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Research Report

Nonword repetition and phoneme elision skills in school-age children who do and do not stutter

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Abstract

Nonword repetition and phoneme elision represent the combined influence of several speech and language processes. In the present study we investigated nonword repetition and phoneme elision performance in school-age children who stutter (CWS) and children who do not stutter (CNS). Participants were 14 CWS (mean = 11.7 years, SD = 2.1 years) and age- and sex-matched CNS (mean = 11.8 years, SD = 2.0 years). Each talker group was further subdivided into two age groups: younger ($N = 7$; 8–11.5 years) and older ($N = 7$; 11.6–15 years). Repeated-measures analyses were conducted on the accuracy and response time (in seconds) data. In nonword repetition, the CWS showed a trend for lower per cent of correct phonemes at the two-syllable level compared with the CNS. In phoneme elision, the younger CWS showed a significantly lower accuracy rate than the older CWS at the two- and three-syllable nonword lengths, while similar differences were not evident between the younger versus older CNS at any of the nonword lengths. No accuracy difference in phoneme elision was noted between the two talker groups. Group differences in speech initiation times were also not evident in either of the tasks. Findings from nonword repetition offer tentative support for difficulties experienced by school-age CWS in phonemic encoding/working memory abilities. Findings from the phoneme elision task suggest a complex pattern of age-dependent performance by the CWS. Comparison of response accuracy and speech initiation times in both the tasks failed to show speed–accuracy trade-off strategies in either of the groups.

Keywords: stuttering, nonword repetition, phoneme elision, phonological encoding, phonological working memory.

What this paper adds?
Previous studies of nonword repetition in children who stutter (CWS) have reported mixed results. In this study, we investigated nonword repetition and phoneme elision in school-age CWS and those who do not stutter (CNS) to investigate the different underlying sub-processes. The findings showed that school-age CWS experience residual difficulties in nonword repetition. Performance in phoneme elision showed an age-dependent pattern of performance in CWS.

Introduction

Stuttering is a fluency disorder characterized by disruptions in the smooth flow of speech (Conture 2001). Several theories have been proposed, with most accounting for stuttering either within a motoric (e.g. Webster 1990, Neilson and Neilson 1991) or a linguistic framework (e.g. Postma and Kolk 1993, Vasic and Wijnen 2005). But evidence for the presence of both speech motor and, arguably, linguistic difficulties in children and adults who stutter counter-indicate such a clear causal dichotomy. This has led several researchers to take a multifactorial approach to stuttering (Conture 2001, Smith and Kelly 1997). In this framework, stuttering is identified as an emerging, dynamic speech motor disorder interacting with multilevel factors including cognitive–linguistic processes.

Of the several cognitive–linguistic processes, phonological processing and its role in stuttering has been described extensively in theories, such as the Covert Repair Hypothesis (Postma and Kolk 1993) and the EXPLAN model (Howell 2004). More recently, the

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role of phonological working memory has also been attributed to the difficulties that persons who stutter have establishing/maintaining fluent speech (e.g. Anderson *et al.* 2006, Byrd *et al.* 2012, Anderson and Wagovich 2010). To explore the role of phonological encoding and phonological working memory in children who stutter (CWS), the nonword repetition task has been a popular choice (e.g. Anderson *et al.* 2006, Bakhtiar *et al.* 2007, Hakim and Bernstein Ratner 2004, Smith *et al.* 2012). Performance in nonword repetition represents the combined influence of several speech and language processes including both working memory and phonological processing (Kent 2000). In addition, examination of the time required to initiate nonword production in part offers a window into the speech motor processes involved. Phoneme elision is yet another task with the potential to offer insights into phonological processing. However, performance in phoneme elision is a relatively unknown in persons who stutter, particularly children. The aim of the present study is to examine nonword repetition and phoneme elision performances in CWS to shed light on the different underlying sub-processes of speech–language planning and production.

Key components of nonword repetition and phoneme elision

Nonword repetition

The process of nonword repetition involves several processes including auditory processing (when the nonwords are presented aurally), encoding the acoustic information into phonological representations, holding the representation in working memory, motor planning and execution of the response (Gathercole 2006). Earlier studies of nonword repetition have been interpreted largely within the context of strength of existing lexical knowledge. For example, younger children experienced more difficulties in repeating nonwords that did not resemble words compared with word-like nonwords, and such differences diminished with age, thereby suggesting that prior lexical knowledge can influence performance (Munson 2001). However, nonword repetition performance involves more than reliance on prior lexical knowledge and working memory. Two other critical processes underlying nonword repetition are phonological encoding and speech motor output. Examining the error responses from nonword repetition can provide information about the phonological encoding process. In addition, examining the time taken to initiate the nonwords can provide insight regarding the language and motor planning processes leading up to production. Thus, the nonword repetition task can be used to study several processes that have been identified as key variables in stuttering causation and maintenance.

Phoneme elision

The phoneme elision task requires the repetition of a nonword with the omission of a target sound (Wagner *et al.* 1999). The elimination of a phoneme from a nonword first requires that the person accurately encode the nonword in his/her working memory. To demonstrate the accurate encoding of the initial nonword, the person must first provide an overt production of that nonword prior to being instructed which phoneme to remove in the subsequent production. To produce the revised nonword, the person must then be able to accurately verbally rehearse the initial nonword, and hold it in his/her memory long enough to allow for accurate segmentation and manipulation of that nonword, all within a timeframe that allows for accurate production of the revised nonword. Thus, poor performance in phoneme elision can indicate an inability to hold and/or manipulate the nonword in working memory.

Nonword repetition skills in children who stutter

Several studies of nonword repetition performance in CWS have identified difficulties with one or more of the key processes involved (e.g. Anderson *et al.* 2006, Anderson and Wagovich 2010, Bakhtiar *et al.* 2007, Hakim and Bernstein Ratner 2004, Smith *et al.* 2012). However, some of these findings have been mixed, thereby necessitating further investigation. For instance, Hakim and Bernstein Ratner (2004) compared eight CWS (4;3–8;4 years;months) to age-matched children who do not stutter (CNS) using the Children's Test of Nonword Repetition (CNrep; Gathercole *et al.* 1994). CWS had fewer correct productions and more phonemic errors than the CNS in one-, two- and three-syllable nonwords, but significant group differences were observed only at the three-syllable level. A higher per cent of phoneme errors was observed in both groups for the longer four- and five-syllable nonwords. Anderson *et al.* (2006) compared performance of 12 CWS and age-matched controls between 3 and 5 years, again using the CNrep. CWS exhibited significantly fewer correct productions of two- and three-syllable nonwords and a higher per cent of phonemic errors in the three-syllable nonwords compared with the fluent peers. The authors from both these studies concluded that CWS have weaker phonological working memory skills compared with typically developing children. Considering that nonword repetition is based on the strength of several underlying processes, to attribute the observed group differences in these studies solely to phonological working memory seems questionable. Phonological encoding difficulties as well as motor planning and/or execution difficulties may have resulted in the observed group differences.

Anderson and Wagovich (2010) investigated nine CWS and 14 CNS between 3;6 and 5;2 for possible relationships between measures of linguistic processing speed and phonological working memory, and attention. Children participated in a picture-naming task (an index of linguistic processing speed) and a nonword repetition task. Findings revealed that the groups did not differ from each other on speed of picture naming. As would be expected, the CWS performed significantly worse in nonword repetition. An unexpected yet critical finding was that the CNS demonstrated a significant relationship between nonword repetition and attention in task performance but the CWS did not. This finding suggests that attention may play a unique role in the differences observed between CWS and CNS is nonword repetition. The authors interpreted the results to underscore the need to consider the underlying skills associated with lexically related aspects of language production when examining performances of CWS and CNS.

Contrary to the earlier studies, a few others have not found performance differences between CWS and CNS in nonword repetition. For instance, Bakhtiar *et al.* (2007) compared nonword repetition performance in 12 Iranian CWS and 12 CNS. The age range of the children in this study was comparable with that reported by Hakim and Bernstein Ratner (2004). Bakhtiar *et al.* (2007) reported that the groups were comparable in mean phonemic errors. These authors also compared reaction times for nonword repetition between the two groups and found no difference. They interpreted the findings as evidence against the Covert Repair Hypothesis (Postma and Kolk 1993), which attributes slowed and/or erroneous phonological encoding in CWS. Comparable speech reaction times offered further support for the lack of group differences in the linguistic and motor planning stages leading up to production. However, cautious interpretation of the findings from this study is warranted as the nonwords used in the study were generated by replacing one or two phonemes in bi- and tri-syllabic Farsi words. The authors failed to describe the frequency of occurrence of the target words from which the nonwords were generated; the extent of 'wordlikeness' of the nonwords may have influenced task performance.

Weber-Fox *et al.* (2008) conducted an evoked response potential study of rhyme judgment in older, school-age CWS and age-matched CNS between nine and 13 years. These authors also tested their participants in a nonword repetition task (NRT; Dollaghan and Campbell 1998), consisting of four nonword lengths (1–4) and four nonwords at each length. They found no group differences in the per cent correct phonemes on the NRT. However, the stimuli employed to determine differences were limited to four syllables in length and consisted only of four nonwords at each length. In a more recent large-scale study, Smith *et al.* (2012) used nonword repetition to explore speech motor and language abilities of 31 children aged 4–5 years diagnosed as stuttering. Testing revealed that half of the CWS that had language and/or phonological disorders produced significantly more errors in the nonword repetition task compared with the CNS. The CWS who had normal language and phonological abilities were comparable with the CNS in nonword repetition accuracy. Findings from the movement variability data, however, revealed that the CWS group showed higher movement variability in task performance. The findings from Smith *et al.* (2012) suggested that while CWS may not differ from CNS in phonological encoding and/or working memory abilities, group differences in this task may be specific to speech motor difficulties. On a cautionary note, the lack of differences in behavioural accuracy in both Weber-Fox *et al.* (2008) and Smith *et al.* (2012) should be extended to a larger and more diverse set of nonwords before the conclusions can be generalized.

Phoneme elision skills in children who stutter

The phoneme elision task has been used to explore phonological working memory relative to the verbal rehearsal system, and to segmentation abilities (Jones *et al.* 2009). Byrd *et al.* (2012) reported comparable performance between adults who do and do not stutter in phoneme elision. Although there are no known studies of phoneme elision performance in CWS, there is some indirect evidence to support the assumption that CWS may have difficulties manipulating phonemes in working memory. For instance, recent findings by Sasisekaran and Byrd (2013) suggest that CWS may experience difficulties with monitoring phonemes within consonant clusters. The authors attributed this preliminary finding to difficulties with segmentation in CWS.

Purposes of the present study

There were three main aims to the present study. First, findings from earlier studies of nonword repetition performance in CWS are mixed. Some of these studies have attributed the observed differences to phonological encoding/working memory deficits while some others have reported difficulties specific to speech motor execution. To this end, the primary aim was to examine the different sub-processes involved in nonword repetition performance–phonological encoding, working memory, and speech motor processes leading up to production. The groups were compared in accuracy from the nonword repetition task in order to examine phonological encoding and working memory abilities of CWS compared with CNS. The time taken to initiate nonword repetition responses were examined in order to investigate if CWS are different from CNS in the language and speech motor planning stages leading up to nonword production. The research question was whether CWS differ from CNS in response accuracy and/or speech initiation times in the nonword repetition task. Based on past reports, we hypothesized that CWS will show lower accuracy rates in the nonword repetition task compared with the CNS. We further hypothesized that poor accuracy is likely to be accompanied by slower speech initiation times thereby confirming linguistic (phonemic) and/or motoric planning difficulties.

Second, we also examined group differences in accuracy and speech initiation times in a phoneme elision task. As suggested by Byrd *et al.* (2012), the phoneme elision task provides additional opportunities to expose the online operational workings of the working memory system in a manner that has not yet been explored in CWS.

Third, the mixed findings from earlier studies can, in part, be attributed to methodological differences. For instance, these studies varied in the age of the participants as well as in the nature of the nonwords used to study task performance. A majority of such studies have been conducted in pre-school CWS (e.g. Anderson *et al.* 2006, Anderson and Wagovich 2010, Smith *et al.* 2012). Considering that a majority of these studies in preschool CWS tested performance in two-, three- and four-syllable nonwords and found significant differences, perhaps the reason that studies in older CWS (e.g. Bakhtiar *et al.* 2007, Weber-Fox *et al.* 2008) did not find group differences at these syllable lengths is because these children outgrow such difficulties with age. Therefore, in order to test for age-related changes in performance and to accommodate the wide age range of participants in our study (8–15 years), the groups were further subdivided into two subgroups: younger (8–11.5 years) and older (11.6–15 years) groups. The research question was to investigate if differences were observed between the younger and older CWS and age-matched CNS in the two tasks.

Finally, given the advances in phonological encoding and phonological working memory that occur with age (Fry and Hale 1996, Sasisekaran and Weber-Fox 2012), we decided to distinguish the nonwords used in this study in two distinct ways. First, we extended the number, length and phonological diversity of the nonword stimuli; and second, we controlled for wordlikeness and phonotactic probability. With these modifications, we aimed to increase task complexity and therefore any observable group differences.

Methods

Participants

Fourteen CWS (two females) and 14 age- and sex-matched CNS between eight and 15 years participated in the study (CWS: mean = 11.7 years, SD = 2.1 years; CNS: mean = 11.8 years, SD = 2.0 years), $t(26) = 0.02$, $p = 0.49$. Participants in each group were further subdivided ($N = 7$ in each subgroup) into a younger (8–11.5 years, CWS, mean = 10.1 years, SD = 0.98 years; CNS, mean = 10.2 years, SD = 1.1 years) and an older group (11.6–15 years; CWS, mean = 13.4, SD = 1.4 years; CNS, mean = 13.3 years, SD = 1.5 years). All participants were right-handed and native speakers of North American English. Participants from both groups were recruited from a pre-existing database at the Speech Fluency Lab, University of Minnesota, and by word of mouth. The test protocol was administered by two trained research assistants under the supervision of the first author. All procedures were approved by the Institutional Review Board, University of Minnesota, and participants received reimbursement for participation. Informed assent and consent was obtained from all participants and accompanying caregivers.

Based on initial screening all participants had a negative history of: (1) neurological deficits, (2) language, speech, reading, hearing difficulties except stuttering in the CWS group, and (3) current usage of medications likely to affect the outcome of the experiment (e.g. for ADHD and anti-anxiety). All participants passed a hearing screening test performed at 0.5, 1, 2, 4 and 8 KHz (20 dB HL) in both ears. The parents of all participants reported age- and grade-appropriate reading skills.

Inclusion criteria for children who stutter

Participants in the CWS group met the following criteria:

- Had received a diagnosis of stuttering by a speech–language pathologist.
- Received a stuttering severity rating between 2 and 7 on a seven-point scale from a parent at the time of testing.

Inclusion criteria (either as per cent stuttered syllables or per cent stuttered words) were not set for the CWS to be eligible to participate. However, speech data from a reading sample and spontaneous speech from the clinician–child interaction were collected from all children in the stuttering group and analysed for disfluencies. Stuttered disfluencies including sound and syllable repetitions, word repetitions (considered as stuttering when the number of iterations were equal to or greater than 3; Yaruss 1998), prolongations, and blocks were coded from the reading and conversation samples by two trained research assistants. The total number of stuttered disfluencies in the entire sample was then counted for each participant. These numbers were then converted to reflect the frequency of disfluencies per 100 syllables. Intra- and inter-judge reliability was calculated on one-third of all samples using the formula:

$$[\text{Total agreement}/(\text{total agreements} + \text{total disagreements})] * 100$$

An intra-judge reliability score of 94% and inter-judge reliability score of 89% were obtained. The disfluency analysis revealed that on average the CWS group exhibited 5.3% (SD = 4.2 percentage points) disfluencies in conversation and 5.3% (SD = 8.3 percentage points) disfluencies in reading. Although all participants in the CWS group were receiving treatment for stuttering at the time of participation, observation during data collection did not reveal the use of fluency induction strategies. Further, the inclusion of participants who were receiving therapy enhanced the ecological validity of the study as most CWS who are at the age of our participants have either previously received and/or would currently be receiving therapy.

Vocabulary, short-term memory, articulation and phonemic awareness

A series of tests was administered to evaluate expressive and receptive vocabulary, articulation, short-term memory, and phonemic awareness skills in both groups. Receptive vocabulary was tested using the Peabody Picture Vocabulary Test—Edition IV (PPVT; Dunn and Dunn 2007). Expressive vocabulary was tested using the Expressive Vocabulary Test (EVT; Williams 1997). Short-term memory span was determined using the forward and backward digit span tests (Weschler's Memory scale; Wechsler 1997). Articulation skills were tested using the Sounds-in-Words section of the Goldman–Fristoe Test of Articulation (GFTA; Goldman and Fristoe 2000). Segmentation skills were tested using the Lindamood Auditory Conceptualization Test (LAC; Lindamood and Lindamood 1979). Two subtests of the LAC were administered to test the cognitive ability to perceive, conceptualize and manipulate speech sounds; skills that constitute phonemic awareness. Scores from Subtests 1 and 2 were used to calculate converted scores that enabled comparison at grade level.

Stimuli

Nonword repetition. The nonword stimuli for this study were taken from Byrd *et al.* (2012). A total of 36 nonwords consisting of an equal number ($n = 12$ for each syllable length) of two-, three- and four-syllable nonwords were selected. Vitevitch and Luce's (2004) web-based method was used to calculate segmental and biphone phonotactic probabilities of the nonwords. The mean sum of segmental probability was 1.217 for the two-syllable nonwords, 1.293 for the three-syllable nonwords, and 1.437 for the four-syllable nonwords. The mean sum of the biphone probabilities was 1.009 for the two-syllable nonwords, 1.021 for the three-syllable nonwords, and 1.024 for the four-syllable nonwords. Thus, the segmental and biphone sums for all syllable length categories were low in phonotactic probability. Mean wordlikeness ratings of the nonwords completed by 20 adults based on a rating scale ranging from 'very unlike a real word' (rating of 1) to 'unlike a real word' (rating of 5) were 2.718 for the two-syllable nonwords, 2.442 for the three-syllable nonwords, and 2.474 for the four-syllable nonwords. The nonwords were further controlled by ensuring that the phonemic onsets and offsets of the stimuli were consistent across all syllable lengths. Two of the 12 nonwords at the two-, three- and four-syllable length began with a vowel. Three to six nonwords at each syllable length began with a stop consonant. Three to five nonwords were fricative initiated at each syllable length. Affricate onsets ranged from one to two per syllable length. Regarding offset consistency, for each syllable length, seven to nine of the nonwords ended with a stop consonant, one to two ended in a liquid or glide, and one to four ended in a vowel. In addition, a fricative offset occurred on two nonwords at the two-syllable length and one nonword at the three-syllable length. Finally, the recorded production of the nonwords consisted of stress placed on the first syllable of each nonword across all syllable lengths.

Phoneme elision. This task required that participants repeat a nonword with a sound or phoneme missing (Wagner *et al.* 1999). The target nonwords for the task were created by requiring the participant to delete alternately the initial consonant sound from the first syllable, the initial consonant sound from the second through fourth syllables, or the final consonant sound in the same nonwords that were used for the nonword repetition task. The end result was that the participant would have to eliminate an initial phoneme at each syllable boundary across all lengths from the beginning to the end of the shortest to the longest nonwords. Thus, elision was based on location, not on phonological property. For example, the initial consonant phoneme elision task for the first syllable of the two-syllable nonwords would include the person having to 'say fackton without saying /f/' with the accurate production being 'ackton'. The initial consonant phoneme elision task from the second syllable for the two-syllable nonword would then be, for example, for the participant to say 'say kentaid without saying /t/', resulting in the production of 'kenaid'. Finally, to complete all potential loci for the phoneme elision task at the two-syllable length category, the participants would then be asked, for example, to say, '"supwig" without the /g/' and then the cycle of loci for the eliminated phoneme would repeat itself until all potential locations were covered at least twice across the syllable lengths. For example, for the two-syllable length nonwords the loci of elimination of first, second, last could be completed four times, the majority of those loci could only be cycled through one time. A complete list of the stimuli used in the phoneme elision tasks can be obtained from Byrd *et al.* (2012).

Stimuli recording and presentation

A female native speaker of Standard American English recorded the nonword and phoneme elision stimuli on a Dell computer using Computerized Speech Lab equipment in a sound-treated room. The microphone was placed approximately 0.45 m from the speaker. For the nonword repetition task, the carrier phrase 'Say' was used for each nonword. For example, 'Say "fackton"'. For the phoneme elision task, the carrier phrase 'Say without saying / /' was used for each nonword. For example, say '"fackton" without saying /f/'. Stimuli presentation order for each syllable length was randomized prior to each session. Intelligibility of the recorded nonwords was verified by an undergraduate speech–language pathology student who listened to and phonetically transcribed the nonwords. The undergraduate's transcriptions were compared with the second author's transcriptions of the nonwords and no discrepancies were found.

Procedure

The entire test session took 1 h and was completed in a quiet room. Two trained research assistants administered the tasks. For the nonword repetition task the following instructions were presented: 'You will be listening to and repeating some made-up words. Please repeat each made-up as clearly as possible.' For the phoneme elision task the following instructions were presented: 'You will be listening to some made-up words. You will be asked to repeat each made-up word with one of the sounds in the word missing. Listen carefully to the recordings. Are you ready to begin?' Before beginning each task participants completed a practice set. During the practice set, participants were presented with a randomly selected nonword from the stimuli list at a syllable length and asked to repeat it. The purpose of the practice set was to establish that participants understood the task requirements. Participants' responses during practice were not corrected as the nonword from practice was repeated again during the experiment. Participant responses from the experiment were recorded both manually and with a digital voice recorder (DVR). For the manual recording, the research assistant conducting the experiment was provided with a sheet containing all of the nonwords and the corresponding International Phonetic Alphabet (IPA) transcriptions. The experimenter was required to mark the cells corresponding to the error productions. For the DVR recording, participant productions were recorded using a high-fidelity Sony DVR that was placed at about 8–10 cm from the speaker's mouth.

For the nonword repetition task, participants were given one attempt to listen to and carefully repeat each nonword. The phoneme elision task was administered after the participant completed nonword repetition at all syllable lengths. Similar to Byrd *et al.* (2012), participants were given the opportunity to first produce the nonword in its entirety prior to having them eliminate one of the phonemes in the elision task. Participants were also provided a maximum of five attempts to listen to and accurately repeat the nonword correctly before advancing to the phoneme elision task. The phoneme elision task was administered irrespective of whether the participant produced the nonword correctly or not in order to prevent the impact of negative feedback from inaccurate productions. However, the phoneme elision data included in the final data corpus consisted only of the nonwords for which the participant was able to produce the nonword accurately prior to completing the phoneme elision task.

Instrumentation

The experimental stimuli were presented using Windows Media Player software. The recorded stimuli were presented through a Toshiba laptop connected to external loud speakers. Responses from the nonword repetition and phoneme elision tasks were recorded using a Sony Digital Voice Recorder. These recordings were manually coded offline for correct/incorrect nonword production and per cent phonemes correct across the three syllable lengths for the nonword repetition task. For the phoneme elision task, the per cent correct responses for each syllable length were coded manually.

Data scoring

The two trained research assistants performed all of the data scoring and analysed the data from both the tasks for accuracy and speech initiation times.

Accuracy. Trials in both tasks were categorized as correct or error responses. In the nonword repetition task, correct responses included trials where participants repeated each nonword correctly. In the phoneme elision task, correct responses included trials where participants repeated a nonword after excluding a pre-identified target phoneme. Error responses in the nonword repetition task were defined as those trials where participants substituted, omitted, distorted or added a target phoneme. Errors in the phoneme elision task were trials where the participant failed to delete the target phoneme from the nonword. In both tasks, trials with disfluencies, such as sound/syllable repetitions and prolongations, were included as correct responses. Any ambiguities in classifying errors and disfluencies were handled on an individual basis.

Responses from the nonword repetition task were further analysed into two different categories. First, the per cent correct nonwords were scored based on offline analysis of each nonword as a correct or error response. Second, the overall per cent correct phonemes (the total number of phonemes that were correctly produced in each nonword divided by the total number of phonemes $*$ 100) at each nonword length were obtained for both groups. It is to be noted that these two measures do not measure the exact same thing; per cent correct nonwords is a measure of the number of nonwords produced correctly using an all-or-none method of scoring, while per cent phonemes correct is a more fine-grained analysis of the nonwords for the extent of phonemic errors.

Inter-judge reliability was computed on the accuracy data from the nonword repetition task and the phoneme elision task. A trained research assistant not involved in the initial analysis rescored four participants from each group on both the tasks. Cohen's kappas of 0.86 for the nonword repetition task and 0.89 for the phoneme elision task were obtained. Similarly, inter-judge reliability on the fluent/disfluent codings resulted in Cohen's kappas of 0.90 for the nonword repetition task and 0.91 for the phoneme elision task.

Speech initiation time (in seconds). In both tasks, speech initiation time (the time in seconds between presentation of the stimuli and subject response) for the correct and fluent productions were obtained from acoustic analysis using PRAAT software. Both error and disfluent trials were excluded from this analysis. No disfluencies were identified in the CNS sample. In the CWS sample, for the nonword repetition task, 10% (SD = 19.9 percentage points) of the trials from the two-syllable nonwords, 20 percentage points (SD = 25.6 percentage points) from the three-syllable nonwords, and 19% (SD = 18.0 percentage points) from the four-syllable nonwords were excluded as disfluencies from the speech initiation time analysis. For the phoneme elision task, 18.4% (SD = 30.3 percentage points) of the trials from the two-syllable nonwords, 17.2% (SD = 21.0 percentage points) from the three-syllable nonwords, and 23.7% (SD = 28.7 percentage points) from the four-syllable nonwords were excluded.

Statistical analysis

Nonword repetition

Data from the nonword repetition task were analysed using three repeated-measures analysis of variance (ANOVA). The first two analyses were run to compare the groups in response accuracy across the three nonword lengths. The third analysis was run to compare the groups in response initiation (in seconds) across the three nonword lengths.

For the first repeated-measures ANOVA, the per cent of correct nonwords (i.e. number of words that were considered to be accurately produced out of total words produced $*$ 100) was the dependent variable. Talker Group (CWS, CNS) and Age Group (younger, older) were the between-subject variables, while Nonword length (two-, three- and four-syllable) was the within-subject variable. For the second repeated-measures ANOVA, the per cent of correct phonemes (i.e. the total number of phonemes that were correctly produced in each nonword divided by the total number of phonemes $*$ 100) was the dependent variable. For this analysis, Talker Group and Age Group were the between-subject variables, while Nonword length was the within-subject variable. For the third repeated-measures ANOVA, speech initiation time (in seconds) was the dependent variable. Talker Group and Age Group were the between-subject variables while Nonword length was the within-subject variable.

Phoneme elision

Two different repeated-measures ANOVA were performed on the phoneme elision data. The first analysis compared the groups in response accuracy across the three nonword lengths. Per cent correct responses was the dependent variable. Talker Group (CWS, CNS) and Age Group (younger, older) were the between-subject variables, while Nonword length (two-, three- and four-syllable) was the within-subject variable.

The second repeated-measures ANOVA was run on the speech initiation time data in order to investigate if the groups were different in the time taken to initiate phoneme elision responses. Talker Group and Age Group were the between-subject variables, while Nonword length was the within-subject variable.

Results

Vocabulary, short-term memory, articulation and phonemic awareness

Table 1 shows the group mean and SD for the different tests. One-way ANOVA with Talker Group (CWS, CNS) and Age Group as the grouping variables revealed non-significant differences in tests of receptive,

Table 1. Means and standard deviations (SD) of children who stutter (CWS) and children who do not stutter (CNS) groups in the tests of vocabulary, articulation, phonemic awareness and digit span

Group			PPVT standard score	EVT standard score	GFTA standard score	LAC converted scores	Forward digit span	Backward digit span
CWS	Younger	Mean	111.3	100.4	104.3	90.0	8.7	6.0
		SD	12.4	10.1	13.7	21.3	3.4	4.5
	Older	Mean	113.6	102.4	108.4	106.3	9.4	6.7
		SD	12.7	3.4	11.9	35.2	1.3	3.9
CNS	Younger	Mean	120.6	104.1	111.9	102.7	9.4	7.9
		SD	18.1	2.2	15.3	23.9	2.7	4.7
	Older	Mean	118.6	103.9	111.7	117.0	11.4	6.7
		SD	11.5	0.9	13.3	9.5	2.1	3.5

Note: EVT = Expressive Vocabulary Test; GFTA = Goldman–Fristoe Test of Articulation; LAC = Lindamood Auditory Conceptualization Test; and PPVT = Peabody Picture Vocabulary Test—Edition IV.

$F(3, 24) = 0.66$, $p = 0.28$, and expressive vocabulary, $F(3, 24) = 0.47$, $p = 0.23$). Non-significant differences were obtained in the test of articulation, $F(3, 24) = 0.67$, $p = 0.28$. Comparison of the LAC converted scores revealed non-significant, but descriptive differences between the groups, $F(3, 24) = 1.5$, $p = 0.12$. Non-significant differences were also observed in the forward, $F(3, 24) = 1.5$, $p = 0.11$, and the backward digit spans, $F(3, 24) = 0.23$, $p = 0.48$.

Nonword repetition

Per cent correct nonwords. The first repeated-measures ANOVA was run to compare the groups in the per cent correct nonwords across the three lengths in the nonword repetition task. Mauchly's test of sphericity revealed $p = 0.93$; therefore, sphericity-assumed p-values are reported. Figure 1 shows the mean (SD) per cent correct nonwords across each nonword length for the younger and older CWS and CNS. This analysis revealed a significant main effect of Nonword length, $F(1, 24) = 59.1$, $p = 0.00001$, eta squared = 0.71. Post-hoc comparisons (t-test comparisons using Fischer's Least Significant Difference method—LSD) revealed that across both groups the four-syllable nonwords (mean = 44.6%, SD = 12.8 percentage points) had the least per cent of correct repetitions (four- versus three-syllable, $p < 0.00001$; four- versus two-syllable, $p = 0.0000001$) followed by the three-syllable (mean = 64.8%; SD = 16.2 percentage points three- versus two-syllable, $p < 0.00001$) and finally the two-syllable nonwords (mean = 80.9%, SD = 13.7 percentage points). All other main and interaction effects were non-significant; Talker Group, $F(1, 24) = 0.29$, $p = 0.59$; Age Group, $F(1, 24) = 1.1$, $p = 0.30$; Talker Group × Age Group, $F(1, 24) = 0.02$, $p = 0.88$; Nonword length × Talker Group, $F(2, 48) = 1.4$, $p = 0.24$; Nonword length × Age Group, $F(2, 48) = 0.49$, $p = 0.61$; and Talker Group × Age Group × Nonword length, $F(2, 48) = 0.21$, $p = 0.81$.

Per cent correct phonemes. A second repeated-measures ANOVA was run to investigate if the groups differed in the overall per cent of correct phonemes. Mauchly's test of sphericity revealed $p = 0.36$; therefore, sphericity-assumed p-values are reported. This analysis showed a non-significant main effect of Talker Group, $F(1, 24) = 0.40$, $p = 0.53$. A significant main effect of Nonword length, $F(2, 48) = 24.6$, $p = 0.00000$, partial eta squared = 0.50, was obtained. A trend for significant Talker Group × Nonword length effect was obtained, $F(2, 48) = 2.8$, $p = 0.06$, partial eta squared = 0.10 (figure 2). This trend was evident as a larger difference between the CWS and CNS groups in the per cent of correct phonemes at the two-syllable level ($p = 0.06$). Differences were not evident at other lengths. All other main and interaction effects were non-significant; Age Group, $F(1, 24) = 1.62$, $p = 0.21$; Talker Group × Age Group, $F(1, 24) = 0.06$, $p = 0.81$; Nonword length × Age Group, $F(2, 48) = 0.08$, $p = 0.92$; Nonword length × Talker Group × Age Group, $F(2, 48) = 0.27$, $p = 0.76$.

Speech initiation time (in seconds). A third repeated-measures ANOVA was run to investigate if the groups differed in the time (in seconds) taken to initiate nonword repetition (figure 3). Mauchly's test of sphericity revealed $p = 0.08$; therefore, sphericity-assumed p-values are reported. A significant main effect of Nonword length was observed, $F(1, 24) = 19.6$, $p = 0.00001$, eta squared = 0.30. Post-hoc comparisons (Fischer's LSD) revealed that across both groups the time taken to initiate the four-syllable nonwords (mean = 0.78 s, SD = 0.29 s) was longest and significantly different from the other two nonword lengths (four- versus three-syllable, $p = 0.00022$; four- versus two-syllable, $p = 0.00020$). The time taken to initiate the three-syllable (mean = 0.62 s; SD = 0.26 s) and two-syllable nonwords (mean = 0.62 s, SD = 0.29 s) were comparable ($p = 0.97$). All other main and interaction

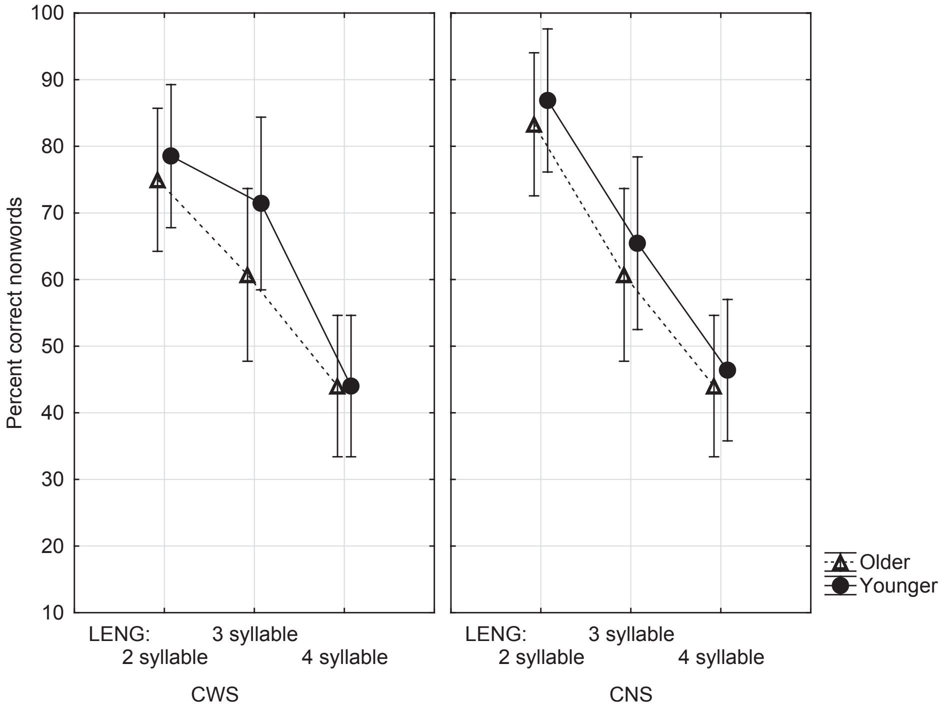

Figure 1. Per cent correct nonwords (and standard deviation) by nonword length and group. Group × Age Group × Nonword length, $F(2, 48) = 0.21, p = 0.81$.

effects were non-significant; Talker Group, $F(1, 24) = 0.50, p = 0.48$; Age Group, $F(1, 24) = 0.09, p = 0.75$; Talker Group × Age Group, $F(1, 24) = 0.53, p = 0.47$; Nonword length × Talker Group, $F(2, 48) = 0.003, p = 0.99$; Nonword length × Age Group, $F(2, 48) = 0.09, p = 0.90$; and Nonword length × Talker Group × Age Group, $F(2, 48) = 0.07, p = 0.92$.

Phoneme elision

Per cent correct. This analysis was done to compare the groups in the per cent of correct elision responses across the three syllable lengths. Mauchly's test of sphericity revealed $p = 0.81$; therefore, sphericity-assumed p-values are reported. A significant main effect of Nonword length was observed, $F(2, 48) = 58.0, p = 0.00001$, eta squared = 0.70. Also observed was a significant interaction of Talker Group × Age Group × Nonword length, $F(2, 48) = 3.8, p = 0.02$, eta squared = 0.13 (figure 4). Post-hoc comparisons (Fischer's LSD) revealed that the younger CWS had a significantly lower per cent of correct responses in phoneme elision at the two- ($p = 0.009$) and three-syllable lengths ($p = 0.035$), while the younger and older CWS were comparable in performance at the four-syllable length ($p = 0.64$). Similar differences were not evident between the younger and older CNS at any of the nonword lengths (two-syllable, $p = 0.96$; three-syllable, $p = 0.79$; four-syllable, $p = 0.33$). All other main and interaction effects were non-significant; Talker Group, $F(1, 24) = 1.0, p = 0.32$; Age Group, $F(1, 24) = 2.8, p = 0.10$; Talker Group × Age Group, $F(1, 24) = 1.6, p = 0.21$; Nonword length × Talker Group, $F(2, 48) = 0.57, p = 0.56$; and Nonword length × Age Group, $F(2, 48) = 0.54, p = 0.58$.

Speech initiation time (in seconds). A second repeated-measures ANOVA was done to investigate if the groups differed in the time (in seconds) taken to initiate phoneme elision responses (figure 4). Mauchly's test of sphericity revealed $p = 0.03$; therefore, Hyun–Feldt (H-F) p-values are reported. No significant effects were obtained in this analysis; Nonword length, $F(1, 24) = 0.73, p = 0.47$; Talker Group, $F(1, 24) = 0.05, p = 0.82$; Age Group, $F(1, 24) = 0.19, p = 0.66$; Talker Group × Age Group, $F(1, 24) = 0.40, p = 0.53$; Nonword length × Talker Group, $F(2, 48) = 0.72, p = 0.48$; Nonword length × Age Group, $F(2, 48) = 0.005, p = 0.99$; and Nonword length × Talker Group × Age Group, $F(2, 48) = 1.03, p = 0.36$.

Discussion

The aim of the present study was to examine the subprocesses underlying nonword repetition and phoneme elision performances in school-age CWS and age-matched CNS divided into two subgroups of younger

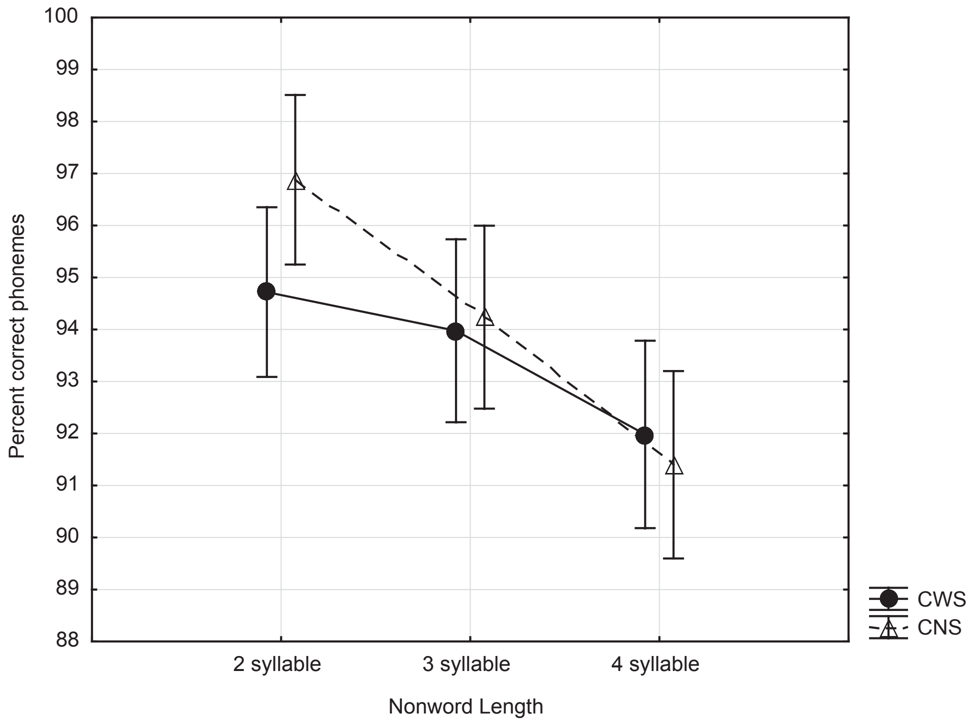

Figure 2. Mean per cent correct phonemes (and standard deviation) across each nonword length by group. Talker Group × Nonword length, $F(2, 48) = 2.8$, $p = 0.06$.

and older participants. Both accuracy and speech initiation times were measured to investigate group differences in underlying phonological and working memory processes and speech motor planning efficiency. Based on earlier reports of poor nonword repetition performance in pre-school CWS attributed to phonological working memory and/or encoding deficits (Hakim and Bernstein Ratner 2004, Anderson *et al.* 2006, Anderson and Wagovich 2010), as well as preliminary evidence for segmentation difficulties in school-age CWS (Sasisekaran and Byrd 2013), it was hypothesized that school-age CWS will show poor performance in nonword repetition and/or phoneme elision compared with the CNS.

Vocabulary, short-term memory, articulation and phonemic awareness

Participants in both groups were tested in skills that may potentially influence task performance. For instance, vocabulary measures are reflective of prior lexical knowledge and the influence of prior lexical knowledge on nonword repetition is well documented (e.g. Edwards and Lahey 1998, Munson 2001). Present findings showed that the groups were comparable in receptive, expressive vocabulary and forward, backward digit spans at the outset, thereby suggesting that any group differences in nonword repetition performance are not attributable to differences in prior lexical knowledge or short-term memory limitations. Although performance in LAC revealed that the CWS groups scored lower than the CNS groups, such differences were not significant. LAC tests probe phonemic awareness skills including the ability to identify and manipulate phonemes. Performance in the phoneme elision, in part, taps into similar skills and therefore, LAC performance may to some extent be predictive of performance in phoneme elision.

Performance in nonword repetition

Two types of measures were used to study nonword repetition performance: the per cent correct nonwords, an all-or-none method of scoring; and the per cent phonemes correct, a fine-grained analysis of the phonemic errors. As expected, a significant effect of nonword length in both these types of analyses revealed that participants in both groups found the four-syllable nonwords to be more difficult that the three- and two-syllable nonwords. However, the CWS were comparable with the CNS in the overall per cent production of correct nonwords. Analysis of phonemic accuracy revealed that the CWS showed a trend for significantly lower per cent of correct phonemes at the two-syllable level compared with the CNS. Any such differences were not evident at the other lengths as the per cent correct

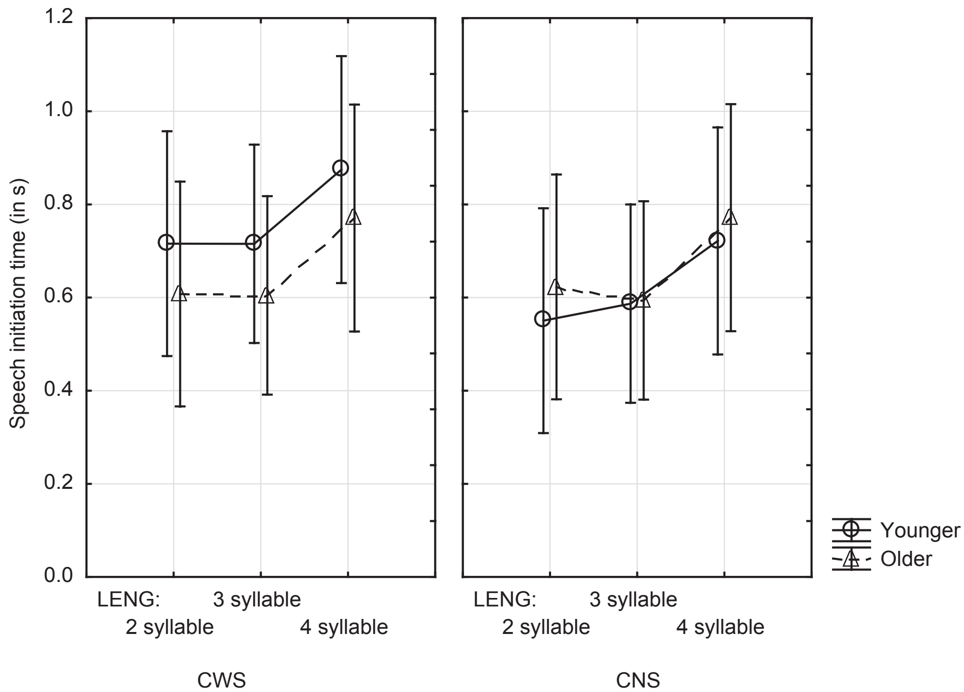

Figure 3. Average speech initiation time (in seconds) and standard deviation of nonword repetition responses by length and group. Talker Group × Age Group × Nonword length, $F(2, 48) = 0.7, p = 0.92$.

production decreased comparably with increasing lengths for both talker groups. A trend toward group difference in the per cent correct phonemes measure, but not in the per cent correct nonwords measure, suggests that the former measure might be a more realistic reflection of the nonword repetition status in CWS. Although only a trend, this finding also corroborates earlier reports of lower phonemic accuracy for two-syllable nonwords in CWS (e.g. Anderson *et al.* 2006). Furthermore, this trend suggests the poor nonword repetition performance in preschool CWS (e.g. Anderson *et al.* 2006, Anderson and Wagovich 2010) may persist at least to a certain degree in school-age CWS.

The trend for lower per cent of correct phonemes at the two-syllable level can be attributed to difficulties in phonological encoding. For instance, the Covert Repair Hypothesis (Postma and Kolk 1993) ascribes an erroneous speech plan and subsequent corrections of such errors to stuttering. It is likely that due to time constraints and/or task-related pressures some of the errors were not detected and/or corrected and therefore, appeared in overt nonword production. However, phonological working memory deficits are equally attributable to the observed trend for significant group difference at the two-syllable level. The inability to hold the nonword in working memory briefly could have resulted in the inability to repeat it back intact. Irrespective of whether a phonological encoding deficit or a working memory deficit is attributable to this difference, careful consideration should be given to the fact that the trend for group differences are seen only at the two-syllable level and not for the longer nonwords. This finding does not fit the response pattern that could be predicted from either an encoding or a working memory deficit, which would have resulted in larger and perhaps, significant group differences with increasing nonword length. Yet another possibility is that the stimuli used in the present study differed in number and phonological properties from past research, thereby suggesting that it may have been challenging for both groups beyond the two-syllable level.

Speech initiation time

In the present study, the speech initiation times to nonword repetition across the three length were measured to investigate if CWS were different from CNS in the stages of language and motor planning leading up to production. The results revealed that across both groups, the four-syllable nonwords had the longest speech initiation time followed by the three- and two-syllable nonwords. However, the groups were comparable in the average time taken to initiation nonword repetition. This finding of comparable speech initiation time to nonword repetition is similar to the finding reported by Bakhtiar *et al.* (2007). Similar findings have also been reported with words of varying syllable length in adults who stutter (e.g. van Lieshout *et al.* 1996). Recall that upon hearing the nonword the listener must encode the serial order of the sound segments, store and retrieve the

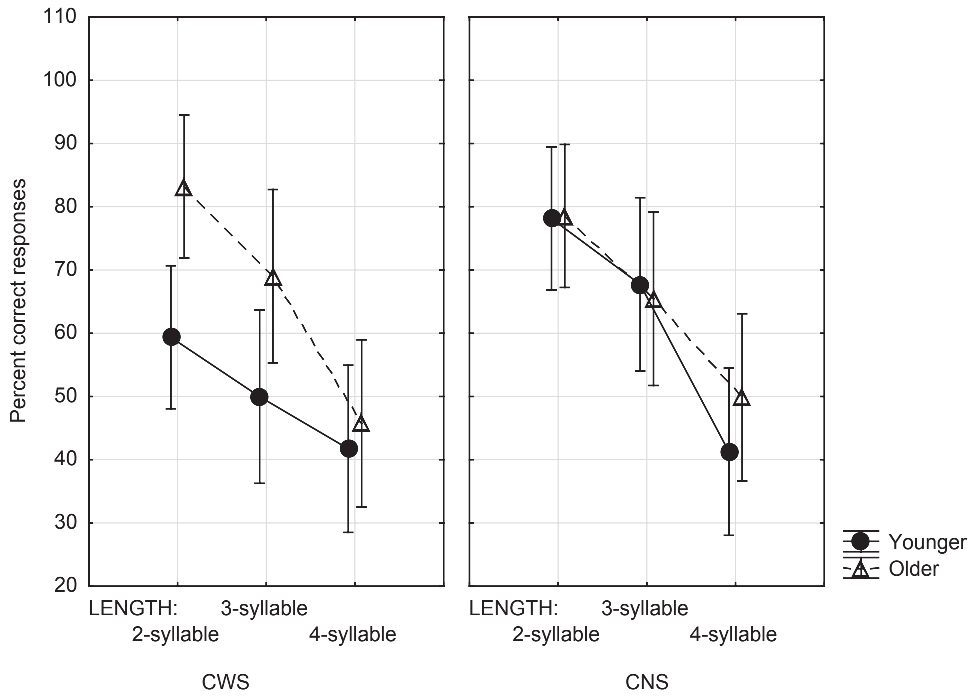

Figure 4. Mean per cent correct responses (and standard deviation) in phoneme elision by nonword length and group.Group × Age Group × Nonword length, $F(2, 48) = 3.8$, $p = 0.02$.

segment sequence from memory, and then plan and execute the requisite movements for reproduction (Gupta and Tisdale 2009, Shriberg *et al.* 2009). If the trend for group difference in the per cent correct phonemes is due to deficits in some of the stages of language planning, e.g. phonological encoding, then this difference may also be evident in the speech initiation time, which is a cumulative measure of language and speech motor planning. One possible explanation for the lack of group differences in speech initiation time may be due to differences in the pattern of speed–accuracy trade-off. For instance, significantly faster initiation of nonword repetition responses could accompany the trend for lower phonemic accuracy for the two-syllable nonwords in CWS. However, examination of the accuracy and speech initiation time data failed to reveal speed–accuracy trade-off strategies used by either of the groups. Yet another possibility is that the speech initiation time, while encompassing several different processes, is a more sensitive measure of the later stages of speech planning (e.g. motor planning) rather than the earlier stages (e.g. phonological encoding).

Performance in phoneme elision

In the present study in addition to nonword repetition, participants were compared in a phoneme elision task. It was assumed that this task was cognitively demanding than the nonword repetition task as it requires participants to hold the nonword in phonological working memory, delete the prespecified phoneme, and then repeat the nonword without the identified phoneme. In this study, participants were required to repeat the nonword accurately once before they could perform the elision task. Thus, we ensured that phonological encoding was done appropriately. Therefore, reduced phonological working memory capacity and/or difficulties in manipulating phonemes, e.g. phoneme awareness skills, are the two variables likely to hamper successful completion of this task.

As expected, both groups showed a reduction in accuracy with increase in nonword length in this task. The findings also showed that the CWS had overall lower scores in this task. Although significant group differences were not observed, lower scores in the phoneme elision task in the absence of significant differences in LAC performance suggest reduced efficiency of phonological working memory in CWS rather than difficulty with manipulating phonemes. This tentative interpretation requires further testing as other studies have reported differences in LAC performance in CWS (e.g. Sasisekaran *et al.* 2013). Furthermore, a distinct age effect was evident as a Talker Group × Age Group × Nonword length interaction. This finding showed that although the CWS group overall was not different from the CNS group, the younger CWS had more difficulties than the older CWS in performing this task, particularly at the two- and three-syllable lengths. Both age groups

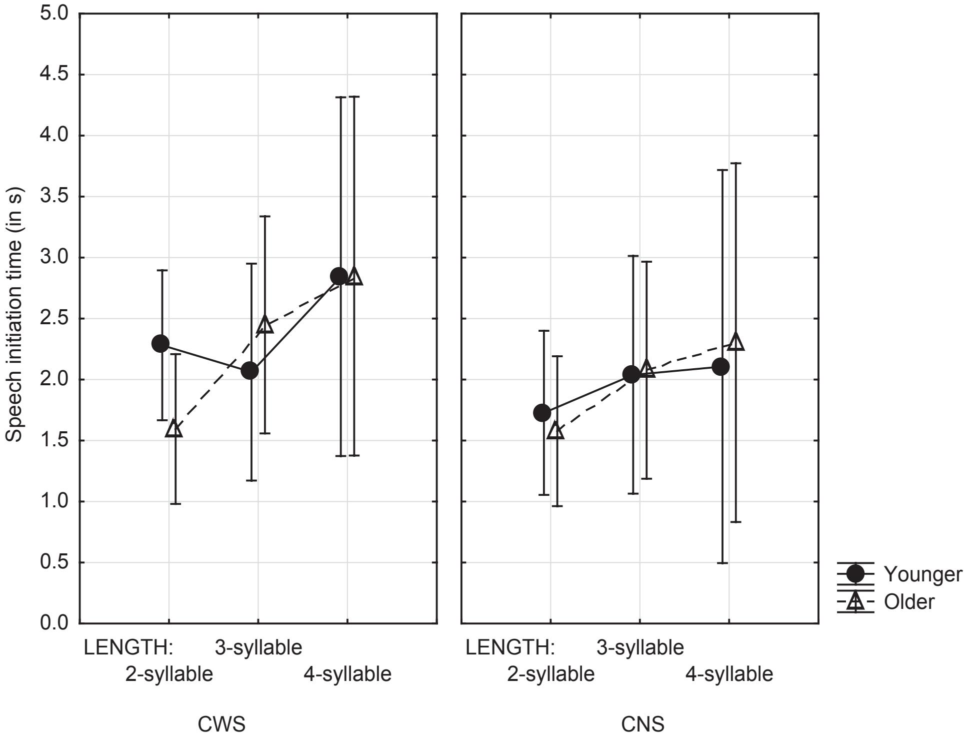

Figure 5. Mean speech initiation time (in seconds) and standard deviation of phoneme elision responses by nonword length and group.

showed reduced and comparable performance at the four-syllable level. A similar age effect was not evident in the CNS. Differences between the younger and older CWS in the phoneme elision task in the absence of such differences in the nonword repetition task suggests that any existing working memory deficits are more likely to be evident in tasks that are more cognitively demanding. For instance, group differences may emerge in nonword repetition or phoneme elision if the task complexity is increased further by including nonwords that do not follow English phonotactic constraints.

The distinct age effect seen in the CWS indicated that the younger CWS may have reduced phonological working memory capacity and therefore reduced efficiency in performing the phoneme elision task, while the older CWS eventually 'catch up' with the CNS. Similar advancements in phonological working memory have also been reported in adults who stutter and adults who do not stutter (e.g. Byrd *et al.* 2012, Sasisekaran *et al.* 2010). Such phonological working memory deficits in younger CWS can have some long-lasting consequences. For instance, models such as the Directions into Velocities of Articulators (DIVA; Guenther 2006) suggest that early acquisition of phonemic knowledge and the subsequent link of such abstract knowledge to concrete speech motor gestures is critical to speech development. With the speculated early deficits in phonological working memory in CWS, the very basic foundation of phonemic knowledge acquisition can be affected and this can have long-lasting consequences on language and speech production.

Speech initiation time

Findings from the response time analysis revealed the CWS and CNS to be comparable in the time taken to respond to the phoneme elision task. This analysis was done primarily to investigate speed–accuracy trade-offs. For instance, lower accuracy in phoneme elision in the younger CWS could be accompanied by faster responses suggesting that the younger CWS were making more errors because they were responding faster. However, poor performance in the younger CWS could not be attributed to speed–accuracy trade-off strategies. In other words, despite taking a comparable amount of time to respond, their per cent phonemes correct was still lower than that of CNS.

Conclusions and limitations

The present finding of a trend for reduced phonemic accuracy in the CWS group at the two-syllable level suggests that school-age CWS continue to show some residual difficulties in nonword repetition. Findings from the phoneme elision task show a complex age-dependent pattern of task performance with the younger CWS experiencing greater difficulties in this task. Phonological working memory deficits seem to offer a better explanation for the observed group differences in phoneme elision.

The conclusion that any one stage of processing, e.g. phonological encoding, is the primary source of difficulty in nonword repetition, will rely on evidence that eliminates the role of other processes, such as phonological working memory and speech motor planning and execution (e.g. Edwards and Lahey 1998, Snowling *et al.* 1991). While attempts were made in this study to investigate the different sub-processes underlying nonword repetition and phoneme elision performances, certain limitations need to be considered in interpreting the present findings. First, a potential limitation of interpreting a phonological encoding deficit or a working memory deficit from the nonword repetition and/or phoneme elision performance of CWS in this study is that this finding is equally attributable to either one of these processes. Future studies need to differentiate these two underlying processes and identify which one of these variables contributes exclusively or more significantly to differences noted in CWS or if the processes equally compromise CWS performance on these types of tasks. Second, while speech initiation time data were used to rule out speech motor planning difficulties as a potential underlying source of poor nonword repetition in CWS, nonword duration itself was not reported. Therefore, speech motor execution, i.e. articulation difficulties, cannot be ruled out as a potential problem source for reduced phonemic accuracy in CWS. Given the higher rate of articulation difficulties reported in CWS (e.g. Blood *et al.* 2003), future studies need to consider speech motor execution and its influence on nonword repetition performance in CWS. Finally, we cannot rule out other possible contributors, such as attention (e.g. Anderson and Wagovich 2010) to group differences noted in present study.

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