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There are Multiple Contributors to the Verbal Short-term Memory Deficit in Children with Developmental Reading Disabilities

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Abstract

Prior research has put forth at least four possible contributors to the verbal short-term memory (VSTM) deficit in children with developmental reading disabilities (RD): poor phonological awareness which affects phonological coding into VSTM, a less effective phonological store, slow articulation rate, and fewer/poorer quality long-term memory (LTM) representations. This project is among the first to test the four suppositions in one study. Participants included 18 children with RD and 18 controls. VSTM was assessed using Baddeley's model of the phonological loop. Findings suggest all four suppositions are correct, depending upon the type of material utilized. Children with RD performed comparably to controls in VSTM for common words but worse for less frequent words and nonwords. Furthermore, only articulation rate predicted VSTM for common words, whereas Verbal IQ and articulation rate predicted VSTM for less frequent words, and phonological awareness and articulation rate predicted VSTM for nonwords. Overall, findings suggest that the mechanism (s) used to code and store items by their meaning is intact in RD, and the deficit in VSTM for less frequent words may be a result of fewer/poorer quality LTM representations for these words. In contrast, phonological awareness and the phonological store are impaired, affecting VSTM for items that are coded phonetically. Slow articulation rate likely affects VSTM for most material when present. When assessing reading performance, VSTM predicted decoding skill but not word identification after controlling Verbal IQ and phonological awareness. Thus, VSTM likely contributes to reading ability when words are novel and must be decoded.

Keywords

learning disabilities; reading disabilities; dyslexia; phonological awareness; short-term memory; verbal learning; children; adolescents

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Individuals with developmental reading disabilities (RD) typically display poor reading, spelling, and other language-based skills. The primary underlying deficit is believed by many to be poor phonological processing (Brady, 1991; Gottardo, Stanovich, & Siegel, 1996; Swank, 1994; Wagner, Torgesen, & Rashotte, 1994). Measures of phonological processing, especially phonological awareness (the ability to manipulate sounds mentally, including segmenting words into their constituent sounds and blending sounds to form words), are among the best predictors of a child's ability to learn to read and account for large amounts of the variance in reading skill after age and IQ are controlled (Goswami & Bryant, 1990; McDougall, Hulme, Ellis, & Monk, 1994; Swank, 1994; Wagner et al., 1994).

Verbal short-term memory (VSTM) also is frequently impaired in RD (for a review see Baddeley, 1990; Jorm, 1983; McDougall & Hulme, 1994; Snowling, 1991; Torgesen, 1985). Moreover, the memory deficit in RD tends to be restricted to VSTM, as visuospatial short-term memory often is intact when stimuli cannot be verbally coded; central executive functioning often is intact when slave-system coding and storage deficits are controlled; and long-term memory (LTM) often is intact when deficits at encoding are controlled (Kibby & Cohen, 2008; Kibby, Marks, Morgan, & Long, 2004; McDougall et al., 1994; Roodenrys, Koloski & Grainger, 2001). It has been suggested that the origin of the VSTM deficit is poor phonological processing, particularly poor phonological awareness, which causes difficulty coding material by its sound (Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1977; Mann, Liberman, & Shankweiler, 1980; Torgesen, 1985; Wagner et al., 1994). In contrast, the ability to code and store verbal material by its meaning may be intact in RD (Kibby, 2008; Kibby & Cohen, 2008; Lee & Obrzut, 1994; McDougall & Donohoe, 2002). Consistent with these findings, children with RD tend to rely on phonological coding less when meaningful content is available (Waterman & Lewandowski, 1993). Although several researchers have suggested that the VSTM impairment in RD is due to poor phonological awareness which affects phonological coding into VSTM, others have suggested that the VSTM deficit is due to a storage buffer that functions less effectively, slow articulation rate, or fewer/poorer quality LTM representations which hinder retrieval (Kibby, Marks, et al., 2004; McDougall et al., 1994; McDougall & Donohoe, 2002). Hence, the primary aim of this study was to clarify the nature of the VSTM deficit in children with RD. Although VSTM often is deficient in this population, the source of this deficit remains under debate.

According to Baddeley (1986, 1990), the phonological loop is the component of working memory specialized for short-term maintenance of verbally-coded material or VSTM. The loop consists of two parts: a phonological store that holds speech-based information and a subvocal rehearsal mechanism/articulatory control process that is based on inner speech. According to Baddeley, the store retains phonological representations of information that decay over time if not rehearsed. The articulatory control process refreshes the memory trace by means of subvocal rehearsal.

Various sources of data provide support for a two-component phonological loop. Two such sources are the “phonological similarity effect” and the “word-length effect” (Baddeley, 1986, 1990). The phonological similarity effect is theorized to indicate the presence of the phonological store. It is the effect where sequences of phonemically similar items (rhyming items) are harder to remember than dissimilar items (non-rhyming items). This effect is thought to occur because the store is based on a phonological code, and phonemically similar items have easily confusable codes. The presence of a phonological similarity effect is believed to reflect a functioning phonological store, whereas a reduced or absent effect is believed to reflect an impaired phonological store. The phonological similarity effect was initially documented by Conrad and Hull (1964) and has been replicated since that time (Gathercole & Baddeley, 1990; Halliday, Hitch, Lennon, & Pettipher, 1990).

The word-length effect is theorized to indicate the presence of the subvocal rehearsal mechanism (Baddeley, 1986, 1990). In this effect sequences of short words are easier to remember than sequences of long words of equal frequency in the language. This effect is believed to occur because short words can be articulated more rapidly, allowing more words to be rehearsed before decay occurs. According to Baddeley, memory span is a function of decay rate and rehearsal rate. The decay rate from the phonological store is constant at about 1.5 to 2 seconds; rehearsal rate is based on the number of words an individual can say per second. The faster items can be articulated, the greater the resulting span. With an impaired subvocal rehearsal mechanism, the word-length effect should be absent or reduced. The word-length effect has been supported by prior research (Baddeley, Thomson, & Buchanan, 1975; Ellis & Hennelly, 1980; Stigler, Lee, & Stevenson, 1986).

When examining the phonological loop in RD, the literature has been discordant. Some researchers have found poor readers have reduced VSTM spans and absent phonological similarity effects, concluding the phonological store is abolished in RD (Liberman et al., 1977; Mann et al., 1980). Others have demonstrated that the phonological similarity effect is comparable to controls when floor effects are controlled, concluding that the phonological store is intact in RD despite a reduced span in this population (Hall, Wilson, Humphreys, Tinzman, & Bower, 1983; Holligan & Johnston, 1988; Johnston, 1982). Kibby, Marks and colleagues (2004) demonstrated a middle ground when controlling floor effects where the phonological similarity effect is present in RD but only when words are short and have fewer phonemes. Hence, while the store likely is not abolished in RD, it may function less effectively, with the level of effectiveness being related to the number of phonemes items contain.

Limited research has been conducted on the subvocal rehearsal mechanism. However, a study by Ellis, Baddeley, and Miles (unpublished study reported in Baddeley, 1986) found poor readers have the expected word-length effect despite having reduced VSTM spans and suggested their rehearsal mechanism is intact. Similar results were found in later studies (Kibby, Marks et al., 2004; McDougall et al., 1994; McDougall & Donohoe, 2002). Thus, the subvocal rehearsal mechanism may be intact in RD when assessed with the word-length effect.

Besides poor phonological coding and a store that functions with reduced effectiveness, two alternate sources of the VSTM impairment in RD have been proposed: slow articulation rate and reduced long-term memory (LTM) representations. McDougall and Hulme (1994) suggested that articulation rate provides a measure of the rate of processing within the phonological loop. More specifically, in the population at large, articulation rate may reflect the efficiency of some time-limited, speech-based mechanism used within the loop, and slow articulation rate may be the source of the VSTM deficit in RD. Slow articulation rates in RD have been documented in various studies (Baddeley, 1986; McDougall et al., 1994; McDougall & Donohoe, 2002; Roodenrys & Stokes, 2001).

Long-term memory also may play a role in VSTM span in the population at large by providing phonological representations of words that can be used to aid retrieval (Hulme, Maughan, & Brown, 1991). Hulme and colleagues (1991) suggested that when retrieval takes place, knowledge about the phonological structure of the material is used to reconstruct words when they have partially decayed in the loop. This theory provides an explanation as to why words are recalled better than nonwords in most individuals. As nonwords lack phonological representations in LTM, such representations cannot be used to carry out pattern completion. Thus, according to Hulme and colleagues, VSTM span is based upon two primary factors: articulation rate and LTM.

Although Hulme et al. (1991) suggested that the contribution LTM makes to VSTM is in terms of providing phonological representations that can be used to aid retrieval, their study provides evidence that the LTM contribution also may be semantic in nature. They required English-speaking controls to remember novel Italian words, and the participants performed poorly. In contrast, when they taught the participants the meaning of the words they performed much better. Thus, some of the LTM contribution to VSTM may be semantic information or links which are used to aid encoding, storage and/or retrieval. In his review, Torgesen (1985) referenced literature suggesting material which can be integrated with existing knowledge may be more easily learned and remembered than that which is highly novel. This supposition has been supported by subsequent research (Dewey, Kaplan, Crawford, & Fisher, 2001; Kibby, 2008; McDougall & Donohoe, 2002; Lee & Obrzut, 1994).

McDougall and colleagues (1994, 2002) examined the role LTM representations play in the VSTM deficit in poor readers. They originally found poor readers had comparable LTM contributions to VSTM span as controls when using high frequency, familiar words, but poor readers had slower articulation rates that were related to their reduced spans (1994). In the follow-up study (2002) McDougall and Donohoe found poor readers have a reduced VSTM span for low frequency words, despite being comparable to controls in span for high frequency words. According to the authors, the reduced span for low frequency words was caused by poor readers having fewer and/or worse quality LTM representations for these words due to limited reading experience. They suggested whereas both groups had exposure to high frequency words, good readers were more likely to have phonological and lexical representations for low frequency words in LTM because they read higher-level text. Furthermore, given reviews by Bishop and Snowling (2004) and Torgesen (1985) poor readers' restricted vocabulary knowledge also may have contributed to the group differences in LTM representations in the low frequency condition. Consistent with this notion, Swanson (1999; Swanson & Trahan, 1996) found vocabulary knowledge was related to VSTM ability and was affected in poor readers. Therefore, based upon the literature reviewed, poor VSTM in RD could be due to poor phonological processing/coding, a phonological store that functions with reduced effectiveness, a phonological loop that functions with reduced efficiency, and/or fewer/poorer quality LTM representations. This study is the first to compare all four suppositions in one project to determine which of these theories best explains the VSTM deficit or if a combination of these theories best explains the deficit.

A related topic of interest is whether VSTM contributes to reading performance. Some researchers have suggested that VSTM is affected in RD because of poor phonological processing; thus, VSTM does not uniquely contribute to reading ability when phonological awareness or others aspects of phonological processing are controlled (Fowler, 1991; McDougall et al., 1994; Pennington, 1991; Rapala & Brady, 1990; Wadsworth, DeFries, Fulker, Olson, & Pennington, 1995). Other researchers have found that VSTM does make a unique contribution to reading ability beyond that of phonological awareness (Cormier & Dea, 1997; Gathercole, Willis, & Baddeley, 1991; Hansen & Bowey, 1994; Tractenberg, 2002). Although how VSTM contributes to reading ability is unclear, some have suggested that children with short spans cannot maintain phonetically-coded material in VSTM well enough to achieve sound segmentation and blending while decoding (Baddeley, 1986; Snowling, 1991; Wagner & Torgesen, 1987). In addition, Snowling (1991) suggested that VSTM problems may lead to difficulty holding partially decoded words in mind while they are compared with the pronunciation of words retrieved from LTM. Hence, VSTM may play a unique role in the reading process beyond that played by phonological awareness.

The aims of this study were twofold: to clarify the nature of the VSTM impairment in children with RD and the extent to which it is related to poor phonological processing/coding as opposed to other factors, and to investigate whether VSTM uniquely contributes to reading ability. The following hypotheses were formed based upon the literature reviewed.

1. When comparing spans for high frequency words, low frequency words and nonwords, group differences were expected for low frequency words but not high frequency words given potential differences in LTM representations for low frequency words. Group differences were expected to be greatest for the nonwords, however. In the nonword condition the most reliance is placed on phonological awareness/coding as these items do not have LTM representations.

2. The RD group was expected to show a less effective phonological store, as evidenced by a reduced phonological similarity effect, but an intact subvocal rehearsal mechanism, as evidenced by a significant word length effect. This finding was expected across all frequency levels (high frequency words, low frequency words, nonwords), even when statistically controlling articulation rate, to reveal that results were not specific to overall efficiency of the loop or item frequency.

3. It was hypothesized that VSTM would predict basic reading ability (word identification and decoding), even when controlling Verbal IQ and phonological awareness.

Method

Participants

Participants included 18 children with reading disabilities (RD) and 18 children without RD. All children were between 9–14 years of age. The RD and control groups were equated for age, grade, gender, nonverbal intelligence, and socio-economic status (SES). SES was measured with The Four Factor Index of Social Status (Hollingshead, 1975).

The RD group was recruited through the local school system. More specifically, special education teachers distributed a letter describing the study to the children in their resource classrooms to take home to their parents. The parents then called the laboratory if they were interested in having their child participate. At the time of data collection, State criteria for a learning disability included (a) a significant discrepancy (at least one standard deviation) between academic achievement and measured intelligence; (b) normal intelligence; and (c) no indication of sensory or motor defects; of environmental, cultural or economic disadvantage; of emotional disturbance; or of insufficient teaching that could account for the learning deficit. For the purposes of this study "normal intelligence" was defined as a Full-Scale Intelligence Quotient (FSIQ) of 85 or greater on the Wechsler Intelligence Scale for Children— Third Edition (WISC-III).

School and psychological testing records were reviewed with parental consent to obtain IQ and achievement scores and to ensure RD participants met criteria for a specific learning disability in reading, including an academic history of struggling in reading. All school psychologists used the WISC-III to measure IQ, but the academic achievement measure varied across psychologists. The measures used included the Wide Range Achievement Test – Revised (WRAT-R), the Wechsler Individual Achievement Test or the Woodcock-Johnson – Revised Tests of Achievement (WJ-R). As a result of this variability, each test's word identification subtest was used as the reading measure to verify participants met the reading/ IQ discrepancy.

There is much debate over the best definition of a reading disability for research and clinical purposes. The discrepancy definition was chosen for this study over the poor reader definition in order to recruit children already diagnosed with a learning disability by the State. However, there was another advantage to its use as well. IQ and memory functioning are at least moderately correlated (Buehner, Krumm, Ziegler, & Pluecken, 2006; de Ribaupierre & Lecerf, 2006; Fuchs & Young, 2006), making the use of a discrepancy definition relevant to a study focused on VSTM. In addition, when using a discrepancy definition, children with RD may perform worse on nonword memory tasks than controls of similar reading ability who do not have RD (Snowling, Goulandris, Bowlby & Howell, 1986). Nonetheless, because of the learning disability definition used in the State at the time of data collection (i.e., at least one standard deviation discrepancy between IQ and achievement), many children in the sample had a mild learning disability in reading. The mean discrepancy was 22.61 with a range of 15–44. Four children had word identification scores in the 90s, with the rest having worse scores.

Control children were recruited from the local community through advertisements in public media and flyers. A screening version of the WISC-III (Information, Vocabulary, Picture Completion, and Block Design) was used to assess IQ. This short-form has a high correlation (0.935) with the full battery (Sattler, 1992). Reading was measured with the WRAT-R to verify controls did not have a learning disability in reading. In addition, controls were screened for previous special education evaluation and assistance in order to rule out those who had a history of learning problems. The mean discrepancy between FSIQ and WRAT-R Reading was −7.11 with a range of −29 to 5. One child had a Reading score of 88, and another had a Reading score of 96. Thus, there was an overlap in reading ability between the two groups for these two children. Nonetheless, they had IQ/Reading discrepancies of 2 and −3 in contrast to the children with RD. The rest of the controls had Reading scores greater than 100, which is better than all children with RD in the sample.

Exclusion criteria for all participants included a history of traumatic brain injury, neurological disorders, and psychiatric disorders including ADHD, as well as use of stimulants or mood-altering drugs and uncorrected vision impairments. All participants were native English speakers. These criteria were screened through parent questionnaires and review of school records. All participants were recruited by means of a free evaluation that detailed the results of the participant's performance on a clinical memory measure also given during this study (California Verbal Learning Test-Children's version; CVLT-C).

Materials

An experimental task was designed to evaluate the functioning of the phonological loop using Baddeley's model (1986, 1990). It required participants to memorize lists of five items presented orally by a computer and recall them in serial order. The task contained two blocks: one assessing the phonological store via the phonological similarity effect and the other assessing the subvocal rehearsal mechanism via the word length effect. Word length (short vs. long items) and phonemic similarity (rhyming vs. non-rhyming items) were within-subject factors. Each block consisted of six practice trials and eighteen experimental trials. The order of the blocks was counterbalanced across participants. The trials were presented in a fixed random order to facilitate scoring.

As part of this task, list content was varied to systematically examine VSTM for different types of material: high frequency words with low age of acquisition, low frequency words with high age of acquisition, and nonwords. Short and long words and phonemically similar and dissimilar words were matched for word frequency using grade three norms from Carroll, Davies and Richman (1971), as the youngest children in the sample were 9 years old. In the high frequency condition the mean frequency for short and long words was 73. In the low frequency condition the mean frequency for short and long words was 0. For the phonological similarity block, in the high frequency condition the mean frequency for dissimilar words was 85, and it was 84 for the similar words. In the low frequency condition the mean frequency for dissimilar and similar words was 0. The short/long and phonemically similar/dissimilar lists also were matched for age of acquisition using norms from Gilhooly and Logie (1980), with a mean of 2.5 (3–4 years) for each frequent word list (short, long, similar, and dissimilar) and a mean of 6.5 (12+ years) for each infrequent word list.

For the block assessing subvocal rehearsal, a trial consisted of a list of five items from one of the following list types: high frequency short words, low frequency short words, short nonwords, high frequency long words, low frequency long words, or long nonwords. There were 3 trials per list type. Thus, this block utilized a 2 (group membership: RD or controls) by 3 (level of frequency: high frequency words, low frequency words, or nonwords) by 2 (word length: short or long items) design. Short items were one syllable, and long items were three syllables.

For the block assessing the phonological store, a trial consisted of a list of five items from one of the following list types: high frequency phonemically dissimilar words, low frequency dissimilar words, dissimilar nonwords, high frequency phonemically similar words, low frequency similar words, or similar nonwords. There were 3 trials per list type. Hence, the block assessing the phonological store used a 2 (group membership) by 3 (level of frequency) by 2 (phonemic similarity: rhyming or non-rhyming items) design. All items were one syllable.

The articulation rate task was based on those used by Hulme et al. (1991) and McDougall et al. (1994, 2002). Stimuli were three high frequency word pairs, three low frequency word pairs and three nonword pairs from each list type (short, long, similar, dissimilar). The items chosen for the articulation rate task were drawn at random from the pool of items used for the VSTM task. Each pair was presented as many times as necessary for the participant to repeat it correctly. The child was then instructed to repeat the pair out loud five times as quickly as possible, and the time taken to do this was recorded. Accuracy was required, and if a child made articulation errors during the task the pair was re-administered. The mean of these times was transformed to yield a measure of articulation rate in items spoken per second. The order in which they repeated the items was counterbalanced.

Two tasks were used to assess phonological processing: a measure of phonological awareness and a measure of phonological decoding. The phoneme deletion task from McDougall et al. (1994) was used as the measure of phonological awareness. This task is included in their Appendix. During this task participants were provided with a nonword and asked to say what word would remain after omitting a specific phoneme (e.g., say "/blu:t/" without the /t/ sound). The Word Attack subtest from the WJ-R was used to evaluate decoding skill.

Procedure

The VSTM task proceeded as follows. Each child was provided with oral instructions explaining the procedure. The children were instructed that they were to memorize a list of orally presented words and recite them in serial order when asked to recall the list. In order to facilitate serial recall, children were told to say "blank" during retrieval if they remembered there was an item in a given position but forgot the specific item. The VSTM task proceeded as follows: following a verbal warning signal, five items were presented sequentially by a male voice from a Macintosh computer. Between items there was an inter-stimulus interval of 1 second. After presentation of the list was complete, there was a three second unfilled retention interval. At the end of the retention interval a tone signaled the start of the recall period. Participants were allowed 20 seconds for oral recall. A separate tone indicated to the children when the recall interval had finished. The computer screen was blank throughout the task.

After parental consent and child assent were obtained, participants performed the VSTM task first in order to attain their best performance. The articulation rate task was given second to avoid enhancing memory for items articulated as it utilized a subset of words/nonwords from the VSTM task. The phonological processing measures were given third. The clinical memory measure used for recruitment purposes was given last (CVLT-C). All participants underwent the same testing order.

Results

Descriptive Data

ANOVA was used to assess for differences between groups on most variables (age, grade, IQ, achievement), but chi-square was used for nominal variables and ordinal variables of limited range (gender, SES). RD and control groups were comparable in age, grade, gender, SES, and Performance IQ (PIQ). They differed in Verbal IQ [VIQ; $F(1,34) = 18.11$, $p < .001$], word identification [$F(1,34) = 84.51$, $p < .001$], spelling [$F(1,34) = 25.90$, $p < .001$] and decoding skills [$F(1,33) = 48.25$, $p < .001$]. See Table 1 for means and standard deviations. These differences were expected given the deficits commonly found in children with RD. Nonetheless, VIQ could be a significant contributor to group differences as it is correlated with VSTM performance. In addition, mean VIQ was average in the RD group but above average in the control group, thus possibly inflating controls' VSTM ability. Hence, VSTM analyses were performed with VIQ as a covariate in an attempt to statistically control for its contribution to group differences in performance.

Performance on the phonological processing measures was assessed using MANCOVA with VIQ as the covariate. The omnibus tests were significant, $F(3,32) = 11.45$, $p < .001$. Children with RD performed worse than controls on phoneme deletion, $F(1,33) = 22.69$, $p < .001$. However, they were comparable to controls in articulation rate, $F(1,33) = 2.67$, $p > .10$. Descriptive data is presented in Table 1.

Subvocal Rehearsal Mechanism

For the VSTM task, data were scored according to serial order given task instructions and prior research in this area; hence, an item was only considered correct if it was in the correct position. Repeated measures ANCOVA with VIQ and articulation rate as covariates was used to test Hypothesis 1. This yielded a significant main effect for group membership (Group), $F(1,32) = 12.17$, $p = .001$, $\eta_p^2 = .28$ but not word frequency [Frequency; $F(2,64) < 1.0$, $\eta_p^2 = .02$] or word length [Length: $F(1,32) < 1.0$, $\eta_p^2 = .01$]. Only one interaction was significant: Group X Length, $F(1,32) = 8.79$, $p < .01$, $\eta_p^2 = .22$. The Group X Frequency interaction was not significant, $F(2,64) = 2.33$, $p = .10$, $\eta_p^2 = .07$

Inspection of adjusted means revealed there were substantial floor effects when lists were scored according to serial order (RD adjusted means: frequent words $M = 2.82$, low frequency words $M = 0.94$, nonwords $M = 0.65$; Control adjusted means: frequent words $M = 3.19$, low frequency words $M = 1.56$, nonwords $M = 1.65$). Hence, it is likely that the Group X Frequency interaction lost significance due to range effects. As a result, lists were re-scored for total number of items recalled to reduce range effects. Repeated measures ANCOVA then yielded significant main effects for Group and Length but not Frequency. Two two-way interactions were significant: Group X Frequency and Group X Length. Articulation rate was a significant covariate. See Table 2 for ANCOVA results.

Based upon hypotheses and the prior literature, a priori analysis of the Group X Frequency interaction was conducted using matrix algebra and one-way ANOVA. Effect size (ES) was calculated using Cohen's d; an ES correlation also is presented to provide a measure more closely aligned with η_p^2. Groups did not differ for high frequency words, $F(1,64) < 1.0$, $d = 0.24$, $r^2 = .02$, but the control group performed significantly better than the RD group on the low frequency words, $F(1,64) = 8.03$, $p < .01$, $d = 0.71$, $r^2 = .14$ and nonwords, $F(1,64) = 37.41$, $p < .001$, $d = 1.53$, $r^2 = .37$. See Figure 1 for adjusted means. An a priori analysis of the Group X Length interaction revealed both groups had a significant word length effect, but the control group's effect was larger [$F(1,32) = 103.20$, $p < .001$, $d = 3.59$, $r^2 = .76$] than the RD group's [$F(1,32) = 19.44$, $p < .001$, $d = 1.56$, $r^2 = .38$]. The difference in the word length effects may be related to range effects, as the RD group recalled fewer items than controls in general [RD adjusted means: short items $M = 2.28$, long items $M = 1.88$; Control adjusted means: short items $M = 2.96$, long items $M = 2.04$].

As word length effects may be influenced by phonological processing (Kibby, Marks et al., 2004) along with articulation rate (McDougall & Donohoe, 2002), a measure of phonological awareness was entered as a covariate (phoneme deletion), along with VIQ and articulation rate when examining the word length interaction. Total number of items recalled was used due to range effects with serial order recall. Repeated measures ANCOVA yielded a significant main effect for Group [$F(1,31) = 4.13$, $p = .05$, $\eta_p^2 = .12$] but not Frequency or Length. The Group X Length interaction was no longer significant [$F(1,31) = 1.89$, $p > .10$, $\eta_p^2 = .06$], but the Length X Phoneme Deletion interaction was significant [$F(1,31) = 4.11$, $p = .05$, $\eta^2 = .12$].

Phonological Store

Data were scored according to serial order. Repeated measures ANCOVA with VIQ and articulation rate as covariates yielded a significant main effect for Group but not Frequency or phonemic similarity (Similarity). The two-way interaction of Group X Frequency was significant. A three-way interaction also was significant, Group X Frequency X Similarity. Articulation rate was a significant covariate. See Table 3 for ANCOVA results.

When conducting a priori analysis of the interaction, group differences in performance increased as items became less frequent, similar to the word length block [$F(1,64) = 1.64$, $p > .10$, $d = 0.32$, $r^2 = .02$ for high frequency words; $F(1,64) = 28.95$, $p < .001$, $d = 1.35$, $r^2 = .31$ for low frequency words; and $F(1,64) = 54.92$, $p < .001$, $d = 1.85$, $r^2 = .46$ for nonwords]. The phonological similarity effect was assessed at each level of Frequency given the nature of the interaction. The RD group did not display a significant phonological similarity effect at any level of Frequency [$F(1,64) = 2.05$, $p > .10$, $d = 0.36$, $r^2 = .03$ for high frequency words; $F(1,64) < 1.0$, $d = 0.15$, $r^2 = .01$ for low frequency words; and $F(1, 64) < 1.0$, $d = 0.21$, $r^2 = .01$ for nonwords]. The control group displayed the typical phonological similarity effect for high frequency word lists, $F(1,64) = 19.73$, $p < .001$, $d = 1.11$, $r^2 = .23$, but they performed worse on the low frequency dissimilar lists than they did on the low frequency similar lists, $F(1,64) = 11.67$, $p < .01$, $d = 0.85$, $r^2 = .15$ and similarly on the phonemically similar and dissimilar nonword lists, $F(1,64) = 1.42$, $p > .10$, $d = 0.30$, $r^2 = .02$. See Figure 2 for adjusted means.

Predictors of Verbal Short-term Memory Functioning

It was believed by the author that VSTM functioning is multifaceted, with varying contributors depending upon the type of material utilized. Given sample size, this was analyzed using the total sample. VIQ, phoneme deletion, articulation rate and word identification were entered into regression equations to assess how well they predict VSTM functioning for the various types of material. VIQ, phoneme deletion and articulation rate were selected in order to statistically compare the various possible contributors to VSTM functioning. More specifically, VIQ was entered as a measure of vocabulary knowledge and acquired knowledge (Bishop & Snowling, 2004; Torgesen, 1985); phoneme deletion was entered as a measure of phonological awareness and coding (Liberman et al., 1977; Mann et al., 1980; Wagner et al., 1994); and articulation rate was entered as a measure of phonological loop efficiency (McDougall et al., 1994). Word identification was entered because groups differed in reading ability.

When analyzing the distribution of the independent variables using the Kolmogorov- Smirnov statistic with the Lilliefors Significance Correction, no assumptions of normality were violated. The variables also were found to have a generally normal distribution when visually inspecting the data using SPSS P-P and Q-Q plots. This also was true of VSTM as each participant's mean number of items recalled was used (for each condition VSTM span represents the mean number of items recalled across 12 trials: 3 trials each of short, long, similar and dissimilar items). When utilizing Stepwise regression, articulation rate alone predicted VSTM for high frequency words (adjusted $R^2 = .37$, Beta = .62, $p < .001$). Articulation rate (Beta = .40, $p < .05$) and VIQ (Beta = .34, $p < .05$) predicted VSTM for low frequency words (adjusted $R^2 = .31$, $p = .001$). Phoneme ideletion (Beta = .55, $p < .001$) and articulation rate (Beta = .32, $p < .05$) predicted VSTM for nonwords (adjusted $R^2 = .50$, $p < .001$). The same variables were, and were not, significant when utilizing Backward regression (Pout = .10), which allows variables to interact before they are removed from the equation.

Predictors of Reading Performance

Hierarchical multiple regression controlling for dissimilar scaling was used to assess whether VSTM predicts reading performance when controlling VIQ and phonological awareness. These analyses also were conducted using the total sample given sample size. VIQ was entered into the first block; phoneme deletion was entered next; and overall VSTM span was entered last. When predicting word identification the final equation was significant (adjusted $R^2 = .73$, $p < .001$), with VIQ (Beta = .43, $p < .001$) and phoneme deletion (Beta = .48, $p < .001$) being significant predictors. The Beta value for VSTM was small (Beta = .13, $p > .10$). When predicting Word Attack the final equation also was significant (adjusted $R^2 = .75$, $p < .001$), with phoneme deletion (Beta = .59, $p < .001$) and VSTM (Beta = .31, $p < .001$) being significant predictors. The Beta value for VIQ was small (Beta = .16, $p > .10$).

DISCUSSION

This study had two primary aims: to clarify the nature of the VSTM impairment in children with RD and to investigate whether VSTM uniquely contributes to reading ability when VIQ and phonological awareness are statistically controlled. This was the first study to compare four theories on the source of the VSTM deficit in a single study to see which is best supported by the data or whether a combination of these theories is most accurate: a phonological store that functions with reduced effectiveness (Liberman et al., 1977; Kibby, Marks et al., 2004), fewer/poorer quality LTM representations (McDougall & Donohoe, 2002; Roodnerys & Stokes, 2001), poor phonological awareness which affects phonological coding of material (Liberman et al., 1977; Torgesen, 1988; Wagner et al., 1994), and reduced efficiency of the phonological loop as reflected by slow articulation rate (Baddeley, 1986; McDougall et al., 1994).

Possible Contributors to the VSTM Deficit in RD

Phonological loop subcomponents—It was hypothesized that the phonological store would function less effectively in children with RD but that the subvocal rehearsal mechanism would be intact when using at task based on Baddeley's model of the phonological loop (Baddeley, 1986, 1990). This finding was expected across all item frequency levels (high frequency words, low frequency words, nonwords), even when statistically controlling articulation rate and VIQ.

In terms of the phonological store, children with RD did not have a significant phonological similarity effect at any level of item frequency, consistent with hypotheses. In addition, the three-way interaction between group membership, item frequency, and phonemic similarity was significant when controlling VIQ and articulation rate, suggesting the deficit in the store is not due solely to slow speech rate or low verbal intellect. Given this study's results and prior literature in the area, the phonological store appears to function with reduced effectiveness in children with RD (Kibby, Marks et al., 2004; Liberman et al., 1977; Mann et al., 1980; Rack, Snowling, & Olson, 1992; Roodenrys et al., 2001; Swanson & Ashbaker, 2000, Swanson & Howell, 2001).

In terms of the subvocal rehearsal mechanism, it was found that the RD group had a large word length effect, even when controlling VIQ and articulation rate, suggesting the subvocal rehearsal mechanism is intact in RD as hypothesized. Nonetheless, the interaction between group membership and word length was significant, with the control group demonstrating a greater word length effect. As the RD group recalled few words in general, range effects likely contributed to the interaction. Another likely contributor is poor phonological processing. Kibby, Marks and colleagues (2004) found children with RD struggle with longer words, likely due to their greater number of phonemes, despite having intact subvocal rehearsal. When phoneme deletion was added as a covariate in this analysis, the phonological awareness by word length interaction was significant and the group by word length interaction was no longer significant. Thus, the subvocal rehearsal mechanism likely is intact in RD, consistent with prior research (Baddeley, 1986; Kibby, Marks et al., 2004; McDougall et al., 1994 & 2002).

Long-term memory representations—Hulme and colleagues (1991;Roodenrys, Hulme, & Brown 1993) suggested two primary factors contribute to VSTM span for words, articulation rate and LTM representations. When comparing spans for high and low frequency words, group differences were hypothesized to be present for low frequency words but not high frequency words given potential group differences in LTM representations for low frequency items. For both blocks of the VSTM task (word length and phonological similarity), children with RD performed quite comparably to controls on high frequency words but performed worse on low frequency words, consistent with this hypothesis.

Of interest, VIQ was not a predictor of VSTM span for familiar words in the total sample, likely due to all children being familiar with these items and having adequate LTM representations for them (age of acquisition was approximately 3–4 years). Consistent with this notion, between-group effect sizes were small for familiar words, and no group differences were found on the clinical memory measure administered for recruitment purposes which utilizes familiar words and encourages semantic coding (CVLT-C). Taken together, these findings suggest VSTM for familiar words is intact in children with RD, consistent with prior literature in this area (Kibby, 2008; Kibby & Cohen, 2008; Lee & Obrzut, 1994; McDougall & Donohoe, 2002), likely due to an adequate ability to code/store/retrieve items by their meaning.

In contrast, the RD group performed worse than controls on low frequency words. This effect was found in both blocks despite controlling articulation rate, suggesting LTM representations for less common words are affected in the RD group. Furthermore, the RD group continued to perform worse on low frequency words when phoneme deletion was controlled in the word length block, suggesting the effect is not due to poor phonological awareness [$F(1,62) = 8.18$, $p < .01$, $d = 0.73$]. Hence, these findings suggest children with RD perform worse on low frequency words due to fewer and/or poorer quality LTM representations, consistent with previous research in this area (McDougall & Donohoe, 2002; Roodenrys & Stokes, 2001).

Prior literature suggests words of low frequency/high age of acquisition are less likely to be known to children with RD due to their lesser vocabulary knowledge (Bishop & Snowling, 2004; Torgesen, 1985; Swanson, 1999) and exposure to the words through reading (McDougall & Donohoe, 2002). In this study, Verbal IQ was reduced in the RD group as compared to controls and both Verbal IQ and articulation rate predicted VSTM for low frequency words, suggesting vocabulary/acquired knowledge plays a role in the VSTM deficit for low frequency items in RD. Nonetheless, when Verbal IQ was statistically controlled groups continued to differ on low frequency items, suggesting other factors also contributed to group differences in LTM representations, such as controls having phonological and lexical representations for a greater number of words through reading more often (Stanovich, 1991) and through reading higher level texts (Stadler, 1993) given prior research in this area (McDougall & Donohoe, 2002). Further research is indicated to determine precisely which combination of factors contributes to group differences in LTM representations.

Poor phonological awareness/coding—Group differences in VSTM span were hypothesized to be greatest for the nonword lists despite controlling articulation rate and VIQ; this hypothesis was supported. It was believed that in the nonword condition the most reliance would be placed on phonological awareness and coding as these items do not have LTM representations. Supportive of this notion, phonological awareness was a strong predictor of nonword VSTM but not VSTM for words in the total sample. Given this study's findings, it appears that poor phonological awareness is related to reduced verbal span in children with RD when phonological coding of items is required, consistent with prior research (Kibby, 2008; Kibby & Cohen, 2008; Kibby, Marks et al., 2004; Liberman et al., 1977; Mann et al., 1980; Wagner et al., 1994). Findings also are consistent with the work of Rack and colleagues (1992) who suggested that children diagnosed with RD using a discrepancy definition are particularly likely to have difficulty on tasks utilizing nonwords.

Articulation rate—Prior research suggests VSTM is deficient in children with RD because they have slow articulation rates which cause their phonological loops to function less efficiently (McDougall et al., 1994; Roodenrys & Stokes, 2001). In this study, articulation rate predicted VSTM functioning for all material, and it was a significant covariate in both the word length and phonological similarity blocks. As memory span is a function of speech rate (Baddelely, 1986, 1990) and some prior research has documented slower articulation rates in children with RD (McDougall et al., 1994, 2002; Roodenrys & Stokes, 2001), some children with RD likely have reduced spans due to having slower articulation rates. Given that this study and other prior research (Kibby, Marks et al., 2004) has not found significant group differences in articulation rate but the RD groups' means were slightly lower than the controls' means, it is likely that this explanation applies to some children with RD but not all.

Multiple contributors—Based on this study's findings, it appears there are multiple contributors to the VSTM deficit in RD, rather than one theory fully explaining the deficit. Each supposition appears to be correct, depending upon the type of material being encoded. Articulation rate appears to be an important contributor to VSTM span regardless of item type; hence, slow articulation rate may cause reduced VSTM functioning when present. This notion is consistent with the work of McDougall and colleagues (1994, 2002) which suggests articulation rate is the main factor determining group differences in VSTM span for familiar words that have adequate LTM representations. When material is less frequently encountered, several factors likely explain the deficit, including fewer/poorer quality LTM representations, poor phonological processing/coding and storage, and slow articulation rate when present. More specifically, when LTM representations are present, children with RD prefer to use semantic coding and linkages to aid verbal short-term storage (Waterman & Lewandowski, 1993). Hence, if LTM representations are limited or inaccurate for a given word, VSTM will be affected. When LTM representations for a given item are absent, reliance must be placed on phonological processing and coding, an area of deficit for children with RD (Liberman et al., 1977; Wagner et al., 1994; Swank, 1994). While the phonological store appears to be deficient for all types of verbal material in RD, this deficit is most evident when material must be stored by its sound. When material can be linked with/coded by its meaning, children with RD prefer to utilize this route to compensate for their malfunctioning phonological store. This idea will be considered more fully next.

Relationship between Reading Ability and the Phonological Store

The phonological similarity block had some interesting results related to the relationship between reading ability and the phonological store. While controls had the expected similarity effect for high frequency words, they had a reverse similarity effect for low frequency words. In contrast, the RD group did not have a significant phonological similarity effect at any level of item frequency. When controls were asked what strategy they used in the low frequency condition, they stated that on the rhyming lists they would say various words that rhymed with list items when unsure. This is consistent with behavioral observations as controls were more likely to say rhyming words not on the list for the phonemically similar lists, suggesting they were using a phonetic coding/retrieval strategy. The RD group did not tend to use this strategy, and, instead, continued to try to provide actual list items. Hence, it appears that good readers will utilize phonetic strategies more readily when it will help their performance whereas children with RD will continue to try to code/retrieve words by their meaning despite being less familiar with them, likely due to their deficits in phonological coding and storage.

Baddeley's model (1986, 1990) suggests there is one VSTM store, and it uses phonological codes. LTM representations merely aid retrieval when using this model (Hulme et al., 1991; Rooderys et al., 1993). Much of the literature the present study is based upon incorporates such an approach. However, the neuroscience and neuropsychology literature suggests there may be more than one verbal store. In fact, there may be at least two verbal short- term storage systems, one used when material is coded phonetically and another used when material is coded semantically/by its meaning (Martin & Romani, 1994; Martin, Shelton, & Yaffee, 1994). Based upon anatomical, quantitative MRI and functional neuroimaging studies, the supramarginal gyrus may be the site of the phonological store, the pars triangularis may be involved with subvocal rehearsal, and multiple aspects of the prefrontal region and temporal lobe may be involved with short-term storage by meaning (Baddeley, 1998; Cabeza & Nyberg, 1997, 2000; Fiez et al., 1996; Jonides et al., 1998; Kibby, Kroese et al., 2004; Smith & Jonides, 1997). If there are multiple stores, then likely the short-term storage mechanism used for meaningful material is intact in RD, and any group differences found for words are due to slow articulation rate and/or reduced knowledge of the words. In contrast, the store which holds phonetically coded items likely is impaired. The latter system is concentrated around the left posterior Sylvian fissure and, thus, is particularly vulnerable in RD (Kibby, Kroese et al., 2004; for a review see Kibby & Hynd, 2001). The notion of two VSTM stores, with the phonological store being impaired in RD, is consistent with this study's findings. It also is consistent with prior research demonstrating VSTM is intact in RD when items can be coded by their meaning, such as passages/stories or lists containing familiar words (Kibby, 2008; Kibby & Cohen, 2008; Lee & Obrzut, 1994), but it is impaired when items must be coded by their sound (Kibby, 2008; Kibby & Cohen, 2008; Wagner et al., 1994). Further neuroimaging research on children with RD is indicated in this area.

VSTM, Phonological Awareness, and Reading Performance

It has been debated whether VSTM makes a unique contribution to basic reading ability or whether the relationship between reading and VSTM is indirect because both rely on phonological awareness skills. Given the literature reviewed, it was hypothesized that VSTM would predict basic reading ability even when statistically controlling Verbal IQ and phonological awareness. Interestingly, what was found was that both sides of the argument were partially supported; whether or not VSTM makes a unique contribution to reading ability varies with which aspect of basic reading is being measured. When word identification was analyzed, only VIQ and phonological awareness successfully predicted reading performance. In contrast, when pseudoword decoding was analyzed, only phonological awareness and VSTM successfully predicted reading performance. This differential makes implicit sense. Word identification often becomes automatic when words are familiar and can be identified by sight through a whole- word/orthographic approach. Hence, VSTM may not be as necessary in this situation. VSTM does appear to play a role in the reading process when words are novel and must be decoded. Under these conditions more emphasis is placed upon phonological segmentation and blending, and phonemes likely are held in VSTM during these processes (Snowling, 1991; Torgesen, Rashotte, Greenstein, Houck, & Portes, 1987). As most material is novel when first learning to read, VSTM may play a particularly important role in the early stages of reading (Baddeley, 1990; Gathercole et al., 1991). Further longitudinal research is warranted in this area.

Limitations and Directions for Future Research

There are various limitations of this study which should be addressed during replication. First, sample size was small which limits generalization to the population of RD at large and reduces power. Sample size also was not sufficient to see if predictors of VSTM and reading differ for RD and controls. Hence, this study should be replicated with a larger sample. Nonetheless, despite small sample size several significant results were found that are supported by prior research. Second, the control group had above average verbal intellect and reading ability overall. While the present study attempted to control for this by using VIQ as a covariate, the best method would be to compare groups equated for both VIQ and PIQ. Third, the study used a liberal discrepancy definition of RD and a mild RD sample. Findings may vary if a more stringent discrepancy definition is used. Nevertheless, significant results were obtained in the expected direction despite the use of a mild sample. Replication of this study comparing poor readers to those defined with a discrepancy definition also would be informative, as prior research suggests poor readers are more heterogeneous as a group than those defined by a discrepancy definition and are more likely to include children with receptive language delays (Bishop & Snowling, 2004). Thus, poor readers may be more likely to have weaknesses with semantic coding and VSTM for words. Fourth, future research should include measures of vocabulary knowledge and exposure to print for various types of text to assess how each contributes to the quality/quantity of LTM representations in RD. Fifth, ADHD was assessed through parent report and by reviewing school records. Therefore, it is possible that children with mild ADHD were included in the sample. When replicating this study, thorough assessment for ADHD is warranted through parent interview and questionnaires such as the Behavior Assessment System for Children or Child Behavior Checklist. It also would be informative to replicate this study using four groups: RD, RD/ADHD, ADHD, and controls. Finally, the age range of the sample was broad; the study should be replicated with a smaller age range or longitudinal design. A longitudinal study also would be informative to determine how vocabulary knowledge, print exposure, phonological awareness, VSTM, and reading ability interact over the course of development.

Conclusions

This study makes two important contributions to the field: it replicates prior research on VSTM functioning in RD, and, perhaps more importantly, it is the first to compare all four theories on the source of the VSTM deficit in a single study, finding each theory is at least partially correct. VSTM likely is impaired in some children with RD due to slow articulation rate. However, in many children with RD the source of the deficit appears to be related to the type of material presented. The semantic short-term storage mechanism/system likely is intact in RD and is the preferred mode of verbal short-term storage in RD. Therefore, when less familiar words are encountered children with RD will attempt to use this system anyway, and the VSTM deficit found likely is related to fewer/poorer quality LTM representations for these items. When completely novel items are encountered or phonological coding is required by a task, a deficient phonological store and poor phonological awareness which affects phonological coding into VSTM likely are the sources of the deficit.

Because VSTM ability influences decoding ability, it is an important area for intervention. Based upon these results, there are several possible areas to target during intervention. First, a thorough evaluation is warranted, focused upon VSTM for different types of material, vocabulary knowledge, exposure to print, and phonological awareness. If any of these areas are deficient, they should be targeted for remediation. For example, if VSTM for words is reduced, then focus should be placed on enhancing the child's knowledge-base and word exposure through activities designed to improve vocabulary and exposure to higher-level print. If VSTM for items coded phonetically is impaired, then additional focus should be placed on enhancing phonological awareness; this should bolster decoding ability as well. Additional

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emphasis also should be placed on helping children link new material to what is already known, facilitating their ability to use semantic coding and storage. Furthermore, given that decoding requires VSTM and phonological awareness, emphasis should be placed on memorizing common words for the child's grade level so that they can be identified by sight, thereby minimizing demands for decoding.

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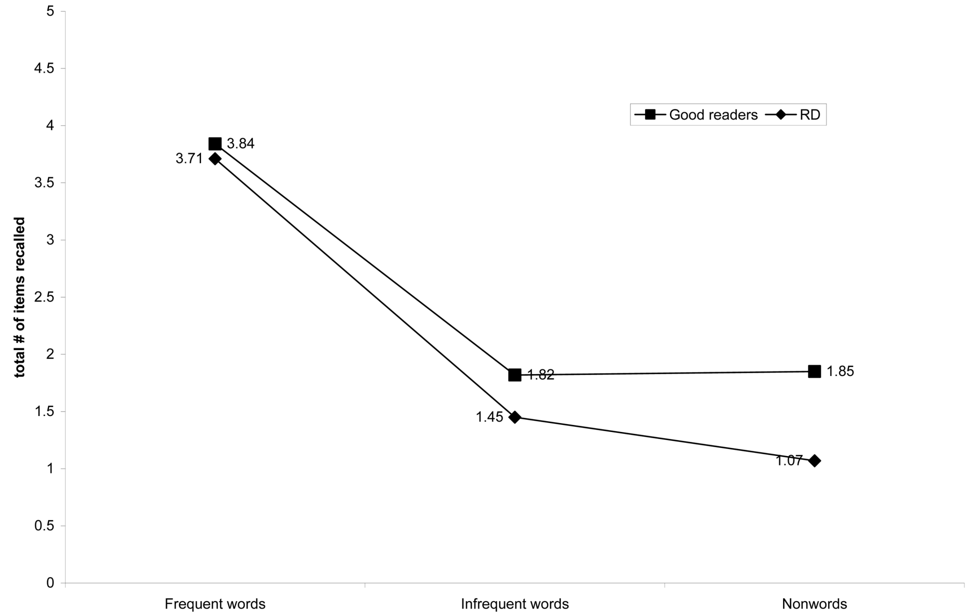

Figure 1.
Adjusted means controlling VIQ and articulation rate for the Group X Frequency interaction in the word length block; data was scored using total number of items recalled.

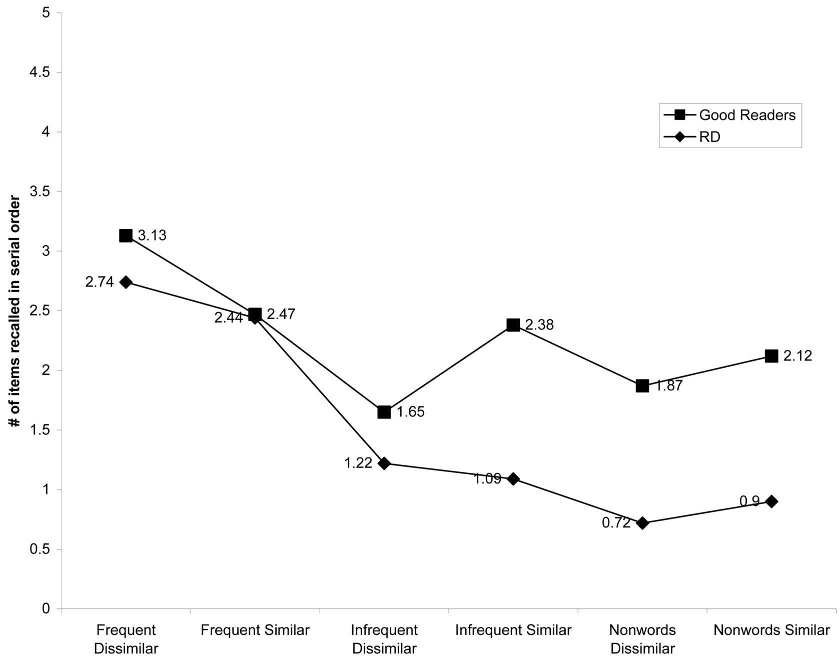

Figure 2.
Adjusted means controlling VIQ and articulation rate for the Group X Frequency X Similarity interaction in the phonological similarity block; data was scored using number of items recalled in serial order.

Table 1

Descriptive Data on Participants

Characteristic	Reading Disability Mean (SD)	Controls Mean (SD)
Age	12.34 (1.19)	11.66 (1.64)
Grade	5.72 (1.27)	5.39 (1.72)
Full-Scale IQ[a]	99.67 (8.62)	106.11 (9.07)
Verbal IQ[b]	97.33 (9.48)	110.44 (9.00)
Performance IQ	103.11 (11.59)	102.33 (14.58)
Word Identification[b]	83.39 (8.15)	114.50 (11.82)
Word Attack[b]	13.35 (5.21)	23.94 (3.73)
Spelling[b]	84.83 (11.99)	109.33 (16.54)
Phoneme Deletion[c]	12.17 (3.87)	19.50 (2.81)
Articulation rate	2.29 (0.53)	2.69 (0.45)
Gender	67% Male	50% Male
Median SES	2.5	2

Note. SES was measured on a 5 point scale according to the Hollingshead (1975) Four Factor Index of Social Status. Word Attack and phoneme deletion were measured in raw scores.

Articulation rate was measured in number of items spoken per second.

[a]Means in this row differ at $p < .05$.

[b]Means in this row differ at $p < .001$.

[c]Means in this row differ at $p < .001$ when VIQ is used as a covariate.

Table 2

ANCOVA Results for the Subvocal Rehearsal Block

Source	df	F	η_p^2	p
		Between subjects		
VIQ	1	3.50	.10	.07
Articulation rate (AR)	1	9.00**	.22	.005
Group (G)	1	8.72**	.21	.006
Error	32	(.68)		
		Within subjects		
Frequency (F)	2	2.10	.06	.13
F X VIQ	2	0.01	.00	.99
F X AR	2	1.10	.03	.34
F X G	2	4.12*	.11	.02
Length(L)	1	4.87*	.13	.04
L X VIQ	1	2.71	.08	.11
L X AR	1	0.19	.01	.70
L X G	1	10.02**	.24	.003
F X L	2	0.44	.01	.65
F X L X VIQ	2	0.50	.02	.61
F X L X AR	2	1.23	.04	.30
F X L X G	2	0.25	.01	.78
F X L Error	64	(.27)		

Note. Values enclosed in parentheses are mean square errors.

* $p < .05$.

** $p < .01$.

Table 3

ANCOVA Results for the Phonological Store Block

Source	df	F	η_p^2	p
		Between subjects		
VIQ	1	0.01	.00	.94
Articulation rate (AR)	1	5.66*	.15	.02
Group (G)	1	10.48**	.25	.003
Error	32	(1.75)		
		Within subjects		
Frequency (F)	2	0.46	.01	.63
F X VIQ	2	0.17	.01	.84
F X AR	2	3.07	.09	.05
F X G	2	5.90**	.16	.004
Similarity (S)	1	0.32	.01	.57
S X VIQ	1	0.71	.02	.41
S X AR	1	0.31	.01	.58
S X G	1	0.86	.03	.36
F X S	2	0.99	.03	.38
F X S X VIQ	2	0.76	.02	.47
F X S X AR	2	0.02	.00	.98
F X S X G	2	5.43*	.15	.03
F X S Error	64	(.33)		

Note. Values enclosed in parentheses are mean square errors.

* $p < .05$.

** $p < .01$.