Short Title: Verbal Working Memory Capacity in DLD

A Comparison of the Storage-Only Deficit and Joint Mechanism Deficit Hypotheses of the Verbal Working Memory Storage Capacity Limitation of Children with Developmental Language Disorder

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Abstract

Purpose: The storage-only deficit and joint mechanism deficit hypotheses are two possible explanations of the verbal working memory (vWM) storage capacity limitation of school-age children with developmental language disorder (DLD). We assessed the merits of each hypothesis in a large group of children with DLD and a group of same-age typically developing (TD) children.

Method: Participants were 117 children with DLD and 117 propensity-matched TD children 7-11 years of age. Children completed tasks indexing vWM capacity, verbal short-term storage, sustained attention, attention switching, and lexical long-term memory (LTM).

Results: For the DLD group, all of the mechanisms jointly explained 26.5% of total variance. Storage accounted for the greatest portion (13.7%), followed by controlled attention (primarily sustained attention 6.5%), and then lexical LTM (5.6%). For the TD group, all three mechanisms together explained 43.9% of total variance. Storage accounted for the most variance (19.6%), followed by lexical LTM (16.0%), sustained attention (5.4%), and attention switching (3.0%). There was a significant LTM by Group interaction in which stronger LTM scores were associated with significantly higher vWM capacity scores for the TD group as compared to the DLD group

Conclusions: Results support a joint mechanism deficit account of the vWM capacity limitation of children with DLD. Results provide substantively new insights into the underlying factors of the vWM capacity limitation in DLD.

Working memory (WM) refers to the ability to store information while at the same time engage in information processing (Baddeley, 2012; Cowan, Rouder, Blume, & Saults, 2012). In typically developing (TD) children, WM relates to a variety of higher-order cognitive abilities. It relates to fluid intelligence (Engel de Abreu, Conway, & Gathercole, 2010), sentence comprehension (Ahmad Rusli & Montgomery, 2017; Boyle, Lindell, & Kidd, 2013), reading comprehension (Gathercole Pickering, Knight & Stegmann, 2004; Niedo, Abbott, & Berninger, 2014), writing abilities (Altemeier, Abbott, & Berninger, 2008; Niedo et al., 2014), and mathematical abilities (Swanson, 2006; Geary, Hoard, Byrd, De Soto, & Craven, 2004). For children with developmental language disorder (DLD), much less is known about the relationship between WM and higher-order cognitive abilities. Children with DLD are those who have difficulty mastering spoken and written language abilities despite having broadly normal-range nonverbal intelligence, hearing sensitivity, and articulation, together with no neurological impairment. Even with normal-range nonverbal intelligence, these children exhibit various cognitive limitations, chief among them verbal WM (Archibald & Gathercole, 2006, 2007; Briscoe & Rankin, 2009; Ellis Weismer, Evans, & Hesketh, 1999; Marton, Campanelli, Eichorn, Scheuer, & Yoon, 2014; Marton & Eichorn, 2014; Marton, Eichorn, Campanelli, & Zakarias, 2016; Montgomery, 2000).

A common index of verbal WM (vWM) is capacity, the amount of information that can be stored (e.g., a phrase or clause) in the moment while performing ongoing processing (e.g., processing incoming material). Relative to same-age TD mates, children with DLD show a disproportionate deficit in vWM capacity (Archibald & Gathercole, 2006, 2007; Briscoe & Rankin, 2009; Ellis Weismer et al, 1999; Montgomery, 2000). Though little debate exists as to whether these children have limited vWM capacity, there is about which memory-related mechanism(s) constrain capacity. One hypothesis holds that their limitation is predominately constrained by storage, i.e., storage-only deficit hypothesis (e.g., Archibald & Gathercole, 2007; Archibald & Griebeling, 2016; Briscoe & Rankin, 2009). Alternatively, the joint mechanism deficit hypothesis proposes that reduced storage and poor controlled attention constrain capacity (Ellis Weismer et al., 1999; Marton et al., 2014; Marton & Eichorn, 2014; Marton et al., 2016). While this account implicates weak inhibitory control as an important constraint on the vWM capacity of these children, other controlled attention mechanisms like sustained attention and attention switching may also be important factors. In addition, this hypothesis does not include long-term memory (LTM) as a potential limiting factor.

The aim of the present study was to determine whether the storage-only deficit hypothesis or joint mechanism deficit hypothesis is the better account of the vWM capacity limitation of school age (7-11 year old) children with DLD. The current joint mechanism deficit hypothesis is absent sustained attention, attention switching, and LTM. These mechanisms, which are important components of current theories of WM (as discussed in further detail below) were included as part of this account in the present study. Findings from this study have important implications for shedding new insights into the nature of the vWM capacity limitation of children with DLD. The results also have implications for better understanding the nature of the connection between the vWM deficits and language difficulties of these children by appreciating the differential contributions of storage, controlled attention, and LTM to the language performance of children with DLD (e.g., Archibald & Griebeling, 2016; Montgomery, Evans, Fargo, Schwartz, & Gillam, 2018).

As an illustration of the importance of this connection, we refer to a recent study by Montgomery et al. (2018). Its purpose was to determine whether the structural relationship of vWM, controlled attention, LTM, and sentence comprehension was similar or different in children with DLD and same-age TD peers. We treated vWM, attention, and LTM as separate yet related constructs given the theoretical assumptions we made about their role in comprehension. The prediction was that controlled attention and LTM (language knowledge) should operate through vWM to influence simple and complex sentence comprehension. The reason we thought vWM would act as the “conduit” through which controlled attention and LTM would indirectly influence comprehension was because both controlled attention and LTM are associated with WM, and comprehension ultimately involves the coordination of verbal processing and storage, i.e., WM. We conducted structural equation modeling in which vWM, attention, and LTM were used as latent (composite) variables to predict comprehension accuracy. Different models of the relationship were tested. The best fitting model for both groups was the one in which vWM mediated the influence of controlled attention and LTM on the comprehension of both sentence types. However, subtle differences occurred between the groups in the magnitude of the influence of attention and LTM on comprehension. For TD children and for both sentence types, LTM had a strong influence, but controlled attention had no effect. The opposite was true for children with DLD. Controlled attention played an influential role in both sentence types whereas LTM was influential only in simple sentence comprehension.

In the present study, our scope was much narrower-- to investigate the mechanism of vWM itself. Our aim was to better understand the potential influences of the WM-related submechanisms of verbal storage, controlled attention, and LTM in defining the vWM capacity of children, both children with DLD and same-age TD children.

Working Memory: Definition and a Few Models

There are a number of different theoretical frameworks of WM, including the multi-component model (Baddeley, 2012; Baddeley & Logie, 1999), embedded processes model (Cowan et al., 2005, 2012, 2014), dual-storage model (Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Hambrick, Tuholski, Wilhelm, Payne, et al., 2004), and time-based resource-sharing (TBRS) model (Barrouillet & Camos, 2001; Barrouillet, Portrat, & Camos, 2008; Gavens & Barrouillet, 2004). Though models of WM differ somewhat in terms of their structural details they all share certain features such as storage, controlled attention, and the idea that WM and LTM are connected (see below). However, we did not align ourselves with a particular model because comparing the relative merits of the models was not relevant to our aim.

In the most recent version of his multi-component model, Baddeley (2012) describes WM as comprising four separable yet interactive components. There is a domain-general central executive, which functions as a controlled attention mechanism. Controlled attention includes such abilities as allocating attention resources to different components of WM or other cognitive systems through sustaining focal attention and dividing or switching attention. The second and third mechanisms correspond to separate, domain-specific memory storage devices, one for the temporary retention of verbal material (phonological loop) and the other for visuospatial input (visuospatial sketchpad). Each storage device is severely limited in its capacity. Input to these devices typically corresponds to activated representations/items stored in LTM. The fourth component is the episodic buffer, a passive store that holds unimodal or cross-modal inputs bound together into larger coherent chunks or episodes (e.g., sentences, stories). The episodic buffer serves as an interface between WM and LTM.

Cowan and associates (Cowan, 1999; Cowan et al., 2005, 2012, 2014) view WM as an embedded system of memory and attention. Working memory represents items activated in LTM that are relevant to accomplishing an immediate cognitive goal. Total WM capacity, limited to about four or five chunks of information, represents the combination of activated items occupying both central storage and peripheral storage. Central storage is limited to about one item and is the immediate object of the focus of attention (Cowan et al., 2005). Central storage and focal attention are thus one and the same. Peripheral storage comprises the remaining activated items that lie just outside the focus of attention. Controlled attention plays a primarily "zooming" role in WM performance by initially zooming out to capture several items during encoding and then zooming in to maintain just one item in central storage. Long-term memory plays an important role in WM capacity because WM represents the activated portion of LTM. Long-term memory also is important from a knowledge perspective; it is knowledge of the input and the ability to process or chunk the input in some meaningful way that promotes WM performance (Cowan, 2016; Cowan, Ricker, Clark, Hinrichs, & Glass, 2015; Gilchrist, Cowan, & Naveh-Benjamin, 2009; Towse, Cowan, Hitch, & Horton, 2008). To illustrate, a child hears the items *1, dog, 9, spoon, fence* and is asked to recall the words in order followed by the digits in order. If the child produces *dog, spoon, fence* followed by *1, 9* such recall would demonstrate the child's ability to process or chunk the items into word and digit categories (based on item knowledge), which, in turn, can facilitate greater accessibility of these items during recall.

Engle and colleagues (Engle, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth & Engle, 2007) have put forth the dual-store model. This model incorporates primary and secondary memory, analogous to the central and peripheral stores in Cowan's model (Cowan et al., 2005). Relative to Cowan and associates, controlled attention for Engle and colleagues, as well as others (Barrouillet & Camos, 2001; Unsworth & Robison, 2015, 2016), appears to play a larger role in keeping initially activated items in LTM in an active state. Sustaining attention during encoding appears to relate to the strength of item activation as well as to item maintenance and subsequent recall (Miller, Gross, & Unsworth, 2019; Unsworth, 2009; Unsworth & Robison, 2015, 2016, 2018). Relative to individuals with weak sustained attention abilities, those with stronger abilities exhibit better item encoding and ability to control lapses of attention on a trial-to-trial basis over the course of a WM task thereby minimizing the loss of items from focal attention.

The TBRS model (Barrouillet & Camos, 2001; Barrouillet et al., 2008; Gavens & Barrouillet, 2004) emphasizes the importance of attention switching in maintaining items in storage. Individuals with good ability to switch their focus of attention between performing the processing activity and maintaining the items in storage score better on WM tasks than those with weaker attention switching ability. Good attention switching abilities allow individuals to rapidly toggle their attention after completing the processing episode to storage in order to maintain items via either refreshing or rehearsing those items lying just outside the focus of attention (Cowan, 1999; Cowan et al., 2005) or primary memory (Engle, 2002).

Finally, the inseparability of WM and LTM is conceptually consistent with connectionist models of language functioning (Acheson & MacDonald, 2009; Christiansen & MacDonald, 1999; Just & Carpenter, 1992; Just Carpenter, & Keller, 1996; MacDonald & Christiansen, 2002). In such models, vWM capacity represents the total amount of activation (mental energy) available to support both language processing and storage (e.g., Just & Carpenter, 1992). Each item in WM has an associated activation level. If each item maintains a minimum activation level, it will continue to "occupy" WM and be available for retention and/or further processing. Items in WM may be of variable size, depending on whether the input has been chunked/grouped together into larger but more coherent units (e.g., phrases, clauses) thereby conserving memory space, a view that is consistent with Cowan's (Cowan, 2016; Cowan et al., 2015) chunking principle. As the processing demands and/or storage demands increase such that the task exceeds an individual's total WM capacity, task performance is impaired because insufficient activation is available to adequately support both processing and storage. Observed differences in vWM capacity across individuals presumably reflects individual variation in the availability of total activation.

Accounts of the vWM Capacity Limitations of Children with DLD

As mentioned, there are two hypotheses about the nature of the vWM capacity limitation of children with DLD. The storage-only deficit hypothesis proposes that a deficit in the storage component of vWM itself is primarily responsible for these children's vWM capacity limitation. The joint mechanism deficit account posits that it is reduced storage and weak controlled attention in combination that constrains the children's capacity.

Storage-Only Deficit Hypothesis. Briscoe and Rankin (2009) took a statistical modeling approach to differentiate the storage-only deficit and joint mechanism deficit hypotheses. The authors administered simple verbal memory tasks (indexing phonological loop capacity) and complex verbal memory tasks (indexing loop and executive attention) to 7-8 year-old children with DLD, same-age TD peers, and younger TD children matched on receptive vocabulary to the DLD group. The relevant comparison for us is between the DLD and same-age TD groups. Results revealed that, relative to the same-age TD group, the DLD group performed more poorly on both the simple and complex tasks. Next, an analysis of covariance (using simple verbal memory score as the covariate) was conducted to compare the groups' vWM scores. The results showed that the groups no longer differed in vWM, leading the authors to argue that the vWM limitation of the children with DLD was due to a storage-only deficit, not a combination of storage and controlled attention deficits.

Archibald and Griebeling (2016) took a different approach. In this study, framed within the TBRS model (Barrouillet et al., Portrat, Barrouillet, & Camos, 2008), the authors proposed that controlled attention may be a critical determinant of vWM performance. According to this model, attention is shared alternately between processing and storage and when attention is captured by the processing activity, it is not available for refreshing or rehearsing the stored items, which leads to a loss of items from storage.

The children completed three vWM tasks differing in "processing load," with processing load becoming increasingly more difficult. The low-vWM load task was a delayed span task in which children saw a series of letters on the computer screen. Following the presentation of the letters a short delay occurred after which the children recalled the letters in serial order (delay condition). The medium-vWM load task involved children seeing a series of letters but between each letter a series of three to eight digits appeared in serial order (e.g., 5, 6, 7) (serial order condition). Children read aloud both the letters and digits. Following the last trial, children recalled the letters in serial order. The high-vWM load task was identical to the medium-load task except the digits were presented randomly (random order condition).

Prior to the three vWM tasks, the children completed a simple letter span task to estimate their simple STM span, which allowed the authors to present letter lists in each vWM task at one item *below* the child's simple letter span. For example, if a child had a simple span of five then he/she received vWM tasks that included four items.

The intent of this manipulation was to hold the storage demands of the vWM tasks constant across the children while varying the processing demands thereby illuminating the effects of processing load (i.e., attention control) on storage. If the children with DLD and TD children perform comparably across the vWM conditions then the interpretation would be that controlled attention does not influence the vWM capacity of children with DLD.

The first assumption of the authors was that the time taken to read the digits (processing component) in the random-order condition would take longer than in the delay or serial order conditions. Thus, greater amounts of time taken to read the digits in the medium- and high-load conditions should lead to greater disruption in switching and allocating sufficient attention to maintain the items in storage. The second assumption was that presenting vWM lists at one below the children's simple span was a sufficiently robust test of the joint deficit mechanism deficit hypothesis (however, see Engle, Fidler, & Reynolds, 1981 and Gillam, Cowan, & Day, 1994 for more conventional methods to equate groups on storage abilities).

The DLD group predictably yielded significantly poorer simple memory span than the TD group. Both groups also showed the expected decrease in letter recall as processing load increased: delay condition > serial order condition > random order condition. Interestingly, the DLD group performed comparably to the TD group across conditions, leading the authors to suggest that the vWM capacity limitation of children with DLD is due to a deficit in verbal storage.

Joint Mechanism Deficit Hypothesis. Other researchers have argued that the vWM capacity limitation of children with DLD reflects dual deficits in storage and controlled attention (Ellis Weismer et al., 1999; Marton & Eichorn, 2014; Marton et al., 2014, 2016; Montgomery, 2000). An interpretation that poor attentional control influences vWM in children with DLD is based on error analyses of children's recall (Ellis Weismer et al., 1999; Marton & Eichorn, 2014; Marton et al., 2014; 2016) and item recall as a function of processing demands (Montgomery, 2000).

Influence of Controlled Attention. Error analyses on listening span tasks have shown that, relative to same-age peers, children with DLD tend to be more affected by item interference as evidenced by their producing more intrusion errors, i.e., target words from previous trials (Ellis Weismer et al., 1999; Marton et al., 2014; Marton & Eichorn, 2014; Marton et al., 2016). Such findings suggest that children with DLD have difficulty inhibiting irrelevant information. Results of a study by Mainela-Arnold, Evans, & Coady (2010) also implicate poor inhibition, but in a slightly different way. These authors had children complete several tasks, including a vWM task and a forward gating task in which they heard small chunks of target words and then guessed what the word was after each successive chunk of a word. Performance on this task reflects children's word recognition abilities, but also inhibition in that nontarget word guesses (competitors) need to be suppressed to ensure accurate word recognition. The children with DLD performed more poorly than the TD group on both measures. Results also showed that performance on the gating task predicted vWM performance. The authors interpreted their results to mean that children with DLD have difficulty inhibiting the lingering activation of nontarget items (e.g., inhibiting words from previous trials on the vWM task), which leads to interference recalling words in the present trial.

Montgomery (2000) used a 3-tier vWM task to compare the item recall of school-age children with DLD and TD children as a function of processing complexity (i.e., controlled attention demands, which was somewhat similar to the approach used by Archibald & Griebeling 2016). Compared with TD children, children with DLD revealed reduced recall in the most demanding processing condition in which they were required to perform two mental operations-- semantically categorize and then arrange items by the physical size of the word referent in each semantic category (*bike, plane*) (*chick*, *dog*). By contrast, the groups performed comparably when asked to recall the words by semantic category regardless of word referent size (*plane, bike*) (*dog, chick*) or regardless of serial order (*dog, bike, chick*, *plane*). Interestingly, Isaki, Spaulding, and Plante (2008) provided similar results and interpretations in a study on adults with DLD. These authors reported a significant difference in item recall between a group of adults with DLD and a control group in a "high" processing load (listening span) task but not in "lower" processing load (storage/recall) tasks, i.e., digits reversed, words reversed, digits forward, and words forward. Together, the findings from these studies suggest that the verbal storage deficits of children with DLD tend to surface when the cognitive/attention demands of the processing activity reach some critical or taxing threshold, preventing the children from allocating sufficient attention to storage.

Influence of LTM on the vWM capacity in DLD. The influence of LTM on the vWM capacity limitation of children with DLD is not well understood. In the present study, we were interested in the influence of lexical knowledge on children's vWM capacity, with a focus on semantic knowledge. The basic idea here is that sensitivity to and knowledge of the to-be-remembered/recalled items affect children's memory performance. The memory literature draws the broad distinction between lexical and semantic (conceptual/meaning knowledge) aspects of words and their influence on the memorability of words (Hargreaves, Pexman, Johnson, & Zdrzilova, 2012; Lau, Goh, Yap, 2017). Lexical properties include such things as lexicality, frequency, concreteness/ imageability, and age of acquisition. Lexical effects are characterized by real words being recalled better than nonwords (Conlin & Gathercole, 2006; Hulme, Maughan, & Brown, 1991). Frequency effects are manifested by higher-frequency words being recalled better than lower-frequency words (Engle, Cantor, & Carullo, 1992; Roodenrys & Quinlan, 2000). Word concreteness/imageability are reflected by more concrete/imageable words being recalled better than abstract or low-imageability words (Campoy, Castella, Provencio, Hitch, & Baddeley, 2015; Walker & Hulme, 1994). Age of acquisition of lexical items also tends to affect their memorability and retrieval, with early-acquired words remembered better and retrieved faster than later-acquired words (Brysbaert, Van Wijnendaele, & De Deyne, 2000; Ellis & Morrison, 1998; Juhasz, 2005).

Semantic knowledge of words (e.g., meanings, word relationships) also affects item memorability and recall. Lists of semantically related words are remembered and recalled better compared with lists of unrelated words (Bourassa & Besner, 1994; Ceci & Howe, 1978; Jeffries, Ralph, & Baddeley, 2004; Poirier & Saint Aubin, 1995). Importantly, however, for both related and unrelated word lists, reactivation and recall of items (from peripheral storage/secondary memory) are aided when participants are able to create a temporal-serial binding of the items, which leads to fewer and more accessible chunks (Camos, Mora, & Oberauer, 2011; Loazia & Campos, 2018; Loazia & McCabe, 2012; Oberauer, Süß, Wilhelm, & Sander, 2007).

Lexical-semantic knowledge of children with DLD would seem to be an important factor to consider when trying to understand these children's vWM capacity limitation. Those with DLD appear to show sensitivity to various lexical properties, including lexicality (Helenius, Parviainen, Paetau, & Salmelin, 2009; Jones, Tamburelli, Watson, Gobet, & Pine, 2010), frequency (Coady, Mainela-Arnold, & Evans, 2013; German &

Newman, 2004; Mainela-Arnold et al., 2010), and age of acquisition (German & Newman, 2004). By contrast, children with DLD demonstrate both quantitative and qualitative deficits in semantic/conceptual knowledge compared with same-age peers. Children with DLD know fewer words than age peers. They also demonstrate less detailed knowledge about words, which leads to less elaborated lexical-semantic networks and weaker links among items in LTM (Capone & McGregor, 2005; Kail & Leonard, 1986; Leonard, 2014; Mainela-Arnold et al., 2010; McGregor, Newman, Reilly, & Capone, 2002; McGregor, Oleson, Bahnsen, & Duff, 2013; Sheng & McGregor, 2010). Such qualitatively poorer knowledge relates to the storage-elaboration hypothesis (Kail & Leonard, 1986; Leonard, 2014). Such underspecified knowledge, in turn, leads to lexical retrieval difficulties for these children.

We know of only two studies that have examined the potential influence of lexical LTM on the vWM performance of children with DLD. In the Mainela-Arnold et al. (2010) study described above, these authors examined the influence of semantic knowledge on the vWM performance of children with DLD and TD children. They showed that semantic knowledge was a significant predictor of the vWM performance of all of the children combined. Marton and Eichorn (2014) studied the potential role of LTM indirectly by examining whether the history of item retrieval from LTM influenced the vWM performance of children with DLD and same-age TD peers. These authors had children complete a traditional listening span task in which they recalled the sentence-final word in a set of sentences (e.g., *Kelly likes to play with her* doll). The to-be-recalled words were high-frequency and early-acquired items. Children also performed a modified listening span task in which they completed a sentence with a word of their choice (e.g., *Fred reads poems to his*__) and then recalled the last word of each sentence from the set of sentences they heard. The authors reasoned that item recall in the modified task should be better than in the traditional task because the words in the modified task already had been retrieved and should thus retain some degree of activation. Predictably, the children with DLD performed more poorly relative to same-age peers on both vWM tasks. However, contrary to the authors' prediction, neither group's recall significantly improved in the modified task. The authors took these results to mean that the recent activation of a word provides no benefit to the vWM performance of children. More generally, though, the poorer performance of the DLD group, regardless of condition, may have reflected their underspecified semantic representations.

Limitations to Our Understanding the Nature of vWM Capacity Deficits in DLD. Understanding the memory-related mechanisms that influence the vWM capacity of school-age children with DLD has been hindered in several ways. Most studies have employed small samples, potentially rendering underpowered analyses. With respect to the role of controlled attention on these children's vWM capacity, only inhibitory control has been considered. Neither sustained attention nor attention switching has received any attention as potential influences. Likewise, LTM has received little research attention as a potential influential factor. The present study overcame these shortcomings.

Motivation of the Selection of the Memory-Related Mechanisms for the Current Study

We focused on three memory-related mechanisms relevant to estimating school-age children's vWM capacity. The first was storage because of its centrality to all models of WM. Our interest was on children's ability to maintain in an accessible state as many of the items initially activated in LTM for later recall (Cowan et al., 2005, 2012; Engle, 2002; Engle et al, 1999). Controlled attention was selected given its established theoretical and empirical importance to WM. We focused on sustained attention because findings in the adult literature show that individuals who can control lapses of attention over time perform better on WM tasks relative to those with poorer control (Unsworth & Robinson, 2015, 2016, 2018). Attention switching was examined because of its importance in allowing individuals to toggle their focal attention between performing the processing activity of a WM task and maintaining items in storage (Barrouillet & Camos, 2001; Barrouillet et al., 2008; Gavens & Barrouillet, 2004). The selection of LTM (i.e., semantic knowledge) was motivated on three grounds. First, the constructs of WM and LTM are theoretically linked (Baddeley, 2012; Cowan et al., 2005, 2012, 2014; Kane et al., 2004). Second, WM and LTM empirically are shown to be one and the same from a storage perspective, i.e., items that occupy WM are the same as those that have been activated in LTM (Loaiza & Camos, 2018; Nee & Jonides, 2013; Öztekin & Cowan, 2015; Öztekin, Davachi, McElree, 2010). Third, current descriptions of the vWM capacity of children (TD and DLD) are absent any mention of the potential influence of LTM. We attempted to remedy this problem in the current study by including LTM as a factor.

Aim and Predictions of the Present Study

The aim of the present study was to understand better the memory-related mechanisms defining the vWM capacity of school-age children. We took a modeling approach to identify the influence of verbal storage, controlled attention (sustained attention, attention switching), and lexical LTM. We also employed two large groups of matched children, 117 with DLD and 117 TD children propensity matched on age, gender, mother's education, and family income, allowing us to build stable models of each group's vWM performance.

Our overall prediction was that each of the mechanisms would account for significant and unique variance in the vWM capacity of both the children with DLD and TD children. We predicted that storage should exert a strong influence in both groups because storage is at the heart of vWM capacity (Baddeley, 2012; Cowan et al., 2005; Engle et al., 1999). LTM should also play an important role based on the theoretical and empirical linkage between WM and LTM (Baddeley, 2012; Cowan et al., 2005; Loaiza & Camos, 2018; Nee & Jonides, 2013; Öztekin & Cowan, 2015; Öztekin et al., 2010). Sustained attention should play a role in enabling item activation during encoding (Miller et al., 2019) and with the maintenance of items in storage over the course of a WM task (Unsworth & Robison, 2015, 2016, 2018). Finally, attention switching should influence vWM capacity because it is attention switching that allows individuals to toggle between the processing component of a WM task and maintaining the items in storage via refreshment or rehearsal (Barrouillet & Camos, 2001; Barrouillet et al., 2008; Gavens & Barrouillet, 2004).

Method

Participants

Participants were 234 children between the ages of seven and 11 years: 117 with DLD (Age_M = 9;5) and 117 TD children (Age_M = 9;5). Children were recruited from four regions of the U.S.: Athens, Ohio; Logan, Utah; San Diego, California; and Dallas, Texas. Children were recruited through various school systems, community centers, and university-sponsored summer camps for children.

The degree of exposure to a second language was controlled, with English being the primary language spoken by all children. Similar to Bedore, Peña, Summers, Boerger, Resendiz, et al. (2012), parents provided a detailed account of their child's language use at home and school. Bedore et al. found that measures of English semantics and morpho-syntax in a large sample of bilingual kindergartners were not affected until children spoke a second language approximately 80 minutes each day. Taking a conservative approach, we excluded any child who spoke more than an average of 30 minutes of another language in the home or at school each day.

To reduce potential participant selection bias we developed a standard approach to define participants as DLD or TD and to match the groups (Montgomery et al., 2018). To define the participants as DLD or TD we used a composite z-score (see below). To match the groups thereby preventing selection bias and controlling for critical developmental and socio-economic factors known to moderate performance on cognitive tasks, we used a propensity matching procedure (see below).

Children had unremarkable medical history and no neurological impairment or emotional disturbance, based on parent report. Participants also had: (a) normal-range hearing sensitivity bilaterally for the frequencies 500 Hz through 4 kHz (American National Standards Institute, 1997); (b) normal-range articulation on the articulation subtest of the *Test of Language Development-4* (Newcomer & Hammel, 2008); and (c) typical or corrected vision. All participants had fluid reasoning scores that were broadly in the normal range on the visualization and reasoning battery of the *Leiter International Performance Scale-Revised* (Roid & Miller, 1997). Although the children in both the TD and DLD groups exhibited normal-range fluid reasoning, the children in the TD group obtained a significantly higher Leiter score than the children in the DLD group [F (1, 233) = $p < .0001$, $p\eta^2 = .17$].

Performance on four language measures determined DLD/TD classification. These were the receptive and expressive portions of the *Comprehensive Receptive and Expressive Vocabulary Test* (CREVT-E & CREVT-R; Wallace & Hammill, 1994) and the concepts and following directions subtest and recalling sentences subtest of the *Clinical Evaluation of Language Fundamentals–Fourth Edition* (CELF-4; Semel, Wiig, & Secord, 2003). The CREVT (Wallace & Hammill, 1994) is a measure of children’s receptive and expressive lexical knowledge, and the two CELF-4 (Semel et al, 2003) subtests are indices of sentence-level receptive and expressive knowledge and abilities. Because two of the subtests were standardized with deviation quotients (M = 100, SD = 15) and two were standardized with scaled scores (M = 10, SD = 3), we converted each child’s norm-referenced scores for the four subtests to z-score scale (M = 0, SD =1) representing the number of standard deviations from the mean on each subtest. From these z-scores a final mean composite z-score was then calculated for each child based on the three lowest of these four z-scores.

DLD and TD classification

Children were classified as DLD if their *mean composite language* z-score on their three lowest of the four subtests was at or below -1SD, which is consistent with the DSM-5 definition of language disorder, multi-dimensional systems for defining DLD (Leonard, 2014; Tager-Flusberg & Cooper, 1999), and other studies (Conti-Ramsden, Ullman, & Lum, 2015; Montgomery, Gillam, Evans, & Sergeev, 2017). Tomblin, Records, and Zhang (1996) reported that the overall language z-score for the children identified with the EpiSLI model was -1.14, and approximately five percent of their SLI group had average z-scores between -1 and 0. In keeping with the EpiSLI classification model, the average composite z-score for the DLD group the present study was -1.48 with a SD of .39 (range = -2.73 to -1.00). The overwhelming majority of the children in the DLD group (84.6%) had mixed receptive-expressive disorders. A few children (14.5%) exhibited expressive-only disorders, and just 1% exhibited receptive-only disorders. With respect to the language domain, 74.4% of the children performed at or below the criterion value on subtests in both lexical and sentential domains; 18.8% had difficulties on the grammatical subtests only, and 6.8% had difficulties on the lexical subtests only.

Children were defined as TD if their mean composite language z-score was *greater* than -1SD. The average composite z-score for this group was .08 (SD = .60, range = -.96 to 1.89). Relative to the DLD group, the TD group attained a significantly higher mean composite z-score [$F(1, 233) = 556.74$, $p < .0001$, $p\eta^2 = .71$]. The TD group also achieved a significantly higher score on each of the four language measures: CREVT-R [$F(1, 233) = 61.85$, $p < .0001$, $p\eta^2 = .21$]; CREVT-E [$F(1, 233) = 37.31$, $p < .0001$, $p\eta^2 = .14$]; CELF-4 concepts and following directions [$F(1, 233) = 50.29$, $p < .0001$, $p\eta^2 = .18$]; and CELF-4 recalling sentences [$F(1, 233) = 63.30$, $p < .0001$, $p\eta^2 = .21$]. Entrance test data for both groups appear in Table 1.

Table 1 about here

Propensity matching

To avoid selection bias and distortion of the results due to differences in participant enrollment, a propensity score matching procedure was used to create the DLD and TD groups from a larger pool of 383 children (127 DLD, 256 TD). Propensity matching is a quasi-experimental approach that approximates the conditions of a randomized experiment by creating control (TD) and experimental (DLD) groups balanced simultaneously on a variety of variables. Propensity scores represent the probability of assignment to either the DLD or TD group (the counterfactual condition) based on a vector of observed covariates.[1] To achieve this sample size, we oversampled TD children by a 2:1 ratio relative to the children with DLD. Using multivariate logistic regression, a single propensity score was calculated for each of the 383 children using the moderating variables of age (continuous variable), gender, mother's education level (no college degree [high school, some college but no degree] vs. college degree [Associate, Bachelors, Masters or doctorate]), and family income (annual income < $30k vs. annual income > $30k). Mother's education and family income were used as proxies for socio-economic status (Shavers, 2007). The nearest neighbor matching method was then used to match individual children with DLD to a TD counterpart. This procedure yielded 117 DLD-TD multidimensionally matched samples.[2] Subsequent nonparametric analyses indicated the groups were not significantly different with respect to age, gender, mother's education, or family income. Demographic data for the two groups appear in Table 2.

Table 2 about here

Tasks

vWM Capacity. Performance on the standardized auditory working memory subtest of the *Woodcock-Johnson III NU Test of Cognitive Abilities* (Woodcock, McGrew, & Mather, 2001) reflected children's vWM capacity. The task required children to maintain activated items in LTM in an active state while performing a

[1] A propensity score is the conditional probability of a child being enrolled in the DLD or control (TD) group given his/her key baseline characteristics (in our case, age, gender, mother's education, family income). Due to its ability to match groups on a high dimensional set of characteristics, i.e., simultaneous matching on several categorical and continuous variables, propensity score technique has become a critical statistical method in modern clinical research (Rosenbaum & Rubin, 1983, 1984; D'Agostino, 1998).

[3] Only 10 of the 127 children with DLD were excluded due to the lack of an appropriate TD match.

2-tier mental operation-- arranging items into two categories and retaining the serial order of items within each category. We used a word-level WM task instead of a listening span task because we wished to estimate children's vWM capacity independent of any sentence-level comprehension requirements, which could disadvantage the children with DLD thereby yielding an underestimate of capacity. Stimulus items included the digits 1 through 9 and 50 words (38 monosyllabic, 12 bi-syllabic). All words had an age of acquisition rating of 5.6 years or lower (mean = 4.1 years) and high ratings of imageability (> 500), concreteness (> 500), and familiarity (> 500) (Coltheart, 1981; Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012).

The test comprised seven blocks of randomly presented words and digits, with each block comprising three trials. No trial included any rhyming words or semantically related words except for the occurrence of digits, minimizing phonological and semantic interference effects. The test began with 2-item blocks and each subsequent block increased by one item up to a final block of eight items.

Procedure. Children were instructed to listen to a man saying some words and numbers (*4, orange, 1, bear*) (storage component) and then to first repeat the words in serial order (*orange, bear*) followed by the digits in serial order (*4, 1*) (processing component). A pure tone signaled the onset of each trial and two pure tones signaled children to recall the items. A block was correct if children recalled all the words in proper serial order followed by all the digits in proper serial order on at least two of the three trials. No trial repetitions were allowed. The test was discontinued when children missed all three trials within a block. The dependent variable was total number of trials correct. Children's responses were scored live and digitally recorded for later transcription, scoring, and reliability. Internal reliability, as reported in the manual, is .86. Item transcription and scoring reliability were at or above .97.

Verbal Storage. The children completed a conventional digit recall task in which they listened to lists of digits and then repeated the string of digits in same order they were presented. Each list contained a random string of digits. Each digit was 500 ms in duration and an interstimulus interval (ISI) of 500 ms separated each item within a trail. Lists ranged from two digits up to nine. The task began with 2-digit lists, with each subsequent list increasing by one item. Each list length comprised three trials. Correct recall at any given list length was defined as proper serial recall on at least two of the three trials. A pure tone signaled the onset of a list and a pair of tones signaled the children to recall the items. No stimulus repetitions were allowed. The task was stopped when the children missed all three trials at any given list length. Children's recall was scored online as well as digitally recorded for later transcription, scoring, and reliability. The dependent variable was total number of trials correct. Internal consistency reliability was .87. Item transcription and scoring reliability were at or above .97.

Auditory Sustained Attention. Children completed a conventional auditory vigilance task as an index of their ability to resist lapses of attention over time (i.e., Unsworth & Robison, 2015, 2016, 2018). The task lasted 10 minutes. Children sat at a table resting their dominant hand/fingers on a red dot located a standard distance from a keyboard. They were told that they would hear a man saying some numbers (1 through 9) and to press the space bar as quickly as they could each time they heard the 2-digit sequence *1-9*. A 500 ms ISI occurred between each digit, which corresponded to the response period during which the children made their button press. Digits were presented in random order.

The primary dependent variable was P_r, a discrimination index representing children's sensitivity to respond correctly to target items amidst a random stream of target and non-target items: $P_r = H – FA$ where H is hits and FA is false alarms. In other words, P_r reflects children's "certainty" of the occurrence of a target item by adjusting for their false alarm rate (i.e., failure to inhibit a response to a non-target). Though not a primary dependent variable, response bias (B_r) was also calculated. Response bias is the probability that children guess that a stimulus is a target when they are uncertain that it is a target: $B_r = FA/[1 – (H – FA)]$. The groups, importantly, did not differ in response bias [$F(1, 231) = 2.00$, $p = .16$, $d = -1.61$].

Reliability. Ten percent of the participants (equal numbers of children with DLD and TD children) from each of the three testing sites was selected at random to re-analyze their original data files. Agreement was 100% between the initial coding and re-analyzed coding of hit scores.

Auditory Attention Switching. This task measured children's ability to switch attention within a single task involving minimal language demands (Evans, Gillam, & Montgomery, 2018). Children were instructed to attend to the stimuli in one ear (target ear) while ignoring different stimuli in the other, and to switch attention from one ear to the other immediately upon hearing a tone in the target ear.

Stimuli. The auditory and visual stimuli were letters (A-E) and digits (1-5). Each spoken number and letter was 250 ms in duration. The visual version of the items were all 32pt Times Roman font, each a different primary color. The numbers were presented in as a small cluster in the upper center region of the touch screen and the letters in the lower center region.

Procedure. Children were told they would hear a man in one ear and a woman in the other ear and that the speakers would be talking at the same time but that each of the speakers would be saying different things (i.e., numbers or letters). The children were told they would hear a beep periodically in one ear or the other and when they did to begin paying attention to what was said in that ear. For example, children may hear in the right ear (target ear) numbers (*1, 5, 3, 2…*) and in the left ear letters (*C, A, E, D…*). Following two or more trials in the right ear, the children would hear a beep in the left ear (new target ear) and would be told to attend to the items in the new ear. The ISI between each item in a string of items was 250 ms. They were instructed to touch as quickly as possible the cluster of letters or cluster of numbers depending on what they heard in the target ear. The cluster of numbers and letters remained on the screen throughout the task. Presentation of the male/female speakers to the left/right ears was counterbalanced across children to control for any possible speaker or ear preference. There was a total of 100 trials, 22 switch trials and 78 non-switch trials. Trials included anywhere from two to nine items (numbers or letters). A fixed random order of trials was presented to the children. The primary dependent variable was percent switch trials correct.

Coding and Reliability. Switch trials were defined as those trials that occurred immediately following the "beep" signaling the children to switch ears and begin attending to the speaker in the target ear. Ten percent of the participants (equal numbers of children with DLD and TD children) from each of the three testing sites was selected at random to re-analyze the original data files. Agreement was 100% between the initial coding and re-analyzed for total switch trials correct.

Lexical LTM. The antonyms subtest of the *Comprehensive Assessment of Spoken Language* (CASL; Carrow-Woolfolk, 1999) served as the measure of children's general lexical-semantic knowledge. The test is appropriate for individuals between the ages of three and 21 years. Children were told they would hear a number of words spoken by the examiner (e.g., *right*) and to provide a word that meant the opposite of the word they heard (e.g., *wrong*). Administration and scoring followed the manual guidelines. The dependent variable was total number of items correct. The internal consistency of the test is .95.

General Procedure

Children were tested in a quiet test room. The standardized tests and experimental tasks were completed over three visits each lasting about 2.5 hours. The order of standardized assessments and experimental tasks were counterbalanced across visits and children. For the experimental tasks, the order of task and stimulus presentation were counterbalanced across participants. Stimulus delivery and response gathering for the computerized tasks were controlled by E-Prime (Schneider, Eschman, & Zuccolott, 2002). Tasks were presented under noise-reduction headphones at a listening level of dB SPL 55-75. All children successfully completed practice trials prior to moving to the experimental portion of each task.

Results

Task Performances

An omnibus multivariate analysis of covariance was performed to determine whether the groups differed on the various tasks. Due to significant group differences on nonverbal IQ, it served as a covariate to factor out its potential influence on task performance. Results revealed a significant group effect, Pillais' Trace = .25, [F (1, 231) = 14.95, $p < .0001$]. Univariate follow up testing indicated that the DLD group performed significantly worse than the TD group on the *Woodcock-Johnson* subtest (vWM) [F(1, 231) = 70.16, $p < .0001$, d = -1.05]. The DLD group also performed significantly more poorly on digit recall (verbal storage) [F(1, 231) = 25.55, $p < .0001$, d = -.93], sustained attention [F(1, 231) = 60.14, $p < .0001$, d = –.36], attention switching [F(1, 231) = 25.34, $p < .0001$, d = -.54], and on the CASL (lexical LTM) [F(1, 231) = 177.13, $p < .0001$, d = –1.3]. Finally, the DLD group performed significantly worse on the vWM task (M trials correct = 4.80) relative to the simple storage task (M trials correct = 8.69) [t (116) = 15.13, $p < .0001$]. The TD group also yielded a significantly lower score on the vWM task (M trials correct = 8.09) relative to the simple storage task (M trials correct = 11.07) [t (116) = 9.44, $p < .0001$]. Table 3 displays descriptive statistics for all of the tasks for each group.

Table 3 about here

Predicting vWM Capacity

To address the aims of this study, we conducted a series of regression analyses using verbal storage, sustained attention, attention switching, and lexical LTM as the predictors and vWM capacity as the outcome. Prior to the regressions, correlation analyses were conducted for each group separately. All of the measures significantly correlated with each other for both groups (see Supplemental Material S1 and S2 for the TD and DLD results, respectively).

TD Group. An initial univariate regression analysis was conducted using propensity score as the independent variable and performance on the vWM capacity task as the outcome to determine whether the collection of demographic variables (age, gender, mother's education, family income) accounted for any variance in the children's vWM capacity. The purpose of this analysis was determine whether these demographic characteristics of the group collectively explained any variance in vWM capacity. The initial univariate regression including just the propensity score as the predictor showed that the collection of demographic variables accounted for a nonsignificant 1.8% of the variance in children's vWM capacity [$F(1,116) = 2.05$, $p = .154$, $p\eta^2 = .01$].

A second univariate regression determined the total amount of variance in vWM capacity contributed by verbal storage, sustained attention, attention switching, and lexical LTM (excluding propensity score). Jointly, all of the predictors accounted for 43.9% of the variance in vWM capacity (adjusted $R^2 = .419$), [$F(4,116) = 21.90$, $p < .0001$, $p\eta^2 = .44$]. Multiple linear regression next identified the amount of unique variance accounted for by each of the predictors. Step 1 included verbal storage, step 2 included storage followed by sustained attention, step 3 included storage and sustained attention followed by attention switching, and step 4 included all the previous variables followed by lexical LTM. Verbal storage contributed 19.6% of significant/unique variance. Controlled attention accounted for an additional 8.4% of significant/unique variance, with sustained attention contributing 5.4% of unique variance and attention switching another 3.0% of unique variance. Lexical LTM accounted for 16.0% of significant/unique variance. The regression results for the group appear in Table 4.

Table 4 about here

DLD Group. The initial univariate regression that included just the propensity score as the predictor showed that the collection of demographic variables accounted less than 1% of the variance was accounted for by these variables [$F(1,116) = .001$, $p = .987$, $p\eta^2 = .001$]. Results of the second univariate regression revealed that all of the predictors in combination accounted for 26.5% of the variance in the children's vWM capacity (adjusted R^2 = .239) [$F(4,116) = 10.09$, $p < .0001$, $p\eta^2 = .28$]. Results of the multiple linear regression showed that verbal storage accounted for a significant/unique 13.7% of the variance in the children's vWM capacity. Controlled attention accounted for 7.3% of significant/unique variance, with sustained attention accounting for all of the variance (6.5%); attention switching accounted for less than 1% of the variance (0.008%). Lexical LTM contributed 5.6% of significant/unique variance. Table 5 displays the regression results for the DLD group.

Table 5 about here

Interaction Analysis. We performed an additional multiple linear regression to assess a possible group interaction with the predictors (verbal storage, sustained attention, attention switching, lexical LTM) in predicting children's vWM capacity. Group (TD, DLD) was the dichotomous variable. The model included single interactions between the group variable and each of the predictors. There were significant main effects for verbal storage and LTM. In addition, the interaction between group and LTM was significant. Results of these analyses appear in Table 6. We knew the four predictor variables were correlated with each other to some degree. Due to possible effects of multicollinearity, we ran an additional model (Table 5 in Supplemental Material (S3)) that incorporated the LTM and group interaction as well as additional three-way interactions with each of the other predictor variables, LTM and group. The significant main effects for verbal storage and LTM remained. As with the single-interaction analysis, only the two-way interaction between group and LTM was significant.

In all the models, both verbal storage and LTM predicted vWM capacity, but LTM interacted with group whereas storage did not. For storage, a 1 point increase was associated with a .24 increase in vWM capacity. For LTM, a 1 point increase was associated with a .25 increase in vWM capacity in the TD group, but only a .13 increase in the DLD group. As depicted in Figure 1, children in the TD group had higher LTM scores to begin with, and stronger LTM scores were associated with significantly higher vWM capacity scores compared with the DLD group. The R scripts of the regression analyses appear in Supplemental Material (S3).

Table 6 and Figure 1 about here

Discussion

Compared with the TD children, the children with DLD exhibited significantly reduced vWM capacity, as measured by performance on the Auditory Working Memory subtest of the *Woodcock-Johnson Cognitive Battery*. Likewise, the DLD group demonstrated significantly poorer verbal storage than the TD group, consistent with previous findings in the DLD literature (e.g., Archibald & Gathercole, 2007; Briscoe & Rankin, 2009; Coady & Evans, 2008; Montgomery, 1995). Relative to the TD group, the DLD group also exhibited significantly poorer sustained attention, as demonstrated by poor performance on a conventional vigilance task (e.g., Spaulding et al., 2008; Victorino & Schwartz, 2015). The DLD group also showed poorer attention switching than their TD peers. To our knowledge, these results are the first to show that children with DLD have difficulty switching their attentional focus within the same task, not just across different tasks (e.g., Henry et al., 2012; Im-Bolter, Johnson, & Pascual-Leone, 2006). We should note, though, that our task switching required children to switch their attention to different target ears and to ignore (suppress) material in the non-target ear, which could have led to interference and poorer task performance. However, the ability to suppress potentially distracting stimuli appeared to be task dependent for children with DLD. For example, relative to TD peers, these children have proved to be no more distractible when performing flanker tasks (Arbel & Donchin, 2014) or visual search tasks (Das & Äystö, 1994) but they have shown greater distractibility on linguistic tasks (Marton, Kelmenson, & Pinkhasova, 2007; Seiger-Gardner & Brooks, 2008). Thus, we cannot conclude with certainty whether the children's poorer performance on our switching task primarily reflected an attention switching difficulty or difficulties with switching and suppressing distractor material.

The Joint Mechanism Deficit Hypothesis is the Better Account of the vWM Capacity Deficit in DLD

For the TD children, verbal storage, controlled attention, and lexical LTM together explained about 44% of variance in their vWM capacity. Verbal storage accounted for nearly half of the total variance (19.6%) while controlled attention and lexical LTM together explained the other half. For the children with DLD, verbal storage, controlled attention, and lexical LTM together explained about 27% of the total of variance in their vWM capacity, just under half the amount of variance observed in the TD group. For the DLD group, like the TD group, verbal storage accounted for the most variance (13.7%). Controlled attention accounted for the next most variance (7.3%). However, sustained attention accounted for all of the variance; attention switching explained no significant variance. These findings differ from the TD group for whom both sustained attention <u>and</u> attention switching were important. Finally, lexical LTM accounted for the least amount of variance (5.6%) in the vWM capacity of the DLD group, which is in stark contrast to the TD group for whom LTM accounted for nearly three times the amount of variance (19.6%). Overall, the findings for the DLD group supported the joint mechanism deficit account over the storage-only deficit account of their vWM capacity deficit. Our findings, more broadly, also supported our prediction that each of the mechanisms should influence the children's vWM capacity. For the TD group, the findings supported our expectations about the general order of the influence of the different mechanisms. However, for the DLD group, this was not the case.

The Role of Verbal Storage. Perhaps not surprisingly, storage exerted quite a strong influence on the vWM capacity of the children with DLD and TD children. These findings suggest that storage capacity in and of itself is an important influence on children's vWM capacity. That the children with DLD exhibited a simple storage deficit and that storage was the largest contributor to their vWM capacity is consistent with the view that storage deficits are a major factor defining these children's vWM capacity limitation (e.g., Archibald & Gathercole, 2007; Briscoe & Rankin, 2009). It is worth noting that we did not find a significant storage by group interaction, indicating that the importance of storage to vWM did not differ for the TD and DLD groups.

The Role of Controlled Attention. For the children with TD, both sustained attention and attention switching significantly contributed to their vWM capacity, with sustained attention explaining a bit more variance than attention switching. Only sustained attention significantly influenced the vWM capacity of the DLD group, attention switching did not. However, recall that the tests of the interaction between sustained attention and vWM were not significant. These results suggest that the importance of controlled attention to the vWM capacity was similar for the children with DLD and TD children. The finding that sustained attention was important to the vWM capacity of both groups is consistent with findings in the adult memory literature showing that the ability to control lapses of attention on a trial-by-trial basis aids WM performance (Unsworth & Robison, 2015, 2016, 2018) thereby promoting stronger activation of items at encoding (Unsworth, 2009).

The importance of attention switching to vWM relates to maintaining items in storage in an accessible state for later recall (Camos, Mora, & Oberauer, 2011; Loaiza & Camos, 2018; Loaiza & McCabe, 2012; Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010). Maintaining items in storage can occur through two different attention-demanding mechanisms, refreshment or rehearsal. Refreshment involves "thinking about" the stored items after each processing episode (in our case, categorizing input items into words and digits) to keep them in an active state (Camos, Mora, & Oberauer, 2011; Chen & Cowan, 2009; Loaiza & Camos, 2018; Loaiza & McCabe, 2012). Refreshment is not yet fully understood (Mora & Camos, 2015), but appears to be related to maintaining representations in an active state through attentional focusing (Johnson, 1992). Refreshment seems to be especially relevant to maintaining the semantic representations of items by establishing temporal-contextual bindings among the items (Loaiza & Camos, 2012; 2018; Loaiza, McCabe, Youngblood, Rose, & Myerson, 2011; Nishiyama, 2018; Oberaurer, 2005), especially for semantically unrelated items (Higgins & Johnson, 2013). In the context of the present study, the children heard random strings of digits and words. Refreshment provides cues at retrieval to aid individuals in recalling series of items. Refreshment appears to be available to children by age 7-8 years (Mora & Camos, 2015). Verbal rehearsal, by contrast, maintains the phonological form of items (Camos et al., 2011; Loaiza & Camos, 2018; Mora & Camos, 2013) thereby facilitating the retrieval of individual items, not a series of bound items, but only if the number of items does not exceed memory capacity (Jarrold & Hall, 2013; Tam et al., 2010). Developmentally, rehearsal is available by age 7-8 years (Gathercole, 1999; Henry, Messer, Luger-Klein, & Crane, 2012). However, as was the case for sustained attention, the tests of the interaction between attention switching and vWM were not significant. These results, too, suggest that the importance of attention switching to the vWM capacity of the children with DLD and TD children was similar.

The Role of Lexical LTM. Lexical LTM played a significant role in the vWM capacity of both the children with DLD and TD children, supporting the claims of a tight relationship between WM and LTM (Cowan et al., 2012; Loaiza & Campos, 2018; Loaiza & McCabe, 2012; Oberauer & Hein, 2012; Towse et al., 2008; Unsworth & Engle, 2007). However, this relationship was statistically different for the two groups. In the TD group, lexical knowledge explained about 16% of the variance in vWM capacity, whereas in the DLD group it accounted for almost three times less variance (5.6%). Further support for the differential role of lexical LTM between the groups comes from three other sources. First, the semi-partial correlation between LTM and vWM (Tables 4 and 5) was almost twice as large in the TD group (r = .47) than in the DLD group (r = .27). Second, the difference between the groups in semantic knowledge was very large (Cohen's d = -1.30). Third, and most important, results of the interaction regression analyses revealed that higher lexical LTM scores were associated with significantly higher vWM capacity scores in the TD group compared with the DLD group. Together, such findings strongly implicate lexical LTM as a major constraining factor defining the vWM capacity limitation of children with DLD and the one factor that clearly discriminates children with DLD from TD children.

How might LTM constrain the vWM capacity of children with DLD? There are a few possibilities. The first, relates to the lexical properties of the test items. The memory literature indicates that sensitivity to such properties as age of acquisition, imageability, and concreteness affect the memorability and recall of words. We might argue that the children with DLD had sensitivity to these three lexical properties of the test items, as the items had a mean age of acquisition rating of 4.6 years as well as high imageability and concreteness ratings. Word frequency and phonotactic characteristics, however, are two properties that may have affected the memorability and recall of the DLD group, properties we could not account for in the present study. Compared with same-age peers, the vWM performance of children with DLD is affected disproportionately by the presence of lower-frequency words than higher-frequency words (Mainela-Arnold & Evans, 2005).

A second possibility relates to the semantic knowledge of the test items by children with DLD. Relative to same-age TD mates, children with DLD have underspecified lexical representations manifested by knowledge of fewer details about words as well as less elaborated lexical networks containing weaker links among items (Kail & Leonard, 1986; McGregor McGregor et al., 2002, 2013; Sheng & McGregor, 2010). The consequence of such weak knowledge is that lexical retrieval is difficult for these children. It is reasonable to assume that our children with DLD had impoverished semantic representations. These representations likely led to weaker initial activation of the input items during encoding. Weaker activation coupled with the inability to refresh or rehearse the stored items during the course of a trial would in turn lead to item decay.

A third possible lexical factor pertains to the nature of the children's phonological representations. Children with DLD have more poorly specified phonological representations compared with same-age peers (e.g., Alt & Plant, 2006; Gray, 2005). Weak phonological representations may have also affected the children's encoding, storage, and retrieval of items (e.g., Mainela-Arnold & Evans, 2005).

Conclusions

The current study demonstrated that the vWM capacity limitation of school-age children with DLD related to the joint effects of reduced verbal storage, difficulties with controlled attention (especially attention switching) , and weak lexical LTM. These findings support the joint mechanism deficit account of these children's vWM capacity limitation. The present findings, especially the finding of weaker relationships between lexical LTM knowledge and vWM in the DLD group as compared to the TD group, provide substantively new insights into these children's vWM functioning.

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Table 1. *Mean (M) standard scores and standard deviations (SD) on the norm-referenced test measures administered to the children with developmental language disorder (DLD) and typically developing (TD) children.*

Measures	**DLD** (N= 117)	**TD** (N= 117)	**Cohen's *d***
Fluid Reasoning			
Leiter [1]			
M	98	110	-0.77
SD	13	14	
Range	76 - 139	76 - 141	
Lexical			
CREVT-R [2] Receptive			
M	87	105	-1.22
SD	9	11	
Range	62 - 112	81 - 146	
CREVT-R [3] Expressive			
M	81	101	-1.32
SD	10	12	
Range	54 – 101	69 - 134	
Sentential			
CELF-4 Concepts & Direct [4]			
M	6	11	-1.33
SD	3	2	
Range	1 - 13	6 - 15	
CELF-4 Recalling Sent [5]			
M	5	10	-1.51
SD	2	2	
Range	1 - 11	4 - 18	
Qualifying z-score [6]			
M	-1.49	0.08	-.3.10
SD	0.39	0.60	
Range	-2.73 – -1.0	-.96 – 1.89	

Notes

[1] Leiter-R: Average standard score on four nonverbal subtests (Figure Ground, Form Completion, Sequential Order, and Repeated Patterns) from the Visualization and Reasoning Battery of the Leiter International Performance Scale-R (Mean = 100, SD = 15)

[2] CREVT-R: Comprehensive Expressive-Receptive Vocabulary Test-Revised, Receptive (Mean = 100, SD = 15)

[3] CREVT-R: Comprehensive Expressive-Receptive Vocabulary Test-Revised, Expressive (Mean = 100, SD = 15)

[4] CELF-4 Concepts & Directions: Clinical Evaluation of Language Fundamentals- 4th Ed (Mean = 10, SD = 3)

[5] CELF-4 Recalling Sentences: Clinical Evaluation of Language Fundamentals-4th Ed (Mean = 10, SD = 3)

[6] Qualifying z-score: Average z-score on the three lowest lexical and sentential measures

Table 2. *Participant demographics for the children with developmental language disorder (DLD) and typically developing (TD) children.*

Demographic	**DLD** (N= 117)	**TD** (N= 117)
Age$_M$ (years; months)	9;6	9;6
Gender		
Male	57%	63%
Female	43%	36%
Race and Ethnicity		
White (Not Hispanic)	61%	72%
African American	10%	0%
Hispanic	12%	12%
Asian	4%	4%
American Indian, Native Hawaiian	3%	3%
More than one race	10%	9%
Mother's Education		
No Response	1%	1%
High School Degree	20%	16%
Some College	30%	27%
Associate Degree	17%	11%
Bachelor Degree	24%	23%
Graduate Degree	6%	20%
Family Income		
0 – 25,000k	42%	32%
26,000k – 50,000k	21%	22%
51,000k – 75,000k	16%	15%
> 75,000k	21%	31%

Table 3. *Summary scores on the memory-related measures for the children with developmental language disorder (DLD) and typically developing (TD) children, and Cohen's d (standardized mean difference) between the groups.*

	Group		
Measure	DLD (N= 117)	TD (N= 117)	Cohen's *d*
VERBAL WORKING MEMORY			
WJ-AWM [1]			
M Trials	4.8	8.1	-1.05
SD	2.8	3.4	
Range	0 - 11	0 - 17	
M Span	2.6	3.8	
SD	1.2	1.3	
Range	0 - 5	0 - 8	
VERBAL STORAGE			
Digit Recall [2]			
M Trials	8.7	11.1	-.93
SD	2.1	3.0	
Range	3 - 14	2 - 19	
M Span	3.8	4.7	
SD	.75	1.1	
Range	2 - 6	2 - 8	
ATTENTION CONTROL			
Sustained Attention [3]			-.36
M (P_r)	.76	.82	
SD	.19	.14	
Range	.10 -1.0	.26 - 1.0	
Attention Switching [4]			-.54
M	79.0	86.4	
SD	15.2	12.2	
Range	42 -100	14 -100	
LEXICAL LTM			
CASL [5]			-1.30
M	23.2	31.4	
SD	6.1	6.5	
Range	7 - 38	14 - 46	

[1] Auditory Working Memory: Woodcock-Johnson III (Total trials recalled, Span)
[2] Digit Recall (Total trials recalled)
[3] Sustained Attention (P_r discrimination index: P_r = Hits - False Alarms)
[4] Attention Switching (Percent switch trials correct)
[5] Antonyms subtest of the Comprehensive Assessment of Spoken Language (Total items score)

Table 4. *Summary of general linear model predicting verbal working memory capacity of the typically developing children. Verbal storage, sustained attention (SA), attention switching (AS) and lexical long-term memory (LTM) as predictors. Model 1 includes storage only, Model 2 includes storage and sustained attention, Model 3 includes storage, sustained attention, and attention switching, and Model 4 includes storage, sustained attention, attention switching, and LTM.*

	Model 1		Model 2		Model 3		Model 4	
Predictors	β	S.E.	β	S.E.	β	S.E.	β	S.E.
Storage	0.500***	0.094	0.434***	0.095	0.439***	0.093	0.246**	0.089
SA			5.783**	2.027	4.484*	2.083	0.894	1.953
AS					5.211*	2.405	3.492	2.153
LTM							0.253***	0.045
R^2	.196***		.249**		.279*		.439***	
Adj R^2	.189***		.236**		.260*		.419***	
F value	27.99***		18.93***		14.59***		21.90***	
Partial Correlation	.442***		.258**		.200*		.471***	

Note. β = unstandardized Beta value, S.E. = standard error, R^2 = R square (coefficient of determination), Adj R^2 = Adjusted R square (adjusted coefficient of multiple determination), F value = probability value, and Partial Correlation.

* Significant at $\alpha < .05$ (two-tailed)

** Significant at $\alpha < .01$ (two-tailed)

*** Significant at $\alpha < .001$ (two-tailed)

Table 5. *Summary of general linear model predicting verbal working memory capacity of the children with developmental language disorder using verbal storage, sustained attention (SA), attention switching (AS) and lexical long-term memory (LTM) as predictors. Model 1 includes storage only, Model 2 includes storage and sustained attention, Model 3 includes storage, sustained attention, and attention switching, and Model 4 includes storage, sustained attention, attention switching, and LTM.*

	Model 1		Model 2		Model 3		Model 4	
Predictors	β	S.E.	β	S.E.	β	S.E.	β	S.E.
Storage	0.511***	0.120	0.377**	0.124	0.367**	0.124	0.233	0.129
SA			3.971**	1.308	3.245*	1.472	2.392	1.455
AS					1.965	1.835	0.568	1.840
LTM							0.134**	0.046
R^2	.137***		.201**		.209		.265**	
Adj R^2	.129***		.187**		.188		.239**	
F value	18.19***		14.35***		9.96***		10.09***	
Partial Correlation	.370***		.274**		.100		.266**	

Note. β = unstandardized Beta value, S.E. = standard error, R^2 = R square (coefficient of determination), Adj R^2 = Adjusted R square (adjusted coefficient of multiple determination), F value = probability value, and Partial Correlation.

* Significant at α < .05 (two-tailed)

** Significant at α < .01 (two-tailed)

*** Significant at α < .001 (two-tailed)

Table 6. *Summary of general linear models predicting auditory working memory with a group interaction. The predictors are verbal storage, sustained attention (SA), attention switching (AS), lexical long-term memory (LTM), and group. All main effects are included in each model. The models differ by including group moderation of each predictor, in turn.*

	Model 1 Verbal Storage		Model 2 Sustained Attention		Model 3 Attention Switching		Model 4 Lexical LTM	
Predictors	β	S.E.	β	S.E.	β	S.E.	β	S.E.
Main Effects								
Storage	0.292***	0.083	0.251***	0.073	0.254***	0.072	0.240**	0.072
SA	1.677	1.178	2.468	1.794	1.768	0.175	1.703	1.161
AS	1.608	1.403	1.612	1.410	3.881	2.034	1.924	1.397
LTM	0.198***	0.032	0.196***	0.032	0.198***	0.032	0.254***	0.040
Group	0.482	1.417	0.246	1.704	2.588	2.197	2.488	1.488
Interactions with Group								
Group x Storage	-0.143	0.143						
Group x SA			-1.421	2.097				
Group x AS					-4.108	2.561		
Group x LTM							-0.125*	0.053
R^2	.494		.493		.498		.504	
Adj R^2	.481		.480		.485		.491	
F value	37.01***		36.83***		37.53***		38.49***	

Note. β = unstandardized Beta value; S.E. = standard error; R^2 = R square (coefficient of determination); Adj R^2 = Adjusted R square (adjusted coefficient of multiple determination); F value = probability value.

* Significant at $\alpha < .05$ (two-tailed)
** Significant at $\alpha < .01$ (two-tailed)
*** Significant at $\alpha < .001$ (two-tailed)

Figure 1. *Verbal working memory score (total trials correct) as a function of long-term memory (LTM) knowledge (total items correct) for the children with developmental language disorder (DLD) and typically developing (TD) children.*