Hand Movement Speeds are Associated with Expressive Language Ability in Children with Speech Sound Disorder

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Abstract

This study tested the hypothesis that children with speech sound disorder have generalized slowed motor speeds. It evaluated associations among oral and hand motor speeds and measures of speech (articulation and phonology) and language (receptive vocabulary, sentence comprehension, sentence imitation), in 11 children with moderate to severe SSD and 11 controls. Syllable durations from a syllable repetition task served as an estimate of maximal oral movement speed. In two imitation tasks, nonwords and clapped rhythms, unstressed vowel durations and quarter-note clap intervals served as estimates of oral and hand movement speed, respectively. Syllable durations were significantly correlated with vowel durations and hand clap intervals. Sentence imitation was correlated with all three timed movement measures. Clustering on syllable repetition durations produced three clusters that also differed in sentence imitation scores. Results are consistent with limited movement speeds across motor systems and SSD subtypes defined by motor speeds as a corollary of expressive language abilities.

Keywords

Speech sound disorder; Motor speed; Central rate limit; Language impairment

Introduction

Many children experience substantial difficulty in acquiring intelligible speech in the absence of a known cause. Customarily termed speech sound disorder (SSD), this disorder is fairly common, although published prevalence rates vary. Generally, SSD is more prevalent among boys than among girls, and prevalence decreases with increasing age. Prevalence estimates range from approximately 1–15.6% and are not only influenced by age and gender but also by the quantitative criteria selected to identify children with SSD. For example, using a criterion of 75% glossable productions in spontaneous speech, Campbell et al. (2003) estimated that 15.6% of three-year-old children have SSD. Using a standard score of −1.14 in a 20-item articulation test, Shriberg et al. (1999) reported a prevalence rate of 3.8% in six-year-old children. Using a four-stage process of identification, including teacher report and a speech-language pathologist report, McKinnon et al. (2007) identified approximately 1.1% of children in an Australian school-age sample in Kindergarten through 6th grade as having SSD. A universally accepted SSD profile and an unequivocal subtype classification are not yet available. Several classification schemes, based on various theoretical frameworks, coexist in the literature (e.g., Bauman-Waengler 2000; Crary 1993; Dodd 1995; Shriberg et al. 2005).

To elucidate the nature and causes of SSD, it is instructive to consider possible but yet unknown biological mechanisms including neurophysiological and genetic factors.

Comorbidity and traits shared with other disorders such as language impairment (LI) and reading disorder (RD), further defined below, raise the question of shared endophenotypes and genotypes, providing stepping stones towards identifying possible biological bases of SSD. This rationale has been used successfully in the past to identify genetic candidate regions linking to articulatory deficits in family samples with SSD (e.g., Stein et al. 2006a,b). In this line of reasoning, comorbidity between SSD and RD and the presence of shared traits was interpreted as a basis for the hypothesis that SSD and RD are, in part, influenced by the same causative genetic mechanisms and that the expression of disorder-specific traits are due to additional and unshared genetic mechanisms. To evaluate this hypothesis of shared traits and genotypes, the authors probed genetic candidate regions known to influence RD, using participant samples with SSD.

In what follows, we provide evidence for SSD comorbidity with LI and RD and review behavioral aspects of these three disorders, for purposes of formulating hypotheses regarding shared endophenotypes. Shriberg et al. (1999) show that SSD and LI are comorbid beyond chance probabilities. Children with SSD also have a higher risk of RD than controls with typical development (TD) (Bishop and Adams 1990; Catts 1993; Snowling et al. 2000), although this risk may be greatest in children with SSD and comorbid LI (Bird et al. 1995; Larrivee and Catts 1999; Leitao and Fletcher 2004; Lewis and Freebairn 1992). Approximately 50% of children with LI will later be diagnosed with RD (Catts et al. 2002; Snowling et al. 2000), and children who have poor listening comprehension, indicating a form of LI, also frequently have poor reading comprehension (Keenan et al. 2006).

LI has been defined as a variously expressed developmental language disorder in the absence of hearing impairment, frank neurological impairment or psycho-emotional disturbance (Leonard 1998). Timed performance during a variety of tasks has been studied extensively in children with LI. Reviewed in Windsor and Hwang (1999), Schul et al. (2004), and Pennington and Bishop (2009), deficits include slow motor, auditory, visual, linguistic, and nonverbal processing. Slowed motor speeds were observed during tasks such as ball rolling with the foot, clapping-and-catching (Powell and Bishop 1992), and bead-threading (Owen and McKinlay 1997; Powell and Bishop 1992). Zelaznik and Goffman (2010) showed that children with LI had slower speeds in standardized measures of gross and fine motor speeds compared to controls, although rhythmic functions were not affected. These results have been interpreted as representing generalized slowed processing in children with LI, although findings are still controversial. Lahey et al. (2001) found that speed of responding was not correlated with severity of LI. Bishop (2007) points out that the rapid auditory temporal processing theory does not explain why some individuals with impaired auditory processing rates have normal language skills.

According to the International Dyslexia Association (Lyon et al. 2003), dyslexia, also termed reading disorder (RD), is a specific learning disability related to written language, characterized by deficits in accurate and/or fluent word recognition, decoding, and spelling. Reduced performance speeds have been observed in individuals with RD, with deficits similar to those seen in LI. For instance, Catts et al. (2002) showed that 279 third graders with RD were slower than controls in response times during motor, visual, lexical, grammatical, and phonologic measures and, additionally, in rapid naming. The motor tasks consisted of tapping a computer key as rapidly as possible during a 5 s interval and a key strike in response to a visual signal. Smith et al. (2008) conducted a longitudinal study of 27 children, age 2 and 3, most of whom were at high familial risk for RD. Those who were diagnosed with RD in grade school had slower speaking rates at age 2 and 3 years, compared to those who did not develop RD.

As in LI, slowed speeds in a wide variety of activities have been described in RD. In addition to slowed motor speeds, slowed performance was observed during judging the order of phonemes in consonant clusters (Rey et al. 2002), rapid symbol naming (Bell et al. 2003), and rapid naming of within- and across-category terms (Schulte-Körne et al. 2006).

Less is known about general processing speeds in children with SSD, compared to children with LI and RD. Articulation rate is the aspect most frequently evaluated in this population. It should be pointed out that articulation rate is not a pure measure of motor speed, as it also incorporates linguistic and cognitive aspects of processing. In a longitudinal study of 16 typically developing preschoolers, nonlinear trajectories of articulation rate and variability were observed, and results were interpreted to indicate the influence of factors outside of neuromotor maturation, including an increased load of phonological and syntactic processing at age 5 (Walker and Archibald 2006). In 20 4- to 10-year-old children with SSD and 20 controls, articulation rates as measured in total duration time, syllables per second and phonemes per second, were slower in the participants with SSD, compared to the controls (Wertzner and Silva 2009). In a longitudinal study of articulation rates and phonetic phrase length in preschoolers with SSD, Flipsen Jr. (2002) showed that the participants with SSD produced fewer syllables per second than peers but appeared to catch up by age 9 years; this finding, however, was interpreted in light of the fact that as preschoolers, the participants produced more articulation errors than their peers with TD. Flipsen Jr. (2003) showed that 12- to 16-year-old children whose speech disorder had not normalized despite intervention had slower speech rates in an embedded word task, compared to children whose speech disorder had resolved. In a study of speech-related skills in parents of children with SSD, Lewis et al. (2007) compared parents with and without a history of SSD and found that the former group had significantly lower skills in a number of traits including multisyllabic word repetition, a task that requires rapid selection and sequencing of phonemes, followed by the execution of sequential motor commands. Together, these studies suggest that articulation rates are slowed in the presence of SSD. The role of oral motor speeds in SSD with the influence of linguistic and cognitive processing factored out is not well understood. Similarly, it is unknown whether individuals with SSD have slowed performance speeds in motor systems other than the speech production system, which, if shown to be the case, would be consistent with a rate limit of motor speeds across motor systems as an associated disorder trait. While there are theoretical frameworks proposing separate motor control systems for speech and other tasks in general (Weismer 2006; Ziegler 2003), it is possible that developmental forms of speech, language, and reading disorders share a distal endophenotype linked to system-wide deficits.

A possible biological substrate for slowed processing is white matter tract abnormality. In typical populations, white matter volume and integrity is associated with information processing speeds (Posthuma et al. 2003), finger tapping speeds (Bartzokis et al. 2008), and theoretically with high frequency brain wave activity (Freeman and Rogers 2003; Weiss and Mueller 2003). White matter differences have been observed in individuals with LI (Jaencke et al. 2007) and RD (Richards et al. 2008). Further evidence for biological causes is the observation that genetic components appear to underlie LI and RD (reviewed in Lewis et al. 2006; Pennington and Bishop 2009; and Peterson et al. 2007).

Detailed neurophysiological studies are not yet available for populations with SSD (reviewed in Peterson et al. 2007). Behavioral genetic studies have concluded that SSD has a strong genetic component (reviewed in Lewis et al. 2006; Pennington and Bishop 2009; and Peterson et al. 2007). Based on the rationale that the same genetic mechanisms could influence both RD and SSD, several known RD genetic candidate regions were probed in samples with SSD but without RD, and linkage to four of them, 1p34-36, 3p12-q13, 6p22, and 5q21, was established for traits related to speech production. Candidate regions for SSD and based on evidence from LI have not yet been investigated.

The present study is built on the general hypothesis that SSD is characterized by slowed motor speeds across motor domains. This hypothesis is based on the observations that SSD is frequently comorbid with LI and RD, that slowed processing including slowed motor speed has been documented in LI and RD and, regarding articulation rates, in SSD; and that SSD shares genetic candidate regions with RD. If confirmed as a corollary to SSD or one of its subtypes, slowed motor speeds could provide motivation for neurophysiologic studies and constitute an endophenotype worth investigating for genetic linkage in future studies.

In two previous studies in a sample of children with SSD and matched controls with TD, we evaluated timing *accuracy*. Here, the focus is on *speeds* in two different motor systems, oral and hand. Subsequent to a pilot study of temporal accuracy in children with motor speech difficulties (Peter and Stoel-Gammon 2005), we investigated timing accuracy in a sample of 11 participants with SSD and 11 age- and gender-matched controls and reported that timing deficits in oral tasks were associated with timing deficits in hand tasks (Peter and Stoel-Gammon 2008). These deficits manifested in small-scale timed intervals, referred to as temporal microstructure, as well as large-scale intervals on the level of rhythmic representation, termed temporal macrostructure. Because these studies focused on timing accuracy, influences of speed were carefully factored out. For instance, timing accuracy in imitated tasks was calculated using correlations between targets and imitations, not differences in absolute durations. Focusing on aspects of motor speed, three research questions are addressed:

1. Are movement speeds from different tasks (maximal rate production and imitation of rapid stimuli) and in different motor systems (oral, hand) mutually associated?
2. How are speech and language measures associated with motor speeds?
3. How does motor speed differ for children with SSD, compared to peers with typical development?

Method

Participants and Test Environment

This study was conducted with the approval of the University of Washington Human Subjects Division and in compliance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Each participant's parent gave informed consent prior to inclusion in the study. Participants with SSD were recruited through referrals by local speech-language pathologists. The referral request contained the following criteria: age 4;6 to 7;0 years; moderate to severe SSD of unknown origin with standardized speech test (articulation and/or phonology) scores below −1.5; monolingual English home environment; hearing screen passed at 25 dB SPL, 0.5, 1, 2, 4, 8 kHz; absence of fluency disorder; no history of sensorineural hearing loss; no history of acquired speech disorder; and no history of diagnosed neurologic disorders or syndromes. Age- and gender-matched controls with TD were recruited through the University of Washington Child Participant Pool—Communication Studies (University of Washington Research Core Center). Criteria for inclusion in the study were identical to those for the participants with speech disorders, but excluding a history of speech disorder.

Participants were 11 children, ages 4;7 (years;months) to 6;6, with moderate to severe SSD and 11 age- and gender-matched controls. Each group consisted of three girls and eight boys. Table 1 shows summary statistics describing the speech and language scores in the SSD and TD group.

Most of the study sessions took place in a quiet clinic room in the University of Washington Speech and Hearing Clinic. In two cases, the sessions took place in a quiet room at a public library. Sessions lasted approximately 90–120 min and included a hearing screening, speech and language testing, and testing with the experimental timing measures described in this study, all of which were administered by the author.

Study Tasks and Derived Variables

Each participant completed eight tasks covering the domains of receptive and expressive language, articulation, phonology, and oral and limb movement. Standardized testing was used to assess language and speech skills, and each test yielded a raw score, a standard score, and a percentile ranking. Receptive vocabulary was tested with the *Peabody Picture Vocabulary Test-III* (PPVT-III; Dunn and Dunn 1997). Sentence comprehension was measured with the Elaborated Phrases and Sentences subtest from the *Test for Auditory Comprehension of Language, Third Edition* (TACL-3; Carrow-Woolfolk 1999). Sentence imitation, a measure of expressive language ability, was tested with the Recalling Sentences subtest from the *Clinical Evaluation of Language Fundamentals- Preschool* (CELF-P, Wiig et al. 1992) or the *Clinical Evaluation of Language Fundamentals—4* (CELF-4, Semel et al. 2003), as appropriate for age. Accuracy of articulation was measured with the *Goldman-Fristoe Test of Articulation—2* (GFTA-2; Goldman and Fristoe 2000). The *Khan-Lewis Phonological Analysis—2* (KLPA-2; Khan and Lewis 2002) uses the word productions from the GFTA-2 to quantify consonant errors in terms of phonological processes such as stopping, cluster simplification, and liquid simplification. Because the GFTA-2 and the KLPA-2 are based on the same word productions, resulting variables are not entirely independent of each other, although they sample different aspects of these productions. Table 2 lists occurrences of individual phonological processes in the KLPA-2 in the participants with SSD, in raw scores as well as in percent expressed relative to the total possible opportunities.

Experimental measures of timing in nonword imitation and clapped rhythm imitation, described in detail in Peter and Stoel-Gammon (2005, 2008), were administered by the first author. Nonword imitation (NWI) was assessed with the Rhythm subtest of the *Tennessee Test of Rhythm and Intonation Patterns* (T-TRIP; Koike and Asp 1981), a nonstandardized test of expressive prosody using sequences of the syllable ‘ma’ in a variety of stress patterns. The sequences vary in length and stress patterns. For instance, Item 1 is MA.ma (where capital letters indicate a stressed syllable, lower-case letters indicate an unstressed syllable, and the period mark indicates a syllable boundary). Item 11 is MA.ma.ma.MA.ma, a much longer and metrically more complex sequence. Items 13 and 14 were excluded from analysis because they contain pauses and many participants began their imitations during the pause rather than at the end of the presented sequence. Each item is presented for imitation twice. Because measuring vowel durations is a well-established procedure that differentiates between stressed and unstressed syllables (Low et al. 2000; Ramus et al. 2000), only vowel durations, not entire syllables, were measured. Because each syllable contained the continuant /m/, this segment would have unnecessarily added an invariant duration, reducing overall variability. As with all acoustic measurements in this study, vowel durations were obtained using Praat 4.2.09 (Boersma and Weenink 2004). Only those vowels bounded by /m/on both edges were analyzed for duration because the endpoint in final syllables cannot always be identified reliably due to variations in ambient noise. In addition, final vowels can introduce confounding because of final lengthening effects. Of the 45 syllables in the set, 18 unstressed and 17 stressed vowels met this criterion of nonfinal position. As a default, the child's second imitation of each stimulus was selected for acoustic analysis. In instances where the first imitation contained a more accurate and/or complete syllable count, that response was selected instead. Table 3 shows the list of syllable sequences used in this study.

To evaluate motor speed in the NWI task, we selected the unstressed vowels for analysis because their short durations necessitate rapid oral movement. To evaluate the participants' speed relative to the adult model in the imitation tasks, a ratio of the imitated duration in relation to the adult's target duration was obtained for each item. Child/adult ratios equal to 1 indicated equivalent durations, while ratios < 1 indicated shorter imitated durations and, hence, faster movement speed, and ratios > 1 indicated longer imitated durations and, hence, slower movement speeds.

The clapped rhythm imitation (CRI) task was designed to closely parallel the NWI task, allowing us to directly compare performance in two different motor systems. Participants imitated clapped rhythms presented to them by the first author. The set of clap sequences contained ten different rhythmic patterns, shown in Fig. 1. Sixteen of the 44 clap intervals represented quarter notes without syncopation, which were selected for analysis to evaluate movement speeds in a rapid task context. In analogy to the NWI task, each item was presented twice, and the second imitation was selected for acoustic analysis by default, unless the first imitation contained a more accurate clap count than the second. Also in analogy to the NWI task, a child/adult ratio was calculated as an indicator of relative movement speed.

In a third task, syllable repetition (SR), movement rates were inferred from syllable durations. Each participant was given the following instructions: "Say 'papapapa' as fast and as long as you can." Each participant had up to three opportunities to produce a string of at least ten syllables. Limits on movement rates during jaw excursions were inferred from longer syllable durations, although actual jaw excursions were not measured. Here, the durations of the entire syllable were used as an estimate of movement rate, in part because norms are available for this unit and also because the onset consonant is a voiceless stop, occupying a smaller durational segment compared to the /m/in the nonword imitation task. Expected mean syllable durations for children between the ages of 4;6–6;5 (years;months) are approximately 187–216 ms, with the shorter durations associated with faster repetitive movement in the older children (Robbins and Klee 1987). Because initial stop consonants tend to be aspirated more than medial stop consonants, they were excluded from analysis. To obtain clearly measurable syllable durations defined by intervals between stop bursts and to control for final lengthening effects, final syllables were excluded from this analysis as well. Hence, for each participant, at least 8 scorable syllables were obtained, with the exception of D05 and D10, for whom only 7 were obtained. Therefore the first seven analyzed syllables were selected for further processing. The mean durations from the first seven analyzed syllables were highly correlated with the mean durations from all analyzed syllables ($r = .96$, $p < .0001$).

Together, these three variables provided opportunities to evaluate movement speeds in hand and oral tasks. Two tasks were imitation tasks, where large child/adult duration ratios were interpreted as slow movement speeds relative to the model. Because of their parallel design and evaluation, they provided direct comparisons between the oral and hand motor systems. Adding the syllable repetition task allowed comparisons between two oral movement tasks, one of which was set in a direct imitation context while the other probed maximal movement speeds where only a minimal amount of modeling was embedded in the verbal instructions ("Say 'papapapa' …"). Although short durations were used as an estimate of movement speed, it is acknowledged that excursions, for instance those of the jaw or the hands, were not explicitly measured and that short durations may or may not incorporate reduced excursions in addition to, or instead of, movement velocities. It should also be noted that the three measures of movement speed are scaled along inherently different ranges, due to the nature of the measurements (the vowel portion of unstressed syllables in the NWI task, entire hand clap intervals in the CRI task, and entire syllables in the SR task). For purposes of correlational and clustering analyses, these scale differences are irrelevant.

Statistical Analysis

To address the first research question about associations among the three measures of movement speed, values for each variable were averaged for each participant, and pairwise correlation coefficients were calculated among these per-participant means. To evaluate research question 2 regarding speech and language traits most closely associated with motor speeds, pairwise correlations were calculated among the three measures of movement speed and the measures of speech (articulation, phonological processes) and language (receptive vocabulary, sentence comprehension, sentence imitation). All *p* values were interpreted under a Bonferroni correction for multiple testing, which involved 18 pairwise correlations, as three measures of speed were tested for mutual correlations (3 tests) and for correlations with the two measures of speech and the three measures of language (15 tests), resulting in an alpha of .0028.

To address research question 3 regarding the role of SSD in movement speeds, summary statistics were calculated for the two participant groups. Groups were compared using t tests, inputting per-participant mean values of the three speed measures. Bonferroni corrections were applied to the three group comparisons, resulting in an adjusted alpha of .0167. To further evaluate the role of motor speeds in SSD, clusters were generated by entering per-participant mean scores for the syllable durations from the SR task into hierarchical agglomerative clustering using average linkage. The number of emergent clusters was entered into K means clustering, and distinctness of clusters was confirmed ANOVA testing. Among the emergent distinct clusters, speech and language scores were compared. Regarding the speech scores, the individual KLPA-2 scores were of particular interest, especially the phonological processes related to segmental and syllable deletion, as it can plausibly be hypothesized that a speech system with speed constraints tends to compensate by omitting segments.

Reliability and Validity Measures

Approximately 18% of the standardized speech and language scores, the acoustic measurements, and the perceptual measures of rhythmic accuracy in the nonword and hand clap tasks were selected for re-measurement. These data came from two randomly selected study participants in each of the two groups, SSD and TD. The standardized speech and language scores were re-measured by two postgraduate students in the Department of Speech and Hearing Sciences at the University of Washington. These two judges, who were speech-language pathologists, received CDs with video footage of the test events and were asked to provide raw scores for the expressive language and speech testing. The judges were blind to the status (SSD or TD) of the participants. Receptive language measures were not re-measured, because it was felt that the first author’s record of these data was sufficiently accurate for the purposes of this study, as participants simply pointed to pictures in response to hearing a word or sentence. The GFTA-2 has a maximum point score of 77; inter-rater discrepancy averaged 3.75 points (range: 2, 6). The KLPA-2 has a maximum point score of 250; inter-rater scores differed on average by 8.75 points (range: 2, 19). Of 52 maximum points in the expressive language task from the CELF-P, one rater pair differed by 5 points, and in the analogous score from the CELF-4 with a maximal point score of 54, three rater pairs differed on average by 1.3 points (range: 0, 3). The acoustic measurements of vowel durations, clap intervals, and syllable durations were re-checked by an undergraduate student and a graduate student in the same university department, following training in the procedures by the first author. For each variable, the discrepancies in ms between the original and the second measurements were converted to relative error scores conditioned on the magnitude of the average from the two measurements and expressed as a percentage, averaged across the selected data. Differences averaged 6.4% in the NWI vowel durations, 2.4% in the CRI clap interval durations, and 0.5% for the SR syllable durations.

Five possible sources of confounding were ruled out. First, participant age, which ranged from 4;7 to 6;6 (years;months), was already accounted for in the standardized measures of speech and language. Age, reported in months, was not correlated with any of the measures of speed: NWI: $r = .0162$, $p = .9430$; CRI: $r = -.0777$, $p = .7311$; syllable duration: $r = .01$, $p = .9848$. Second, nonlinear positional effects are commonly observed in speech and music tasks and needed to be accounted for in this study of motor speeds. Byrd and Saltzman (2003) proposed that speech timing is modulated by positional effects relative to prosodic boundaries. In this model, the clock rate of articulatory movements slows as a prosodic boundary is approached and speeds up again with increasing distance from the boundary. Similar nonlinear rate effects have been described with respect to music (“accelerando-ritardando”; “final lengthening”; Gabrielsson 1999). Because of these positional effects on durations, speed measures were calculated for each item separately, and items in final position were excluded from analysis. For the child/adult ratio in the two imitation tasks, imitated durations were set in proportion with the corresponding target item before averaging these ratios. Third, we ruled out variability in the live presentations of the modeled clap sequences for the clapped rhythm imitation task, which is essential to obtain valid and reliable measures in the participants’ imitations. Item by item, clapped quarter notes were presented across participants with an average variability of 13% (overall mean = 236 ms; SD = 31 ms; coefficient of variation: .13). This level of variability was considered sufficiently consistent for the purposes of this study. Fourth, in assessing the participants’ language skills, care was taken to observe whether phonological deficits acted as sources of confounding, artificially lowering the language scores. For instance, final consonant deletion, a phonological error, can evoke the impression of a language delay because syntactic marker suffixes are deleted. In the present sample, only one participant omitted final consonants systematically, and his prevailing error types during language testing consisted largely of word omission, word insertion, word substitution, and word order reversals. The language scores in this study thus appear not to be confounded by speech errors. Lastly, we ruled out confounding from timing inaccuracies. In the imitation tasks, it was of crucial importance to align a child’s imitation to the corresponding target. Where the metric pattern was correctly reproduced, this correspondence was readily achieved. Where this was not the case, a determination of what constituted an omitted, inserted, or reversed syllable or clap followed the metrical alignment of the imitation with the model along landmarks of longer durations, which, in the NWI case, were stressed syllables and, in the CRI task, half note intervals. Further details regarding the alignment procedures to ensure correct imitation-target correspondences are found in Peter and Stoel-Gammon (2008). Omitted, extraneous, or reversed items were excluded from the analysis.

Results

Characteristics of the Raw Data

Three measures of movement speeds, child/adult ratios of unstressed vowel durations from a nonword imitation (NWI) task, child/adult ratios of quarter-note clap intervals from a clapped rhythm imitation (CRI) task, and syllable durations from a syllable repetition (SR) task, were collected from 11 children with SSD, age 4;7 to 6;6, and 11 age- and gender-matched controls with TD. In the NWI task, the SSD group produced fewer unstressed syllables that met criteria for metrical accuracy and, hence, could be scored ($N = 168$) than the TD group ($N = 185$). In terms of scorable CRI clap intervals, the groups differed only by one interval (SSD: $N = 164$; TD: $N = 165$). In general, the participants imitated the rapid oral and hand movements with longer durations than the adult model (average ratio NWI = 1.46, CRI = 1.11). Exceptions to this pattern were T02 and T10, who averaged faster durations in the CRI task than the model, and T06, who averaged faster durations in the NWI task than the model. Table 4 shows the speed scores from the NWI, CRI, and SR tasks, averaged for each participant.

Research Question 1: Mutual Associations Among Speed Measures

The three measures of movement speed were evaluated for mutual correlations. In the non-word and clapped rhythm imitation tasks, the child/adult duration ratios, averaged for each participant, were correlated at $r = .54$ ($p = .0097$), which did not reach the adjusted statistical significance level of .0028. Syllable durations were correlated with the child/adult ratios from the NWI task at $r = .79$ ($p < .0001$) and with the adult/child duration ratios from the CRI task at $r = .61$ ($p = .0025$). Both of these correlations met the adjusted significance level.

Research Question 2: Traits Associated with Motor Speed

To evaluate the associations between measures of movement speed and measures related to speech (articulation, phonological processes) and language (receptive vocabulary, sentence comprehension, sentence imitation), pairwise correlation coefficients were calculated, based on per-participant mean values. Results indicated that sentence imitation was significantly and negatively correlated with all three measures of movement speed, specifically with mean child/adult ratios from the NWI task at $p = -.74$ ($p = .0001$), mean child/adult ratios from the CRI task at $p = -.64$ ($p = .0014$), and mean child/adult ratios from the SR task at $p = -.74$, $p = .0004$. The negative sign of the correlation indicates that shorter durations, which were interpreted as representing faster movement rates, were associated with higher sentence imitation scores. All other correlation pairs also carried a negative sign but did not reach alpha. The closest approximation came from the correlation between receptive vocabulary and the child/adult ratio from the NWI task ($r = .60$, $p = .0029$). Articulation was correlated with syllable durations at $r = -.28$ ($p = .2087$), the child/adult duration ratio from the NWI task at $r = -.35$ ($p = .1139$), and the child/adult duration ratio from the CRI task at $r = -.27$ ($p = .2304$). Phonology was correlated with syllable durations at $r = -.46$ ($p = .0311$), the child/adult duration ratio from the NWI task at $r = -.42$ ($p = .0525$), and the child/adult duration ratio from the CRI task at $r = -.26$ ($p = .2389$). Figure 2 shows a scatterplot of child/adult duration ratios from the NWI unstressed vowels as a function of syllable durations from the SR task, where the labels indicate standard scores from the sentence imitation task.

Research Question 3: The Role of Speed in SSD

Summary statistics show that the participants with SSD, on average, tended to exhibit slower motor speeds than their peers with TD, although overlaps were seen between the groups. In the NWI task, child/adult ratios for vowel durations averaged 1.55 (SD = .38) in the SSD group and, in the TD group, 1.36 (SD = .32). This difference was not statistically significant ($t = 1.32$, $p = .1002$). In the CRI task, the SSD group averaged child/adult ratios of 1.14 (SD = .08) and the TD group, 1.09 (SD = .10). This difference was also not statistically significant ($t = 1.21$, $p = .1205$). In the SR task, the average syllable duration in the SSD group was 258 ms (SD = 45 ms) and, in the TD group, 239 ms (SD = 25 ms). For reference, expected syllable durations range from 216 ms for the younger participants to 187 ms for the older participants in this study (Robbins and Klee 1987). As in the other two measures of speed, the group difference was not statistically significant ($t = 1.27$, $p = .1088$).

To further evaluate SSD associations with movement speeds, participants were grouped according to their mean speed scores, based on SR durations. Per-participant mean durations were entered into hierarchical agglomerative clustering, using average linkage. The output (Fig. 3) was consistent with three main clusters. Using K means clustering with $K = 3$, based on the output from hierarchical agglomerative clustering, three distinct clusters were generated. ANOVA testing confirmed statistically significant differences among the clusters ($F = 70.86$, $p < .0001$). Cluster 1, consisting of [D01, D02, D03, D04, T01, T02, T04, T05, T06, T07, T08, T09, T10, T11], had the overall shortest durations (NWI mean unstressed vowel child/adult ratio = 1.27; SD = .17; CRI mean clap interval child/adult ratio 1.08; SD = .07; syllable duration from all scored syllable: 226 ms; SD = 13 ms). Syllable durations in this cluster approached expectations for participant ages (Robbins and Klee 1987). Cluster 2, consisting of [D05, D07, D09, D10, D11], had intermediate movement speeds (NWI mean vowel child/adult ratio = 1.65; SD = .34; CRI mean clap interval child/adult ratio = 1.10; SD = .02; syllable duration from all scored syllable: 266 ms; SD = 12 ms). Syllable durations were slower than expected, given participant ages (Robbins and Klee 1987). Cluster 3, consisting of [D06, D08, T03], had by far the slowest movement speeds (NWI mean vowel child/adult ratio = 2.01; SD = .31; CRI mean clap interval child/adult ratio = 1.28; SD = .08; syllable duration from all scored syllable: 323 ms; SD = 16 ms). Syllable durations were far longer than expected, given participant ages (Robbins and Klee 1987).

To characterize speech and language scores in the clusters, only the speech scores from the participants with SSD were evaluated because of the obvious bimodal distribution of the participants with, and without, SSD in this study, while language scores from all participants in the clusters were included. Cluster 1 contained participants with SSD whose GFTA-2 standard scores ranged from 40 to 66 (mean = 54.5) and whose KLPA-2 standard scores ranged from 40 to 87 (mean = 64.8); overall, language scores were within or above typical limits in this cluster (receptive vocabulary: mean = 116.9, range = 97, 147; sentence comprehension: mean = 11.9, range = 8, 15; sentence imitation: mean = 11.8, range = 9, 16). Cluster 2 contained participants with SSD whose GFTA-2 standard scores ranged from 41 to 74 (mean = 61.6) and whose KLPA-2 scores ranged from 46 to 69 (mean = 56.0). Language scores in this cluster were also typical except for one child, D05, with low scores in receptive vocabulary and sentence imitation (receptive vocabulary: mean = 100.8, range = 78, 109; sentence comprehension: mean = 10.0, range = 7, 12; sentence imitation: mean = 7.4, range = 2, 10). The two participants with SSD in cluster 3 had GFTA-2 standard scores ranging o 50 an 67 (mean = 58.5) and KPLA-2 standard scores of 40 and 48 (mean = 44.0). Receptive vocabulary (mean = 94.3, range = 89, 104) and sentence comprehension (mean = 11.3, range = 9, 14) were within or above normal limits in this cluster as a whole. Sentence imitation scores in this cluster were far below normal limits (mean = 4.0, range = 4, 6). ANOVA testing showed that the clusters differed significantly only for sentence imitation ($F = 18.49$, $p < .0001$), with the greatest differences shown between clusters 1 and 2, and 1 and 3, whereas clusters 2 and 3 did not differ significantly.

Regarding the phonological processes captured with the KLPA-2 (Table 2), three of these processes address segmental or syllable deletion: cluster simplification, deletion of final consonants, and syllable reduction. Only the participants with SSD produced phonological processes. In cluster 1 [D01, D02, D03, D04], on average, .82 of these processes (range: 0, 2) was expressed in more than 10% of opportunities. On average, participants omitted final consonants in 4.5 % of opportunities, omitted syllables in 2.9 % of opportunities, and reduced clusters in 30.0 % of opportunities, resulting in an overall deletion rate of 15.0%. In cluster 2 [D05, D07, D09, D10, D11], on average, 1 of omission processes (range: 0, 2) were expressed in more than 10% of opportunities. Final consonants were deleted in 6.8 % of opportunities, syllables were omitted in 3.1 % of opportunities, and clusters were reduced in 23.9 % of opportunities, averaging 11.3% of deletions relative to given opportunities overall. In cluster 3 [D06, D08], D06 expressed two of these processes in more than 10% of opportunities and D08 expressed all three processes beyond 10% of opportunities (mean = 2.5, range: 2, 3). Final consonants were omitted in 30.7 % of opportunities, syllables were omitted in 17.3 % of opportunities, and clusters were reduced in 58.7 % of opportunities, with an overall average of 35.2% of deletion errors relative to opportunities. Average deletion rates were not statistically different among the three clusters ($F = 2.68$, $p = .1289$).

Discussion

The purpose of this study was to test the hypothesis that children with SSD have a generalized reduction in processing speed that explains their speech problems. Under investigation was (1) whether movement speeds in two oral tasks, nonword imitation (NWI) and syllable repetition (SR), and one hand task, clapped rhythm imitation (CRI), were mutually associated, (2) how the sampled speech and language traits were associated with movement speeds, and (3) what role movement speeds play in SSD.

In general, the participants imitated the rapid oral and hand movements with longer durations than the adult model. Given that finger tapping speeds have been shown to increase in childhood and adolescence, then decrease with advancing age (Bartzokis et al. 2008), slower motor speeds in children, compared to non-elderly adults, are to be expected. In general, child/adult ratios were greater in the unstressed vowel durations from the NWI task, compared to the clap intervals from the quarter notes in the CRI task. It should be remembered that, in the NWI task, only vowels were measured, not the whole syllable, and durations for vowels were shorter than those for syllables.

Regarding research question 1, addressing mutual correlations among the three measures of movement speed, unstressed vowel durations from the NWI task, clap intervals from the CRI task, and syllable durations from the SR task, syllable durations were positively and significantly correlated with the child/adult duration rations from the NWI and CRI tasks, whereas the positive correlation between the two child/adult ratios from NWI and CRI approached but did not reach statistical significance. The NWI and CRI tasks were designed to allow direct comparisons between the oral and limb motor systems. The SR task was designed as a maximum rate task taxing the motor speech system. The strongest and most significant association was seen between the speed measures from the NWI and SR tasks. With respect to both participant groups together, these findings imply the following: First, movement rates in two different oral motor tasks, an imitation task and a maximum rate task, were strongly correlated, suggesting an underlying and shared limit of oral movement rates that was evident in a maximum rate task as well as an imitation task. Second, movement rates in an oral task (SR) and a limb movement task (CRI) were mutually associated, suggesting that slowed movement speeds were limited by a central mechanism that transcended motor domains. Third, it is possible that motor speeds, while generally under central control, have some system-specific components such that oral movement speeds are mutually more closely associated than oral movement speeds and movement speeds in other domains. Associations of motor speed across motor systems should be further investigated in larger samples and additional motor systems.

The SR task was designed as a maximal rate task while the NWI and CRI incorporated elements of precision in a rapid movement context, given a model. These two types of movement tasks, imitation and maximal rate, involve different cognitive processes such as an additional working memory component in the imitation task, and they have been associated with differences in motor patterns (Adams et al. 1993; Smith et al. 1995). Nonetheless, we report a robust correlation between the SR and NWI measures of movement speed. It would be of interest to examine this correlation in individuals at varying ages, as movement rates in young children and elderly adults are more rate-limited compared to non-elderly adults (e.g., Bartzokis et al. 2008). It is possible that we found a correlation between a maximal rate task and an imitation task in children because of their more generally limited movement speeds. Alternatively, these rate limits may be associated regardless of task type and age.

Regarding research question 2 addressing associations of speech and/or language abilities with measures of movement speed, the strongest associations were seen between the sentence imitation task and all three measures of movement speed. In all cases, shorter durations implying more rapid movement speeds were associated with higher language scores. This observation is consistent with the recent literature on slowed processing speeds in children with language impairment (LI), as reviewed in Schul et al. (2004), Pennington and Bishop (2009), and Windsor and Hwang (1999). While the LI studies focused on children with low language abilities, our study shows these correlations in the presence of typical and high language scores in addition to several low scores, motivating new questions regarding the role of processing speeds in children in the full range speech and language abilities, including average and superior abilities.

Regarding research question 3 about the role of movement speeds in SSD, average speeds in all three tasks tended to be slower in the SSD group than in the TD group, although none of these group differences were statistically significant. The overlaps between the two groups indicate that movement speeds cannot be used to differentiate conclusively between SSD and TD.

A clearer pattern of association was seen when syllable durations from the SR task were used to create three distinct clusters of participants with minimal within-cluster differences and maximal between-cluster differences. Whereas no published norms for the two speed measures from the NWI and CRI tasks are available, the average syllable durations in cluster 1 met expectations given the participants' ages while those in clusters 2 and 3 were far longer. The fact that all but one of the controls fell into the cluster with the shortest syllable durations whereas five participants with SSD fell into the intermediate cluster and two, into the cluster with the longest durations creates the appearance that SSD is associated with longer syllable durations and, by interpretation, slower motor speeds. This view, however, would be confounded by the fact that the clusters also differed significantly in their sentence imitation scores, whereas the speech and phonology scores from the participants with SSD did not differ significantly among the clusters. As shown above, sentence imitation was significantly correlated with all three measures of timed motor activity. Together, these findings support the conclusion that motor speeds in children with SSD are not so much associated with measures of speech production but, rather, with measures of expressive language ability. This conclusion is further corroborated by the fact that T03, who showed no evidence of SSD and had typical receptive language scores but a low expressive language score, fell into the cluster with the longest syllable durations.

When the speech scores from the participants with SSD alone were considered, the phonology scores followed the cluster structures in that the highest scores were seen in the cluster with the fastest movement speeds and the lowest scores, in the cluster with the slowest speeds, although this association was not statistically significant. The same trend did not hold for the articulation scores, where the highest scores were associated with intermediate movement speeds and the lowest, with the slowest movement speeds. A closer look at those phonological processes involving deletions on the level of segments and syllables showed that the cluster with the slowest movement speeds had the highest proportion of deletion errors, whereas the cluster with fastest speeds had the lowest proportion of deletion errors, although this configuration was not statistically significant.

With respect to the role of movement speeds in SSD, these results can be summarized as follows: First, the presence of SSD did not predict slowed motor speeds. Second, two subcohorts of the participants with SSD appeared to have slower motor speeds compared to the controls but this cluster structure was not so much related to the presence of SSD but to the concomitant expressive language difficulties in these participants. Third, while there was a trend for increased omission errors in participants with slowed motor speeds, this aspect should be further evaluated in future studies and interpreted with respect to two possible hypotheses, one related to compensatory action resulting from speed constraints in the speech system and the other, to linguistic deficits related to low expressive language abilities.

Implications for Future Studies and Limitations of this Study

As stated in the Introduction, one rationale for examining motor speeds in SSD was to inform future neurophysiologic and genetics studies. The hypothesis that slowed motor speeds characterize SSD or one or more of its subtypes was confirmed largely conditioned on concomitant expressive language difficulties. Therefore, motor speeds may prove to be a more relevant trait in studies evaluating the genetics of LI, compared to such studies of SSD. A subsequent sample should be evaluated for the possibility that a subset of children with SSD shows reduced motor speeds independently of expressive language ability.

Limitations of the study must be acknowledged. Because of the relatively small sample size and the use of clustering algorithms, which are by definition non-inferential, results cannot be generalized to the population at large. Any conclusions from the data in this study are most relevant to the given database itself. The present study, hence, motivates further hypothesis testing. Durations of syllables, vowels, and clap intervals were used as estimates of movement speed, but velocity was not directly measured. Short durations could potentially be achieved without an increase in velocity via a decrease in excursion. Nonetheless, the results from this study are consistent with those reported in the recent literature on processing speeds in children with LI and RD. Durations derived from an imitation task do not directly tax maximal motor rates, but the child/adult ratios show increased durations in the children's imitations relative to the model. In the NWI task, this measure correlated meaningfully with the maximal motor rates from the SR task, validating the durational characteristics in the imitation task as an estimate of motor speed. Future studies should corroborate the present results in larger participant samples. They should also probe additional variables to explore the possibility of an underlying biological mechanism such as slowed neurophysiologic processing affecting performance in a variety of domains including linguistic and cognitive functioning, a field of study that has already been fruitful in populations with LI and RD. The finger tapping task described by Bartzokis et al. (2008) may prove a powerful tool to explore associations between motor speeds and white matter integrity behaviorally in individuals with SSD. As mentioned, brain imaging and genetic studies would be instrumental in exploring the biological substrates of SSD in greater depth. The respective roles of perceptual and productive processing were not addressed in this study and should be considered in the future. Similarly, the effects of speech therapy in the expression of SSD were not specifically taken into account in this study and should be explored in future studies.

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Fig. 1.
Score for the clapped rhythm imitation task (adapted with permission from Peter and Stoel-Gammon 2008)

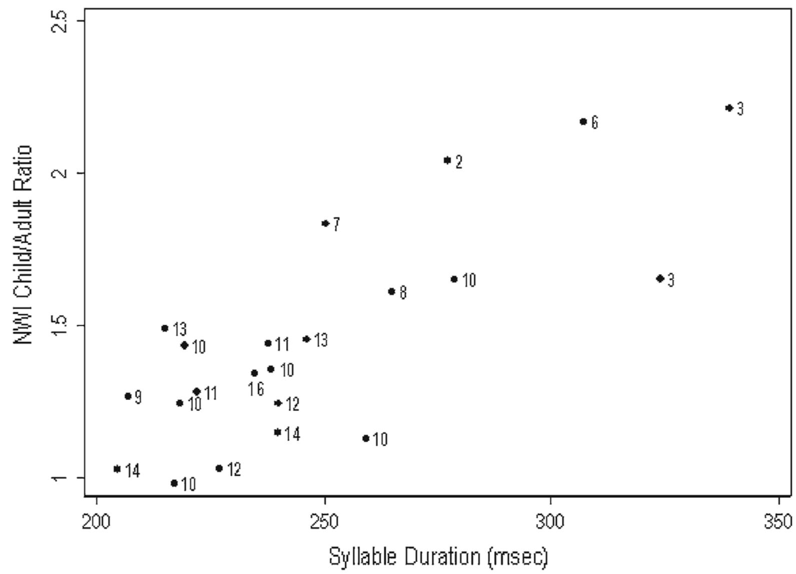

Fig. 2.
Scatterplot of unstressed vowel child/adult ratios from the NWI task as a function of syllable durations from the SR task *(r* = .79, *p* < .0001*)*. *Labels* indicate standard scores from the sentence imitation task (mean = 10, standard deviation = 3)

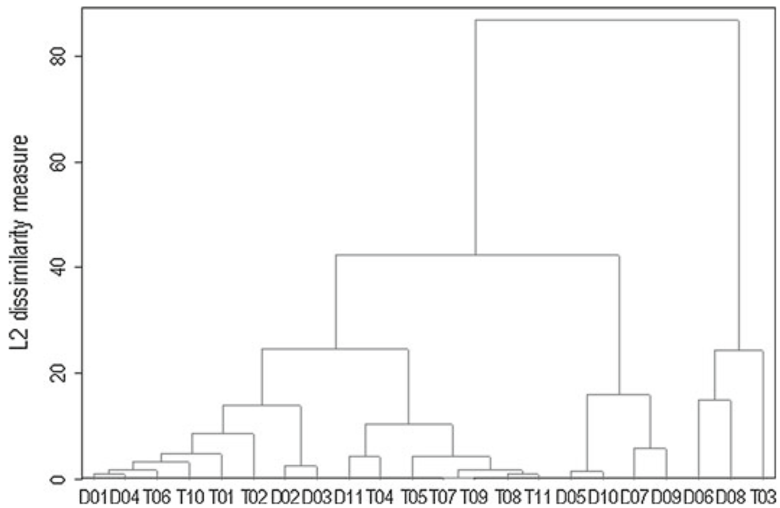

Fig. 3.

Dendrogram of hierarchical agglomerative clustering based on syllable durations from the SR task

Table 1

Descriptive statistics of speech and language measures in the SSD and TD groups

Measure	Population mean (SD)	SSD mean (SD)	SSD range	TD mean (SD)	TD range
Articulation	100 (15)	58.5 (11.6)	40, 74	106.2 (9.7)	84, 117
Phonology	100 (15)	55.6 (16.7)	40, 87	103.9 (10.2)	80, 113
Receptive vocabulary	100 (15)	102.3 (13.2)	78, 120	118.1 (14.3)	97, 147
Sentence compr.	10 (3)	10.6 (1.7)	7, 13	12.2 (2.0)	8, 15
Sentence imitation	10 (3)	7.8 (3.7)	2, 14	11.6 (2.6)	6, 16

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Table 2

Phonological processes from the KLPA-2 in raw scores (and percent expressed) in the participants with SSD

Process level	Phonological process	D01	D02	D03	D04	D05	D06	D07	D08	D09	D10	D11
Reduction	Final consonant deletion	6 (14)	0 (0)	0 (0)	2 (5)	2 (5)	1 (2)	2 (5)	26 (59)	1 (2)	10 (23)	0 (0)
	Syllable reduction	1 (4)	0 (0)	0 (0)	2 (8)	2 (8)	4 (15)	0 (0)	5 (19)	2 (8)	0 (0)	0 (0)
	Stopped fricatives and affricates	18 (58)	2 (6)	0 (0)	3 (10)	3 (10)	4 (13)	17 (55)	9 (29)	2 (6)	0 (0)	0 (0)
	Cluster simplification	9 (35)	14 (54)	1 (4)	15 (58)	17 (65)	10 (38)	0 (0)	20 (77)	5 (19)	6 (23)	3 (12)
	Liquid simplification	18 (58)	11 (35)	20 (65)	8 (26)	18 (58)	26 (84)	15 (48)	12 (39)	25 (81)	27 (87)	19 (61)
Place, manner	Velar fronting	10 (53)	0 (0)	0 (0)	15 (79)	4 (21)	14 (74)	12 (63)	2 (11)	10 (53)	12 (63)	0 (0)
	Palatal fronting	3 (33)	0 (0)	0 (0)	6 (67)	0 (0)	0 (0)	7 (78)	1 (11)	6 (67)	3 (33)	8 (89)
	Deaffrication	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Voicing	Initial voicing	8 (31)	0 (0)	0 (0)	3 (12)	2 (8)	2 (8)	0 (0)	7 (27)	0 (0)	0 (0)	0 (0)
	Final devoicing	5 (16)	1 (3)	1 (3)	4 (13)	12 (38)	9 (28)	5 (16)	0 (0)	8 (25)	1 (3)	0 (0)

Table 3

Schematics of stimuli in the nonword imitation task

Item number	Rhythm pattern
1	MA.ma
2	ma.MA
3	MA.ma.MA
4	ma.MA.ma
5	MA.ma.ma
6	MA.ma.MA.ma
7	ma.MA.MA.ma
8	ma.ma.MA.ma
9	ma.MA.ma.ma
10	ma.MA.ma.MA
11	MA.ma.ma.MA.ma
12	ma.MA.ma.ma.MA.ma

Capital letters indicate stressed syllables, lower-case letters indicated unstressed syllables, and periods mark syllable boundaries

Table 4

Measures of movement speed

Participant code	NWI adult mean vowel duration (ms)	NWI child mean vowel duration (ms)	NWI child/adult ratio	CRI adult mean clap intervals (ms)	CRI child mean clap intervals (ms)	CRI child/adult ratio	SR (ms)
D01	82.2	113.5	1.43	228.7	245.1	1.08	219.2
D02	82.2	99.8	1.27	228.8	273.0	1.20	206.8
D03	82.2	82.6	1.03	217.2	229.5	1.07	204.4
D04	82.2	103.5	1.24	237.4	263.3	1.11	218.3
D05	82.2	155.7	2.04	264.4	288.8	1.12	277.3
D06	82.2	134.3	1.65	238.7	355.2	1.54	324.0
D07	82.2	90.0	1.13	231.4	251.3	1.10	259.0
D08	82.2	175.9	2.21	275.2	350.6	1.31	339.2
D09	82.2	128.9	1.61	226.8	240.4	1.07	264.8
D10	82.2	130.2	1.65	235.3	259.4	1.11	278.8
D11	82.2	144.3	1.83	217.8	236.1	1.10	250.3
T01	82.2	104.1	1.28	240.2	281.7	1.19	222.0
T02	82.2	83.5	1.03	213.6	209.3	0.99	226.9
T03	82.2	171.9	2.17	234.7	308.2	1.33	307.2
T04	82.2	117.0	1.45	250.4	263.2	1.06	246.0
T05	82.2	107.1	1.34	243.8	258.7	1.07	234.7
T06	82.2	82.2	0.98	241.7	338.4	1.41	216.9
T07	82.2	92.5	1.15	228.5	236.8	1.04	239.6
T08	82.2	108.1	1.36	229.9	248.6	1.09	238.5
T09	82.2	101.3	1.24	246.6	261.7	1.05	239.8
T10	82.2	119.2	1.49	244.6	237.8	0.98	214.9
T11	82.2	114.8	1.44	227.0	258.6	1.15	237.6

Table adapted with permission from Peter and Stoel-Gammon (2008)

D disorder, *T* typical, *NWI* nonword imitation, *CRI* clapped rhythm imitation, *SR* syllable repetition