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Working memory in school-age children with and without a persistent speech sound disorder

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Abstract

Purpose: The aim of this study was to explore the role of working memory processes as a possible cognitive underpinning of persistent speech sound disorders (SSD).

Method: Forty school-aged children were enrolled; 20 children with persistent SSD (P-SSD) and 20 typically developing children. Children participated in three working memory tasks – one to target each of the components in Baddeley's working memory model: phonological loop, visual spatial sketchpad and central executive.

Result: Children with P-SSD performed poorly only on the phonological loop tasks compared to their typically developing age-matched peers. However, mediation analyses revealed that the relation between working memory and a P-SSD was reliant upon nonverbal intelligence.

Conclusion: These results suggest that co-morbid low-average nonverbal intelligence are linked to poor working memory in children with P-SSD. Theoretical and clinical implications are discussed.

Keywords: speech sound disorders, working memory, school-aged children, Baddeley's working memory model, nonverbal intelligence

Introduction

Speech sound disorders (SSD) are characterized by delays in the accurate production of age-appropriate speech sounds (Lewis et al., 2015). As the speech sound system develops, children rely on emerging skills in multiple domains including perceptual, cognitive, linguistic, and motoric, for accurate speech production. Presumably, an impairment in any one of these domains could result in abnormal speech sound development. For approximately 3.9% of children, abnormal speech sound production persists past the age of 8 years (Lewis et al., 2015; Roulstone, Miller, Wren, & Peters, 2009; Wren, McLeod, White, Miller, & Roulstone, 2013). Despite decades of research, the causal mechanisms associated with persistent SSD (P-SSD) remain elusive (Munson, Baylis, Krause, & Yim, 2010).

One active area of debate is the impact of working memory on the development of speech. Empirical data have shown the critical importance of working memory on speech learning in young children (Adams & Gathercole, 1995; Couture & McCauley, 2000; Munson, Edwards, & Beckman, 2005; Raine, Hulme, Chadderton, & Bailey, 1991; Speidel, 1993). Prominent models of working memory state that it is a cognitive function in which auditory and/or visual information are temporarily stored and manipulated (Baddeley, Gathercole, & Papagno, 1998; Cowan, 1988; Cowan, Cartwright, Winterowd, & Sherk, 1987; Gathercole & Baddeley, 1990; Gathercole, Willis, Baddeley, & Emslie, 1994). Working memory has been shown to significantly contribute to one's ability to perform crucial activities such as reading, word learning, acquiring language, mathematical processing and reasoning (Gathercole, Alloway, Willis, & Adams, 2006). For speech production, it is necessary to accurately and consistently store sounds and readily and appropriately retrieve them (Oakhill & Kyle, 2000). As such, if this system of storage and retrieval is deficient, or circumscribed in some way, it is likely to manifest as a phonological deficit (e.g. speech sound disorder, dyslexia, or both). Because phonological skills are necessary for both speech production and literacy success, it is prudent to examine potential underlying mechanisms. Working memory is a plausible contributor, at least in part, to the speech production deficits seen in children with SSD.

Working memory

There are several conceptualizations of working memory processes. Two prominent models are offered by Cowan (Cowan, 1988; Cowan, Cartwright, Winterowd, & Sherk, 1993) and Baddeley (Baddeley & Hitch, 1974) both support the overarching role of WM as a "holding tank" for information while it is either transferred into long-term memory storage, manipulated and immediately used, or it is forgotten. Additionally, both models account for specific components dedicated to the processing of sensory information. The models diverge in the mechanisms presumed to process specific sensory information. For instance, Cowan suggests that the "active memory" processes all sensory information; whereas Baddeley hypothesizes that there are separate subsystems that process phonological information versus visual information. Thus, for the methodological purpose of the present investigation, it is prudent to explore this cognitive construct within a framework that assumes phonological information has a dedicated processing center. The seminal work of Baddeley and Hitch (1974) proposed a model of working memory with three empirically-supported components: phonological loop, visual-spatial sketchpad and central executive. The phonological loop serves as a store for auditory information, (e.g. speech). The visual– spatial sketchpad stores visually presented information (e.g. pictures). The primary responsibility of the central executive component is to allocate attention resources to either the phonological loop or visual– spatial sketchpad (Baddeley, 1992). The phonological loop is described as consisting of two subcomponents – a phonological store and an articulatory rehearsal mechanism. The phonological store is a limited capacity space where information is organized based on similar features. The articulatory rehearsal mechanism allows information in the phonological store to be refreshed through subvocal articulation to avoid decay (Baddeley, 2007). It is possible that, for older children with P-SSD, the articulatory rehearsal mechanism is negatively affected by their difficulty producing speech. As they get older and their speech sound disorder persists, the lack of maturation of the speech production system contributes negatively to their acquisition of strong phonological representations. This can negatively affect a child's ability to achieve academic success with reading, writing and spelling (Sutherland & Gillon, 2005).

Some evidence suggests that there is a relationship between phonological working memory and speech sound production skills. In a case study, Speidel (1993) found that a child with a history of a speech sound disorder performed more poorly on nonword repetition – a common metric for phonological working memory – compared with his typically developing twin. Follow up studies have reported that pre-school aged children (Adams & Gathercole, 1995; Munson, Edwards, & Beckman, 2005) and school-aged children (Couture & McCauley, 2000; Raine, Hulme, Chadderton, & Bailey, 1991) with various SSD also have weaker performance on tasks that tap phonological working memory, such as nonword repetition. In addition, Crosbie, Holm, and Dodd (2009) reported weak executive functioning in children with speech sound disorders. Convergently, there is evidence to support the plausible role of a phonological working memory deficit in children with SSD; however, this has yet to be examined in a well-controlled sample of *older* children with *persistent* SSD. Weak speech production skills could make it difficult for children with SSDs to accurately and distinctly reactivate phonological information before it decays in memory. In particular, it is possible that older children who have P-SSD may have inefficient phonological working memory skills as a result of many years of inaccurate speech production. In the present study, we used Baddeley's Working Memory model (Baddeley & Hitch, 1974) to examine the three primary components of working memory – phonological loop, visual spatial sketchpad and central executive – in older children with a P-SSD compared to their age-matched typically developing peers.

Working memory in speech sound disorders

In a small sample ($n = 5$) of young school-aged children with SSD, Couture and McCauley (2000) considered the role of working memory within the Baddeley and Hitch (1974) framework. Results supported weaknesses in phonological memory recall, but the authors cautioned the interpretation due to the small sample size and the unclear directionality of the phonological memory deficits (Couture & McCauley, 2000). An additional limitation to the Couture and McCauley (2000) study was that only the phonological loop was tested; the other constructs of the Baddeley and Hitch (1974) model (i.e. visual spatial sketchpad and central executive) were not examined. Presently, only one investigation included working memory tasks outside the domain of phonological working memory. Adams and Gathercole (1995) grouped preschoolers as having high and low phonological working memory, based on their performance on nonword repetition and digit span recall tasks. The children with low phonological working memory had more speech errors, but had scores similar to children with high phonological working memory on visual–spatial and central executive tasks. Their results suggest that although there was a link between low phonological working memory and speech production skills in preschoolers, there was not a link between visual spatial memory or central executive tasks and speech production skills. Of note, Adams and Gathercole (1995) selected participants based on working memory performance, and not on speech production ability. Still, this study lends crucial support to the possibility that working memory may contribute to persistent phonological deficits. In order to expand upon this work, we present a study that selected children based on their diagnosis of SSD was particularly designed to examine the three aspects of working memory, according to Baddeley and Hitch (1974), in older children with P-SSD.

The current study

In this study, we examined working memory – phonological loop, visual–spatial sketchpad and central executive components of Baddeley's Working Memory model (Baddeley & Hitch, 1974) – in school-age children with and without a P-SSD. Extrapolating from past literature, we predicted that children with a P-SSD would perform more poorly than their typically developing peers on a phonological working memory task while performing similar to their peers on visual–spatial and central executive tasks. Such results would support the notion that children with a P-SSD have working memory limitations specific to the phonological loop. Predicated on previous reports, children with P-SSD are more likely than their typically developing peers to have poor expressive vocabulary skills and low-average nonverbal intelligence (Anthony et al., 2011; Nathan, Stackhouse, Goulandris, & Snowling, 2004; Raitano, Pennington, Tunick, Boada, & Shriberg, 2004). Similarly, expressive vocabulary skills have been reported to be closely tied to nonword repetition skills (Gupta & Tisdale, 2009; Rvachew & Grawburg, 2008). Both expressive vocabulary and nonverbal intelligence have been linked to low working memory performance in children (Adams & Gathercole, 1995; Baddeley, 2007); although a divergent report from Raine, Hulme, Chadderton, and Bailey (1991) suggested that short-term (not working) memory impairments existed in children with SSD in the absence of additional deficits in intelligence. As such, another aim of our study was to examine the influence of nonverbal intelligence and expressive vocabulary on working memory abilities in children with P-SSD.

Method

Participants

Participants were 40 children in second- through fifth-grade recruited from the Lincoln, Nebraska community. Children ranged in age from 7.5 years to 11.8 years (M = 9.3). This age range was selected because the majority of children should have normal articulation skills by the age of 8 years (Smit, Hand, Freilinger, Bernthal, & Bird, 1990). Thus, if a child continues to have difficulty producing speech sounds past the age of 8, it is likely a P-SSD. The sample of 40 was composed of two groups: participants with P-SSD (n = 20; 13 males, 7 females) and participants who were typically developing (n = 20; 10 males, 10 females). Participants were statistically matched on age and grade and were recruited as part of a larger study of school-age children with a P-SSD (Farquharson, 2012). A power analysis was conducted to inform sample size, using similar medium to large effect sizes as reported in Storkel (2001). Table I contains descriptive statistics by participant group. Table II provides details regarding the specific phoneme errors for each child within the P-SSD group.

Children were identified as possible participants through database searches, local SLP recruitment and flyer distribution. Children with SSD were not required to be currently receiving treatment. This was primarily because many older children with SSD can be dismissed from treatment before their disorder is completely resolved (Raitano et al., 2004) or they no longer qualify for services because they have not made adequate progress (Preston & Edwards, 2007).

Table I. Descriptive statistics for participants by group, typically developing (TD) and persistent speech sound disorder (SSD).

	N	*Mean*	*SD*	*SEM*	*Min–Max*	*t*	*p*
Age in months							
SSD	20	112.3	14.93	3.33	90–140		
TD	20	113.0	15.26	3.41	89.7–14	–0.15	0.879
Grade							
SSD	20	3.3	1.1	0.252	2–5		
TD	20	3.3	1.1	0.252	2–5	0.00	0.999
Articulation[a]							
SSD	20	80.5	12.9	2.8	52–100		
TD	20	104.4	1.9	0.4	101–107	–8.16	0.000
Nonverbal IQ[b]							
SSD	20	102.1	13.3	2.9	83–130		
TD	20	117.3	13.1	2.9	88–136	–3.65	0.001
Expressive vocabulary[c]							
P-SSD	20	98.7	15.4	3.4	71–126		
TD	20	111	13.2	2.9	89–140	–2.7	0.01

a. Goldman–Fristoe Test of Articulation – 2 (Goldman & Fristoe, 2000).
b. Reynolds Intellectual Assessment Scales (Reynolds & Kamphaus, 2003).
c. Expressive One Word Picture Vocabulary Test (Brownell, 2000).

Table II. GFTA-2 scores and specific phoneme errors.

Child ID	*Standard score*	*Raw score*	*Percentile*	*Phoneme(s) in error*
1	75	10	4	/s, z/
2	90	5	8	/s, z/
4	59	23	1	/r, s, z/
8	92	4	7	/r/
10	100	1	26	/r/
11	100	2	23	/r/
14	82	10	48	/r/
15	89	6	9	/r/
16	67	17	4	/r/
20	82	10	8	/s, z/
23	74	12	1	/r/
25	78	9	4	/r/
26	63	23	1	/r, s, z/
28	79	10	5	/s, z/
33	93	7	18	/ʃ, θ, ð /
34	52	28	2	/r, l, k, g/
36	82	9	6	/s, z/
46	91	5	6	/s, z/
48	79	10	5	/r/
52	84	7	6	/s, z/
Mean	80.55	10.4	9.6	
SD	12.95	7.18	11.38	
Min	52	1	1	
Max	100	28	48	

GFTA-2: Goldman-Fristoe Test of Articulation – 2nd Edition.

All participants: inclusionary criteria. All participants were monolingual English speakers with normal vision (corrected; according to parent questionnaire), normal hearing and age-appropriate nonverbal intelligence. To ensure each had normal hearing, all participants passed a pure tone hearing screening administered at a level of 25 decibels at 500, 1000, 2000 and 4000 Hertz (ASHA, 1997). It was anticipated that children with P-SSD would differ from their peers in both nonverbal intelligence and expressive vocabulary (Anthony et al., 2011; Nathan et al., 2004; Raitano et al., 2004). The nonverbal intelligence subtests from the *Reynolds Intellectual Assessment Scales* (RIAS, Reynolds & Kamphaus, 2003) were used to confirm age-appropriate nonverbal intelligence. Two subtests from the RIAS were used to confirm nonverbal intelligence: Odd- Item-Out and What's Missing? The Odd-Item-Out subtest involved looking at pages from a test book, each page containing six pictures. Participants were then asked to determine which item "does not belong" with the others (e.g. five sedan-style cars and one large truck – the child should indicate that the truck does not belong). The What's Missing? subtest involved looking at single pictures and determining what is missing from the picture (e.g. a bird without a beak – the child must identify that the beak is missing). Note that, although all participants had age-appropriate nonverbal intelligence, the P-SSD group was significantly lower than their typical peers ($p = 0.001$; see Table I). Expressive vocabulary was used for descriptive information via the Expressive One Word Picture Vocabulary Test (Brownell, 2000). The EOWPVT measures naming ability by showing participants single pictures on pages of an easel and asking the participant to verbally identify the picture (e.g. a picture of a windmill; the child should respond that the picture is a windmill). The groups also differed significantly on expressive vocabulary ($p = 0.01$; see Table I). To examine any relevant contributions of these factors, we examined the role of nonverbal intelligence and expressive vocabulary in a mediation analysis.

Children with P-SSD: inclusionary criteria. Children were selected for the P-SSD group based on the presence of a speech sound disorder evidenced by a speech sample and a standardized assessment. A speech sample was obtained using a 5–7-min story elicitation task. Each participant was shown a wordless picture book and asked to tell the story that corresponded with the pictures. Speech samples were transcribed by the first author, an experienced pediatric speech-language pathologist. Ten per cent of speech samples were transcribed by a second trained listener, a speech-language pathology graduate student. Recall that typically developing children correctly produce all speech sounds in the English language by 8-years-old (Smit et al., 1990); thus any consistent speech sound errors were considered to be the result of a P-SSD. Articulation skills were also assessed using a standardized, norm-referenced test of single word productions, the *Goldman–Fristoe Test of Articulation – 2nd Edition* (GFTA-2*;* Goldman & Fristoe, 2000). The GFTA-2 elicits articulation of consonants and consonant clusters in initial, medial, and final word positions and is scored using phonetic transcription. Participants who had a standard score less than 85 (1 standard deviation below the mean of 100), *or* a percentile rank below 11, *or* a consistent speech sound error(s) during the speech sample were classified as having a P-SSD. All participants classified as having a P-SSD had at least one consistent speech sound error. There were no children in this sample with inconsistent errors. Of note, two participants in the P-SSD group achieved standard scores of 100 on the GFTA-2. These two participants (ages 11;0 and 9;6) had a consistent error on /ɚ/, which is not included as a target sound on the GFTA-2. However, six of the words on the GFTA-2 contain the /ɚ/ phoneme and both of these participants misarticulated all six productions. Additionally, both participants consistently exhibited this error during conversational speech, which is atypical when compared with developmental norms (Smit et al., 1990). Table II displays the details for each child with a P-SSD.

Children who are typically developing: inclusionary criteria. Typically developing participants had no history of speech production difficulties and had never received speech-language treatment, per parent report. Normal articulation was validated via the same speech sample and standardized assessment administered mentioned above. All participants in the typically developing group were required to achieve a standard score above 85 on the GFTA-2 and exhibit no articulation errors (consistent or inconsistent) in the speech sample.

Data collection

Data were collected in a quiet and well-lit room in a university clinic, a local school, or a participant's home. Each participant received a total of 3 h of data collection administered over the course of 1–2 months. Each session lasted 60–120 min. Frequent breaks were available and taken as necessary/ requested.

Experimental tasks

Three experimental tasks were administered to represent each of the three constructs of working memory within the Baddeley and Hitch (1974) model: phonological loop, visual spatial sketchpad and central executive skills.

Phonological loop task. Nonword repetition has been used extensively in research as a metric of phonological working memory skills (see Baddeley, 2003 for review and Gathercole & Baddeley, 1990 for an example). In the present study, phonological working memory was measured by a bespoke serial recall nonword repetition task administered on a laptop via Direct RT software (Jarvis, 2010). The stimuli consisted of consonant–vowel–consonant nonwords that followed the phonotatics of the English language, but carried no meaning (see Table III for stimuli list). Additionally, although not a focus in the current study, neighborhood density values were manipulated for all nonwords (Storkel & Hoover, 2010), such that half of the words were dense and half of the words were sparse. Participants listened to randomized nonword lists increasing in length: 4 one-nonword lists, 4 two-nonword lists, 4 three-nonword lists and 4 four-nonword lists. After listening to each list, the participants saw a smiley face on the screen, indicating that they were to repeat the nonwords back in serial order. Percentage of consonants correct (PCC) was calculated for the words recalled in accurate serial order. Words that were not recalled in serial order were not counted in the PCC or the analyses.

Great care was taken to control for the speech sound production errors in the P-SSD group. Note that there is not presently a standard approach to scoring such a task, with respect to accounting for a child's speech sound errors. Indeed, recent studies that have utilized nonword repetition tasks do not report scoring details (e.g. Lewis et al., 2015; Munson, Kurtz, & Windsor, 2005). However, Dollaghan and Campbell (1998) reported a scoring procedure in which phoneme substitutions and omissions were counted as incorrect; distortions were counted as correct. In the Dollaghan and Campbell (1998) study, the participants were children with language impairments, some of which likely had co-morbid speech sound disorders, but that information was not noted (but, see Shriberg et al., 2009 for an updated syllable repetition task administered to pre-school-aged children). Similarly, Deevy, Weil, Leonard, and Goffman (2010) scored a nonword repetition task two different ways: one in which speech sound errors were counted as response errors and one in which speech sound errors were counted as correct if the

Table III. Nonword repetition stimuli.

buk	fʊʃ
tʃæn	heb
hæb	hɑs
hɪb	dʒɛp
hɪʃ	dʒaɪf
kɛp	dʒʌb
paɪv	tɑg
pɑb	wæb
pɑs	wɑg
tætʃ	jɪb
wʊk	jub
	zæb

phoneme was not in the child's inventory. In the present investigation, we implemented a specific scoring approach, similar to the second approach in Deevy et al. (2010), to account for the persistent speech sound errors in school-aged children. For each child, their consistent pattern of speech errors was determined (e.g. /θ/ substituted for /s/ in all contexts), and those specific errors were marked as correct. That is, for the child who repeated the nonword /hɑs/ as /hɑθ/, the production was scored as correct if produced in the correct serial order (e.g. PCC would be calculated as 100% – two correct consonants produced out of two opportunities). This procedure greatly reduced the possibility that production errors were solely responsible for reduced phonological memory in our group with a P-SSD. Importantly, we scored the nonword repetition task both ways: counting the consistent speech sound error as correct, and also counting it as incorrect. The P-SSD and TD groups were significantly different on this task, regardless of scoring approach. No children in our sample exhibited inconsistent speech production errors, therefore, any error in production during the nonword repetition task was assumed to be an error in recall. The responses to the nonword repetition task were transcribed using broad transcription. For each word, PCC was calculated. An item was counted as incorrect if it was in the wrong order and/or if it was recalled with missing or incorrect phonemes (with the exception of the aforementioned speech sound error correction). Table IV displays the percentage of consonants correct for each group at each level.

Table IV. Means, standard deviations, standard error of the mean and significance tests for NWR task by group.

	Mean	*SD*	*SEM*	*p*
NWR 1 word PCC				
P-SSD	80.55	19.58	3.72	
TD	81.5	13.06	3.72	0.858
NWR 2 word PCC				
P-SSD	76.05	15.23	2.98	
TD	84.85	11.18	2.98	0.044
NWR 3 word PCC				
P-SSD	70.6	16.58	3.6	
TD	77.25	15.68	3.6	0.200
NWR 4 word PCC				
P-SSD	50.1	16.18	3.23	
TD	63.75	12.5	3.23	0.005

NWR: nonword repetition; P-SSD: persistent speech sound disorder; TD: typically developing.

Ten per cent of the sample was double-scored and the inter-rater reliability was 93%. Any conflicts were resolved between the two coders until consensus was reached, which resulted in an ultimate inter-rater reliability of 100% for 10% of the data that was double-scored.

Visual–spatial sketchpad task. Visual–spatial skills were tested using the Spatial Relations subtest from the *Woodcock-Johnson III Test of Cognitive Abilities* (Woodcock, McGrew, & Mater, 2001). This subtest is reported to measure "manipulation of visual images in space" in which the participant is required to manipulate objects "in the imagination of the 'mind's eye"' (p. 7). The Spatial Relations task required participants to examine four pieces of a puzzle and decide which two or three combined to form the intended complete shape. The task increases in complexity as the shapes are rotated and become more similar. Participants were required to hold visual representations of the small shapes in working memory while examining how those shapes may combine differentially to form the larger complete shape.

Central executive task. Central Executive function was assessed using a stop signal inhibition task (Gray, Hogan, Alt, Cowan, & Greene, 2011–2016). The task was set within a child-friendly "pirate game" in which monsters invaded the pirate's island. Participants saw a variety of monsters appear singularly upon the computer screen. Participants were instructed to press the space bar on the computer each time they saw a monster flash on the screen (i.e. go trial) unless they heard an auditory signal at the same time they saw the monster (i.e. stop trial). On the stop trials, the stop signal was presented simultaneously with the visual stimulus. Participants were required to inhibit the natural response to press the space bar. This task is designed to measure inhibitory control, which is a function of the central executive portion of working memory.

Result

In this study, we examined performance on three working memory tasks between a group of children with P-SSD and their typically developing peers. Because our groups differed significantly on nonverbal intelligence and expressive vocabulary scores, we conducted mediation analyses to determine the role of these variables in the relation between working memory and the presence of an SSD (see Supplemental materials for histograms displaying the range of expressive vocabulary and nonverbal intelligence scores for children in the P-SSD group). Mediation analyses allow for the examination of mechanisms that affect the relation between two variables (MacKinnon, Fairchild, & Fritz, 2007). Specifically, mediation analysis examines if a simple relation (e.g. the presence of an SSD and working memory ability) operates via a third variable that is related to both the predictor and the outcome (e.g. nonverbal IQ; Fields, 2013). For our purposes, we wanted to examine if the relation between the presence of a P-SSD and working memory ability was mediated by either nonverbal intelligence or expressive vocabulary. If either serve as a mediating variable, it would indicate that there is a change in the relation between P-SSDs and working memory *because* of the child's nonverbal intelligence or expressive vocabulary.

Phonological loop task results

The nonword repetition task examined phonological working memory by requiring participants to repeat novel phonological sequences of increasing length. This task was chosen because it examines serial recall (i.e. the ability to repeat a string of phonological information in the same order that it was presented) but eliminates the confounding effects of word familiarity that are known to influence performance (Baddeley, 2003). The nonword repetition task was scored using per cent of consonants correct for each word recalled in serial order at each word length (i.e. 1–4 words). Data were submitted to a repeated measures ANOVA with one within-subject factor, length (1, 2, 3 or 4 nonwords) and one between-subjects factor, group (P-SSD or typically developing). The results showed a significant main effect of length such that performance decreased significantly for all children as the length of nonwords increased, F (2, 38) = 46.11, $p < 0.001$, partial $\eta^2 = 0.548$. There was also a significant main effect of group, F (2, 38) = 6.347, $p = 0.016$, partial $\eta^2 = 0.143$, highlighting that children with a P-SSD performed less well than children who were typically developing, albeit in the same pattern. There was not a significant interaction between group and nonword length ($p = 0.229$). **Figure 1** illustrates these results. Follow up t-tests examined group performance in percentage of consonants correct at each level of nonword repetition. Table IV displays these results, indicating that the groups significantly differed when they were to recall two and four nonwords in serial order.

To further examine this relation, we employed mediation analyses (Baron & Kenny, 1986; Hayes, 2013) examining the role of nonverbal intelligence and expressive vocabulary. Doing so allowed us to examine the extent to which the relation between group membership (i.e. P-SSD or typically development) and performance on the nonwords repetition task was changed

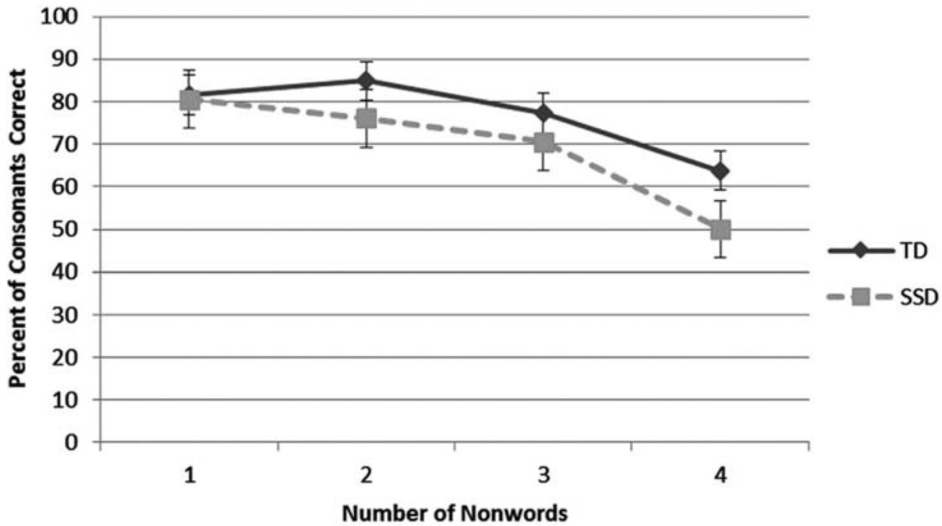

Figure 1. Group differences on nonword repetition task performance.

due to the child's nonverbal intelligence score. Our data were submitted to a mediation regression, with group membership as our outcome variable, PCC scores from the nonword repetition task as the predictor variable, and nonverbal intelligence as the mediator variable. Results supported a significant and positive relation between nonword repetition and nonverbal intelligence, $\beta = 0.536$, $p = 0.013$. Further, unstandardized indirect effects were computed using bootstrapping with a 95% confidence interval. The confidence interval did not overlap 0, CI = –0.111 to –0.0074, indicating significant relation. **Figure 2** displays this relation. Interestingly, similar results were not found when expressive vocabulary was the mediating variable. Specifically, there was not a significant relation between nonword repetition and expressive

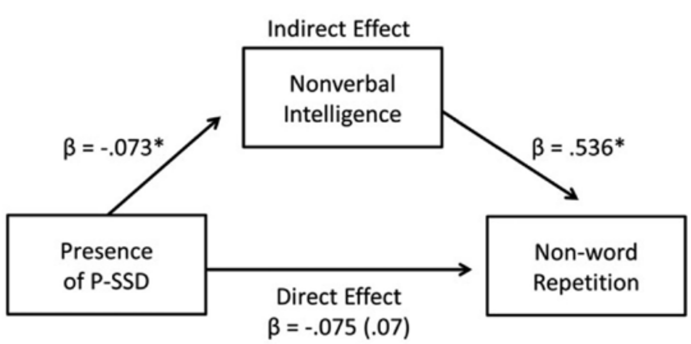

Figure 2. Results of mediation analysis.

vocabulary, $\beta = -0.050$, $p = 0.077$. The indirect effect of nonword repetition skills and the presence of a P-SSD was not mediated by expressive vocabulary; the 95% confidence interval overlapped 0, CI = –0.115 to 0.0009.

Visual–spatial task results

The visual–spatial task required participants to identify which puzzle pieces appropriately paired together to form a whole piece. Standard scores from the spatial relations subtest were used for analysis. Mean standard score for the children with P-SSD was 99.35 (SD = 17.43) and the mean score for the typically developing children was 106.35 (SD = 6.66). Data were submitted to a univariate ANOVA and results revealed a nonsignificant group difference, F (38) = 1.37, $p = 0.261$, partial $\eta^2 = 0.663$. Because this main effect is not significant, a mediation analysis is not warranted.

Central executive task results

The stop signal task was developed by Gray et al. (2011–2016) based on Logan and Cowan (1984). This task examined one aspect of the central executive – inhibition. Participants were required to press a button in response to visual stimuli and to inhibit that response when the visual stimuli were paired with an auditory stimulus. A signal response analysis was used to examine group performance (Stanislaw & Todorov, 1999). In doing so, we computed the average hit rate and average false alarm rate per group. Hit rate is calculated by dividing the number of hits (e.g. pressing the space bar accurately during a go trial) divided by the total number of opportunities to hit the space bard accurately (i.e. 54). False alarm rate is calculated by dividing the total number of false alarms (i.e. pressing the space bar incorrectly during a stop trial) divided by the total number of stop trials. Next, a z-score is computed for the hit rate and the false alarm rate. The z-scored false alarm rate is subtracted from the z-scored hit rate to compute d′. Values of d′ near 0 indicate that there was no difference between the go trials and the stop trials. Larger d′ values indicate a difference between the go trials and stop trials. Children in our typically developing group received a mean d′ score of 4.57 and children in our P-SSD group received a mean d′ score of 5.06. These scores indicate that both groups equally detected a difference between the go trials and the stop trials. Because this group difference was not significant, mediation analysis was not considered.

Discussion

The goal of this study was to examine working memory in school-age children with a P-SSD compared to their typically developing peers. Our results revealed poor phonological working memory for children who had P-SSD. However, the relation between phonological working memory ability and the presence of a P-SSD was mediated by nonverbal intelligence scores. Interestingly, expressive vocabulary did not mediate this relation, even though previous research has reported a strong connection between vocabulary and working memory skills (Gupta & Tisdale, 2009; Rvachew & Grawburg, 2008). Two recent studies have corroborated the finding that children with P-SSD often have lower nonverbal intelligence (Cabbage, Farquharson, & Hogan, 2015; Lewis et al., 2015). As such, it is interesting to consider the complexities presented by children with P-SSD. We propose three primary plausible explanations for the complexities seen in the present study; the first of which relate closely to our results and the second two require further investigation: (1) deficits in phonological working memory skills, (2) deficits in establishing motoric representations within memory, and (3) deficits in binding between linguistic and motoric skills within the episodic buffer of working memory.

Weak phonological working memory

In our sample, we found that nonverbal intelligence mediated the relation between phonological working memory and the presence of a P-SSD. Although all children in the present study had normal nonverbal intelligence scores, it appears that children who have a P-SSD paired with a low average nonverbal intelligence are likely to exhibit weak phonological working memory skills. Indeed, similar results were reported by Lewis et al. (2015), who longitudinally examined outcomes for adolescents who had early speech sound disorders. Specifically, Lewis et al. (2015) found that children between the ages of 11–18 years who had P-SSDs, when compared to children with and without a history of speech sound disorders, had weaker working memory skills, evidenced by performance on a nonwords repetition task, and also had lower nonverbal IQ scores. This is clinically relevant, considering that it is not commonplace to test nonverbal intelligence in children with any form of speech sound disorder. It is commonplace that children with linguistic-based disorders perform less well than their typically developing peers on nonverbal intelligences tests (Lord et al., 1997). As such, standard practice in studies involving children with linguistic-based disorders is to include nonverbal intelligence as a co-variate in analyses examining group differences. In the extant literature on speech production skills, nonverbal intelligence is not often considered. However, an important point of convergence between our work and that of Lewis et al. (2015) supports the need to further the consider the influence of nonverbal intelligence in children with PSSDs.

A connection between speech production ability and working memory ability is clear when considering the role of the articulatory rehearsal mechanism. It has been shown that articulation rate contributes to one's ability to retain information in the phonological loop by keeping phonological information "fresh" for recall via the articulatory rehearsal mechanism (Baddeley, 2007). It follows then that poor articulation *ability* may contribute to poor performance on a phonological loop task. Of course the inverse is plausible as well. A child with a speech sound disorder would then rely on poorly specified phonological representations to produce sounds in words, resulting in the speech sound disorder (Sutherland & Gillon, 2005). The role of low average nonverbal intelligence may be explained through the process of redintegration. Redintegration refers to a process by which "… linguistic knowledge is used to correct errors …" (Baddeley, 2007, p. 46). Redintegration has been used to explain why repeating nonwords is more difficult that repeating real words, and why longer words are more difficult to recall than shorter words. As such, perhaps a child with a speech sound disorder who has normal or high nonverbal intelligence used redintegration to bootstrap into phonological memory skills. Nonetheless, more work is needed to disambiguate the complex developmental and causal associations between poor phonological working memory, linguistic knowledge linked to redintegration, and poor speech production in children with a P-SSD. Additionally, a more robust examination of not just the phonological loop, but its subsidiary components – the phonological store and the articulatory rehearsal mechanism – may provide insight into the connections between speech production and access to items within phonological working memory.

Deficits in establishing motoric representations within memory

Baddeley (2003) suggested that perhaps it is the process of setting up speech motor plans that contribute to the use of the articulatory rehearsal mechanism. This, and other models of motor production (Guenther, 2006; Levelt, 1983,), may also explain the findings in the present study. Levelt (1983) offers a model of speech production that allows for both linguistic and motoric inputs and outputs. Although the model is comprehensive, it does not account for disordered speech production. Specifically, in his explanation of self-monitoring and speech repairs (Levelt, 1983), he suggests that speakers are always aware of speech errors and stop to make repairs. However, children with speech sound disorders often do not have an awareness of their errors (Rvachew, Ohberg, Grawburg, & Heyding, 2003; Rvachew & Jamieson, 1989; Strömbergsson, Wengelin, & House, 2014;). As such, this creates a disconnect in the application of Levelt's model to children's with consistent and persistent speech sound errors. Guenther (2006) in his Direction into Velocities of Articulators (DIVA) model proposes an auditory and somatosensory feedback loop that allows for the development and storage of a motor representation for speech sound production. As such, it is plausible that children with P-SSD have a weakness within this feedback loop, which results in aberrant motoric representations. Previous research has supported a relation between motor skills and SSD (Krishnan et al., 2013; Peter & Stoel-Gammon, 2008; Redle et al., 2015). In such reports, children with SSD exhibit weaker oral and fine motor skills compared to typically developing peers. Additionally, children in these studies exhibit low normal scores on language and cognition measures. Interestingly, the analyses in these studies as well as the proposal of the DIVA model does not directly account for potential expressive language and cognitive differences in children with P-SSDs. It is very likely that motoric skills and linguistic skills interact in a way that either complements speech production, or works in a negative cycle to attenuate speech production skills (Farquharson, 2015; Nip, Green, & Marx, 2009). Certainly, more work is needed to validate this relation.

Binding of linguistic and motoric abilities

In 2000 and again in 2012, Baddeley offered updates to his seminal model from 1974. Both updates included a fourth component – the episodic buffer. The episodic buffer is conceptualized as a limited capacity space in which information from various sources is bound together for temporary use or manipulation (Baddeley, 2000). Presumably, for speech production, the episodic buffer offers a space to integrate phonological and linguistic representations with motor representations. As such, it is plausible that children with P-SSD do not have obvious or radically poor linguistic or motoric skills, but instead have poor binding. If this is true, this may explain why children with P-SSDs often have normal, albeit low average, linguistic and motor skills and, importantly, provides support for a cognitive deficit. Although some researchers have reported difficulty in determining sensitive ways to measure the episodic buffer (Henry, 2010; Nobre et al., 2013), it is a logical next step to include in the study of this population of children.

Limitation & future direction

Although this study was the first to comprehensively examine the role of working memory skills in older children with P-SSD, it is not without limitations. First, although our sample size was determined via an a priori power analysis, it is surely a possibility that we may observe different and larger effects with more participants. However, our sample size is in line with the current standard for the study of speech sound disorders (Baker & McLeod, 2011). Second, we believe future research should include a dynamic, rather than static, assessment of visual spatial skills. Although the task used in the present study is reported to measure visual spatial manipulation skills, it may not be a sensitive measure of visual recall. Third, future work should conduct more fine-grained analyses of responses for serial nonword repetition tasks. Such an analysis would provide insights into possible primacy and recency effects that may differ between children with P-SSD and their typical peers. Fourth, we did not include a measure of speech perception abilities. Recent work has reported that there are mixed findings regarding the speech perception skills for children with SSD (Cabbage, Farquharson, & Hogan, 2015); however, it has certainly been implicated as a weakness in young children with SSD (Rvachew, Ohberg, Grawburg, & Heyding, 2003). Additional studies have suggested that speech perception is only problematic for a subset of children with speech sound disorders (Broen, Strange, Doyle, & Heller, 1983; Rvachew & Jamieson, 1989). Finally, we did not collect comprehensive details regarding the history, severity, and type of speech sound disorder that may have been present for the children in our sample during their early years of development. That is, some children may have exhibited an/r/ distortion from early on whereas other children may have initially had substantial errors comprised of multiple phonological processes and only have a residual/r/error at the time of this study (Karlsson, Shriberg, Flipsen, & McSweeny, 2002; Shriberg, Flipsen, Karlsson, & McSweeny, 2001). Certainly, this information could engender different results. Future longitudinal studies of this nature are necessary to continue to explore the causal mechanisms that contribute to protracted speech sound errors, which often cause later literacy and social-emotional deficits.

Conclusion

In sum, the results of the present study suggest that children with P-SSDs present with complex linguistic and cognitive deficits. Our research question explored the relation between working memory and the persistence of a speech sound disorder in school-aged children. Results supported a weakness in phonological working memory in this population of children, when compared to their typically developing peers. Our follow-up analyses explored the added relation of nonverbal intelligence and expressive vocabulary. Although expressive vocabulary was not related to working memory performance, co-morbid low-average nonverbal intelligence was linked to poor working memory in children with P-SSD.

Clinically, these results have substantial importance with respect to assessment. First, it is not commonplace to test nonverbal intelligence (and sometimes language) in children with speech sound disorders. Our results suggest that this construct may inform prognosis for children with speech sound disorders. That is, it is plausible that younger children at risk for P-SSDs have low nonverbal intelligence and that this may serve as a red flag for earlier intervening services. Second, working memory appears to be a sensitive measure of phonological skills. As such, nonword repetition may be a helpful early screener to determine risk of persistence in children with SSDs.

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Supplementary material — Supplemental data for this article can be found following the References.

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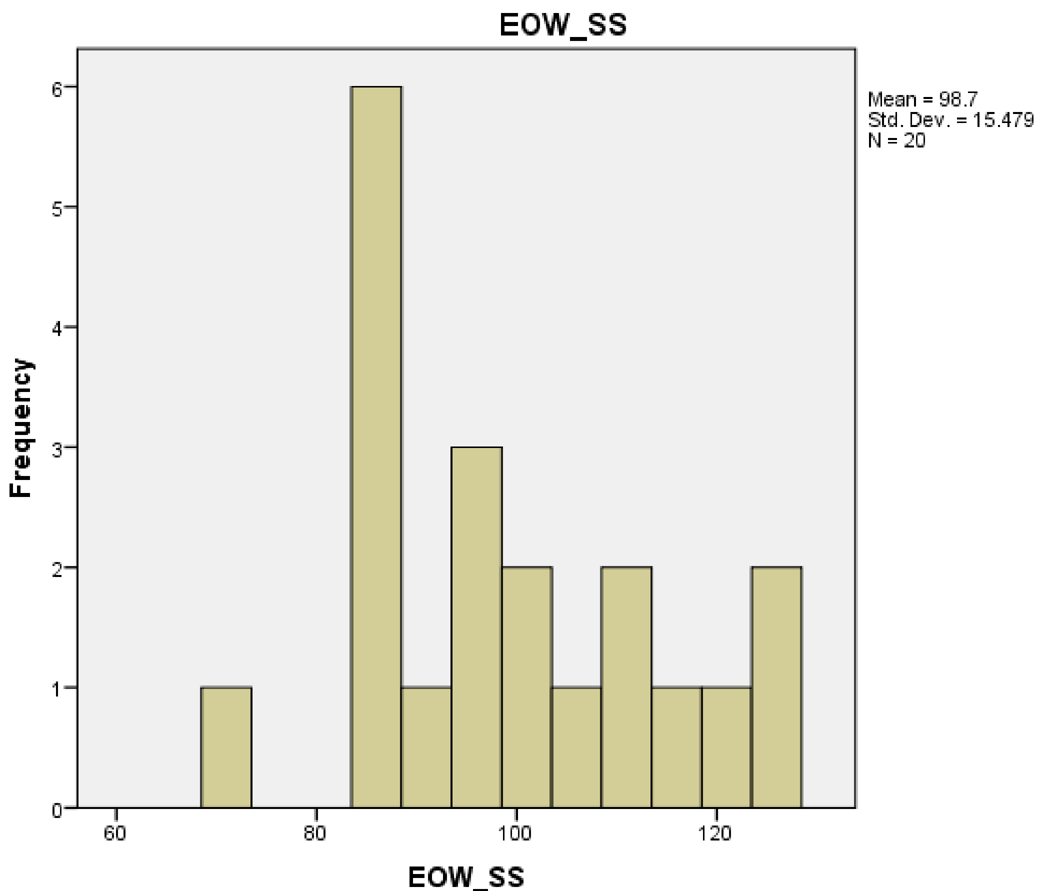
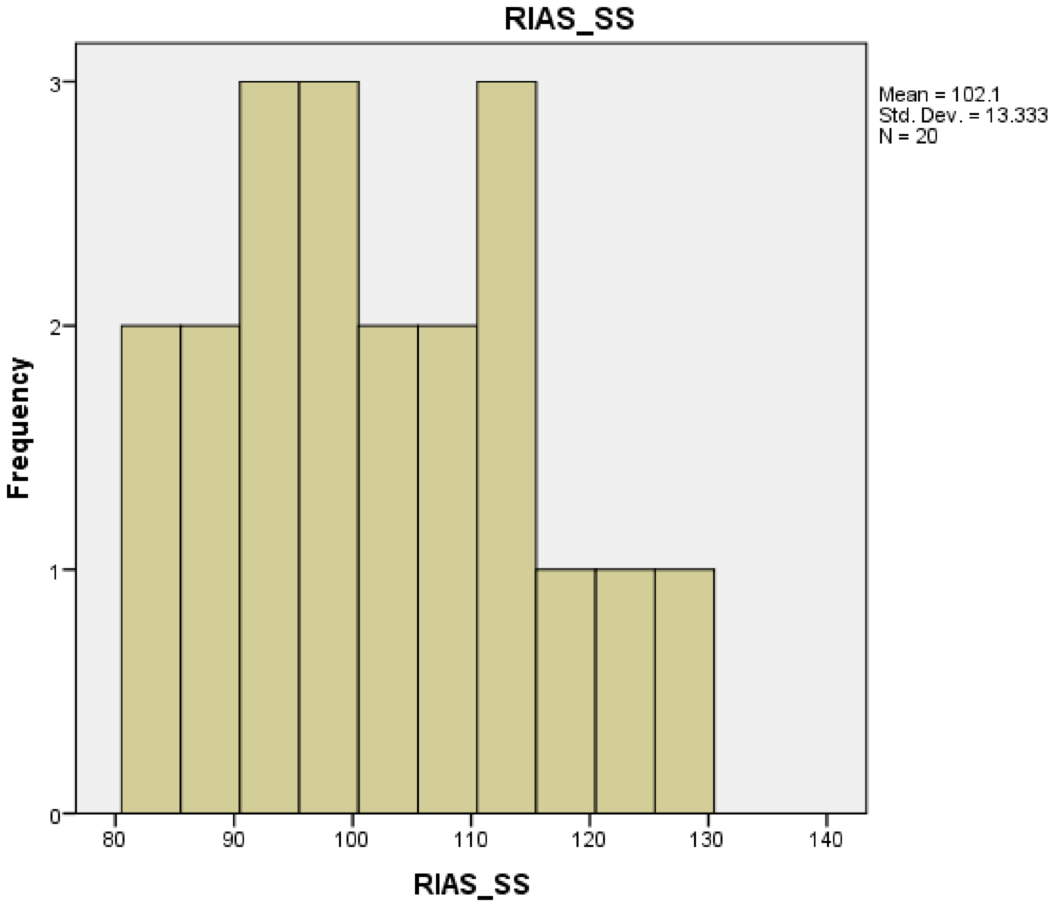
Supplemental Material

Expressive Vocabulary and Nonverbal intelligence histograms for children with persistent speech sound disorders




RIAS_SS
Mean = 102.1
Std. Dev. = 13.333
N = 20
Frequency
0
1
2
3
80
90
100
110
120
130
140
RIAS_SS