Working, declarative, and procedural memory in children with developmental language disorder

Ms Emily Jackson[1] (Corresponding Author)
Emily.Jackson@postgrad.curtin.edu.au
A/Prof Suze Leitão[1]
S. Leitão@exchange.curtin.edu.au
Dr Mary Claessen[1]
M.Claessen@curtin.edu.au
Dr Mark Boyes[2]
Mark.Boyes@curtin.edu.au

[1]School of Occupational Therapy, Social Work, and Speech Pathology, Curtin University, WA, Australia
[2]School of Psychology, Curtin University, WA, Australia

Corresponding author:
Ms Emily Jackson
Postal address: School of Occupational Therapy, Social Work, and Speech Pathology
GPO Box U1987, Perth, WA, 6845
Telephone: +61450472525
Email: Emily.Jackson@postgrad.curtin.edu.au

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Abstract

Purpose: Previous research into the working, declarative, and procedural memory systems in children with developmental language disorder (DLD) has yielded inconsistent results. The purpose of this research was to profile these memory systems in children with DLD and their typically developing peers.

Method: One hundred and four 5 to 8-year-old children participated in the study. Fifty had DLD and 54 were typically developing. Aspects of the working memory system (verbal short-term memory and verbal working memory, and visual-spatial short-term memory) were assessed using a nonword repetition test and subtests from the Working Memory Test Battery for Children. Verbal and visual-spatial declarative memory were measured using the Children's Memory Scale, and an audio-visual Serial Reaction Time task was used to evaluate procedural memory.

Results: The children with DLD demonstrated significant impairments in verbal short-term and working memory, visual-spatial short-term memory, verbal declarative memory, and procedural memory. However, verbal declarative memory and procedural memory were no longer impaired after controlling for working memory and nonverbal IQ. Declarative memory for visual-spatial information was unimpaired.

Conclusions: These findings indicate that children with DLD have deficits in the working memory system. While verbal declarative memory and procedural memory also appear to be impaired, these deficits could largely be accounted for by working memory skills. The results have implications for our understanding of the cognitive processes underlying language impairment in the DLD population; however, further investigation of the relationships between the memory systems is required using tasks that measure learning over long-term intervals.

Key words: *working memory, declarative memory, procedural memory, developmental language disorder*

Introduction

Developmental language disorder (DLD) is a neurodevelopmental condition in which language problems occur in the absence of a known biomedical condition, intellectual disability, or acquired brain injury (Bishop et al., 2017). DLD has a prevalence rate of approximately seven percent, and may co-occur with motor coordination disorder and Attention-Deficit/Hyperactivity Disorder (Bishop et al., 2017; Norbury et al., 2016). Hallmark features of DLD include impairments in morphosyntax (e.g., use of past tense verb forms; Leonard, 2014), and a body of literature also highlights deficits in vocabulary development (e.g., see Kan & Windsor). However, it is important to note that DLD is characterised by a heterogeneous profile of linguistic and cognitive abilities due to the complex aetiological basis of the disorder, which involves interactions between various genetic and environmental risk factors (Bishop, 2006; Pennington, 2006).

A body of research has explored the idea that language problems in DLD are related to memory impairments (for reviews, see Montgomery et al., 2010; Ullman et al., 2019). Specifically, the working, declarative, and procedural memory systems have been the focus of research, and while individual variation must be acknowledged, the research generally supports the hypothesis that the procedural and working memory systems are impaired in children with DLD, while the declarative memory system remains intact (i.e., the Procedural Deficit Hypothesis; Lum & Conti-Ramsden, 2013; Ullman, 2013; Ullman & Pierpont, 2005). In this study we aimed to replicate and extend the findings of previous research that has examined the relationships between these three memory systems in children with DLD (Lum & Bleses, 2012; Lum et al., 2010; Lum et al., 2012) in order to contribute to the knowledge base regarding the cognitive underpinnings of language impairments in this disorder.

The relationship between the working, procedural, and declarative memory systems

Evidence demonstrates the existence of neural systems for working, declarative, and procedural memory that are at least partly distinct, yet interacting (Baddeley, 2003; Squire, 2004; Ullman, 2004). The working memory system supports the short-term storage and processing of information and, according to Cowan's account, involves a 'focus of attention' which holds a limited number of items, which are an activated subset of long-term memories (Cowan, 1995; Lum et al., 2012). Baddeley, on the other hand, proposes a model for the working memory system that subsumes multiple components, including the central executive, which coordinates and controls information processing in the phonological loop, visuospatial sketchpad, and episodic buffer (Baddeley & Hitch, 1974; Baddeley, 2012). The phonological loop and visuospatial sketchpad are slave mechanisms responsible for temporary storage of verbal and visuospatial information, respectively, while the episodic buffer binds information from multiple sources to form chunks of information for further processing (such as transference to long-term memory). Similar to Cowan's 'focus of attention', the central executive in Baddeley's model underpins these processes and has a limited attentional capacity (Baddeley, 2003).

In line with research by authors such as Alloway et al. (2009), Archibald (2018), and Gray et al. (2017), in the present study we adopt the term 'verbal short-term memory' to refer to the capacity for hearing and temporarily storing phonological material (i.e., in the phonological loop) with no secondary processing involvement. This component is typically measured using simple span tasks, such as serial recall of digits or nonwords that increase in length (Estes et al., 2007; Henry & Botting, 2016). 'Verbal working memory' is distinguished by the involvement of concurrent processing activity in the central executive (Archibald & Gathercole, 2006a). While verbal short-term memory tasks involve minimal processing demands, verbal working memory tasks engage both storage and secondary processing (Freed et al., 2012). For instance, backward digit recall tasks involve the brief retention of verbal information plus additional processing, to complete the higher-order cognitive task of repeating digits in reverse order. Research supports the distinction between verbal short-term memory and verbal working memory abilities (e.g., see Gray et al., 2019), which highlights the importance of exploring these as distinct yet related processes. Finally, we use the term 'visual-spatial short-term memory' to refer to the temporary storage of visual or spatial information (i.e., in the visuospatial sketchpad; Baddeley, 2012), which is measured using simple storage tasks (e.g., pattern recognition and pattern recall; Vugs et al., 2013).

While the working memory system maintains information "… in the order of seconds, declarative and procedural memory support long-term knowledge, and can store information for years" (Lum et al., 2012, p. 1139). Procedural memory is involved in the implicit acquisition, consolidation, and automatisation of cognitive, perceptual, and motor skills (West et al., 2017). Learning in this system typically requires multiple exposures to lay down the pattern, but once complete, the processes can be carried out with relative automaticity (Lum & Conti-Ramsden, 2013). On the other hand, declarative memory involves explicit (conscious) learning, storage, and retrieval of knowledge for semantic and episodic information (Lum & Conti-Ramsden, 2013). Knowledge can be encoded quickly from a brief instance, but is strengthened through consolidation, and with repeated opportunities to re-encode from the environment (Lum et al., 2015). The 'Declarative/Procedural Model' has been proposed to describe the involvement of these systems in language development. Specifically, procedural memory is thought to underlie the acquisition and use of grammar, particularly rule-based grammatical forms (e.g., regular past tense), and may also support the learning of regularities in language including morphological and phonological forms (Ullman, 2004). The declarative system is proposed to be responsible for aspects of learning lexical information; specifically, in the binding of conceptual, phonological, and semantic representations (Lum et al., 2010). Declarative memory may also play a compensatory role in grammar development in the face of impaired procedural memory (Ullman & Pierpont, 2005).

While working, declarative, and procedural memory have been explored as distinct systems, there is also evidence of their interactions (Quam et al., 2018; Ullman, 2004). The working memory system is suggested to function as a 'gateway' for storing, organising, and retrieving material from long-term memory (Lum & Bleses, 2012). Specifically, research demonstrates evidence of a close relationship between working and declarative memory, particularly for the processes of encoding and retrieving information (Lum et al., 2015). Working memory supports encoding by temporarily storing novel stimuli as they are encountered, and also works to re-organise or chunk information prior to being encoded into declarative memory (Blumenfeld & Raganath, 2006). Furthermore, evidence from fMRI studies shows that brain regions underlying working memory are activated during declarative memory recognition tasks, supporting the notion that this system works as a temporary hold to monitor information retrieved from declarative memory (Cabeza et al., 2002; Simons & Spiers, 2003). In contrast, the relationship between working memory and procedural memory systems is less well understood; however, there is evidence that the basal ganglia and its associated circuitry (which underlies the procedural memory system), is also involved in the function of working memory (Ullman et al., 2019). This relationship has been demonstrated through various neuroimaging studies in typically developing and language-disordered populations (e.g. see Menon et al., 2000). However, further research is required to behaviourally examine the influence of working memory on learning during procedural memory tasks (Quam et al., 2018).

Working, procedural, and declarative memory in DLD

A body of research provides evidence that children with DLD have an impaired ability to process verbal information in the working memory system (Archibald, 2017; Henry & Botting, 2016; Montgomery et al., 2010). Notably, however, most findings relate to group averages in empirical studies, and there is evidence that approximately 20-25% of individuals with DLD may be unaffected (Alloway et al., 2009; Lum et al., 2015). Groups of children with DLD tend to perform poorly on verbal short-term memory tasks (i.e., those that impose storage demands only; Archibald & Gathercole, 2006b). Findings of impaired task performance on measures such as digit recall and nonword repetition have been well-replicated; however, the effect for nonword repetition in children with DLD tends to be larger than for digit recall (Archibald & Gathercole, 2006a). This nonword repetition deficit is shown to be highly heritable in DLD, and as such is considered a reliable phenotypic marker of the disorder (Bishop et al., 1996). It is likely that the nonword repetition deficit reflects impairments in verbal short-term memory, as well as in other factors related to phonological processing, such as sensitivity to the phonological structure of words (Edwards & Lahey, 1998). Additionally, the nonword repetition deficit in children with DLD highlights the interdependent relationship between the working memory system and long-term memory. On many tasks evaluating the working memory system, the stimuli are familiar (e.g., digits), and so these items may activate in long-term memory to support temporary retention (Archibald, 2018). On nonword repetition tasks, the stimuli do not exist as complete chunks in long-term memory; however, segments of the stimuli (such as strings of phonemes and syllables) may be well-established. Children with limited vocabulary knowledge, however, have reduced quality of stored phonological representations in their lexical stores to support temporary processing in short-term memory (and subsequent production of the items), and as such they are subject to facing higher working memory load and poorer nonword repetition performance (Archibald, 2018; Munson et al., 2005). It is important that research with DLD populations includes both digit recall and nonword repetition tasks to capture the potential effects of the different processing demands underlying these tasks.

There is evidence that children with DLD also exhibit deficits on more complex processing tasks (e.g., backwards digit recall) that engage verbal working memory (Gray et al., 2019; Henry & Botting, 2016). The observed deficit across verbal short-term and working memory tasks has been named a ‘dual deficit’ (Archibald & Gathercole, 2006a), which describes an underlying impairment in the phonological loop capacity and in the use of flexible processing resources of the central executive (Archibald & Gathercole, 2006a; Baddeley, 2003; Ellis Weismer et al., 1999). However, this dual deficit has not been consistently found: some research has highlighted intact verbal working memory in children with DLD but impaired verbal short-term memory (Archibald & Griebeling, 2016; Freed et al., 2012; Lum et al., 2015).

The visual-spatial domain of the working memory system has been less-well investigated than the verbal domain for children with DLD. A body of research points to intact visual-spatial storage in these children (e.g., see Alloway et al., 2009; Archibald & Gathercole, 2006a; Archibald & Gathercole, 2006b, 2007b; Lum et al., 2012); however, other research highlights a significant impairment (see Vugs et al., 2013 for a meta-analysis). Additionally, longitudinal research demonstrates a slower pattern of development for visual-spatial storage in children with DLD (Hick et al., 2005). These findings support the suggestions that DLD is associated with more general limitations across verbal and visual-spatial domains within the working memory system, but further investigation is required.

As an extension of the Declarative/Procedural Model of language, Ullman and Pierpont (2005) proposed the Procedural Deficit Hypothesis (PDH) to provide an account for memory deficits underlying the general profile of language impairments observed in DLD. The central claims of the PDH are that children with DLD have a core deficit in procedural memory, which underlies their hallmark impairment in grammar (Conti-Ramsden et al., 2015). Within this framework, the working memory system is also posited to be impaired as a result of its reliance on similar brain structures as the procedural system (as described above). Declarative memory, however, is theorised to remain intact, which would result in generally spared lexical processing (Ullman et al., 2019). There is considerable evidence of an impaired procedural memory system in children with DLD that emerges from research using a range of tasks (Krishnan et al., 2016). Most frequently, procedural memory has been assessed in children with DLD using serial reaction time (SRT) tasks (Nissen & Bullemer, 1987). These task paradigms usually emphasise visuomotor sequence learning, and typically involve repeated exposure to a visual stimulus on a computer display. Participants are required to select a target item from the visual stimulus, and reaction times are measured. Stimulus presentations usually follow a predefined sequence, and learning is indicated by reaction times decreasing across multiple exposures to the sequenced stimuli (Krishnan et al., 2016). Other measures of procedural memory include those that tap learning in the verbal domain, such as artificial grammar learning tasks and speech-stream tasks (Obeid et al., 2016).

Lum et al. (2014) conducted a meta-analysis of eight studies that used visuomotor SRT paradigms, which revealed a significant impairment in the groups of children with DLD compared to control groups (with a small effect size of 0.33). However, there was considerable variability among study findings. Six of the eight included studies reported statistically non-significant between-group differences, likely due to issues with statistical power (i.e., resulting from small sample sizes). Age of participants moderated performance (studies with younger children yielded larger effect sizes), as did the number of exposures to the stimulus sequences (i.e., there were smaller group differences in studies that provided a higher number of training exposures; Lum et al., 2014). More recently, Obeid et al. (2016) conducted an updated meta-analysis and found similar results. Across 14 studies that used a range of visuomotor and auditory-verbal procedural learning tasks (e.g., SRT tasks, artificial grammar, and probabilistic classification), children with DLD showed significantly poorer performance in comparison to control groups (effect size of 0.47). Contradictory to Lum et al., (2014), Obeid et al. (2016) did not find a relationship between age and task performance. Obeid et al. (2016) suggested that this may have been because the original effect was relatively weak, or because performance on different types of procedural memory tasks may develop differently with age. Furthermore, task modality did not moderate the effect sizes, with similar deficits in performance observed on tasks that were verbal or non-verbal in nature. It is clear that the pattern of performance on procedural memory tasks is complex, with varied factors influencing performance, and that further research with larger sample sizes is required (Obeid et al., 2016; West et al., 2017). Across these two meta-analyses, the influence of working memory on task performance was not investigated, which is a factor that may further contribute to task performance (Ullman, 2004). If performance on procedural memory tasks can be accounted for by working memory abilities, it could call into question whether the task adequately taps procedural memory, or whether performance is confounded by a reliance on the working memory system to aid the learning of sequences across trials (Hedenius, 2013). It may also be the case that procedural memory itself is unimpaired in children with DLD, but that problems with the short-term processing of information in working memory impedes the acquisition of skills in the procedural memory system (Krishnan et al., 2016).

With regards to declarative memory, the PDH predicts that this system is spared in children with DLD (Ullman & Pierpont, 2005). This has been well-supported with respect to learning in the nonverbal or visual-spatial domain (Bavin et al., 2005; Lum et al., 2012; Lum et al., 2010; Riccio et al., 2007). For instance, children with DLD tend to perform comparably on tasks requiring them to learn and recall visual and spatial information, such as dot locations or paired picture associates (Bavin et al., 2005; Cohen, 1997). In contrast, some research indicates that children with DLD perform poorly on declarative memory tasks involving verbal information (Lum & Conti-Ramsden, 2013, for a meta-analysis). Notably, however, after controlling for verbal short-term and working memory abilities, these deficits are usually not apparent (Lum et al., 2015). This pattern was demonstrated by Bishop and Hsu (2015), whereby children with DLD (and groups of age and grammar-matched peers) took part in a verbal declarative learning task (learning novel vocabulary items). The children with DLD performed poorly at the initial block of learning, and performance was predicted by verbal short-term memory scores. While their vocabulary learning scores remained below their age-matched peers over subsequent sessions, both groups made similar gains across sessions (Bishop & Hsu, 2015). These findings indicate that initial encoding in verbal declarative learning is impaired for children with DLD, but that declarative memory itself may be intact (Cabeza et al., 2002; Bishop & Hsu, 2015; McGregor et al., 2013; Records et al., 1995). It is important that research examines the impact of verbal short-term and working memory skills when examining declarative memory in children with DLD in order to unpack whether an apparent declarative memory deficit may be accounted for by impairments within the working memory system (Lum et al., 2015).

The interactions between the working, procedural, and declarative memory systems are complex, yet only a handful of studies have examined all three systems in the same cohort of children with DLD (Lum et al., 2010; Lum et al., 2012; Lum & Bleses, 2012). In this series of studies, groups of children with DLD (ages ranging 5.6 to 11.4 years), and their age-matched typically developing peers were assessed on a variety of measures of the working, declarative, and procedural memory systems. There is some inconsistency between the study findings. For instance, Lum et al. (2010) observed statistically significant group differences on the verbal declarative memory task, even after controlling for receptive vocabulary and nonword repetition scores. Similarly, Lum et al. (2012) found that the children with DLD had significantly poorer verbal declarative memory performance, and the group difference remained significant after controlling for performance on a battery of working memory tasks (but with a smaller effect size). In two of the studies (Lum et al., 2010; Lum et al., 2012), the groups of children with DLD performed significantly less accurately than their peers on the SRT task (i.e., procedural memory), and Lum et al. (2012) went on to demonstrate evidence of this impairment even after holding working memory constant. In contrast, Lum and Bleses (2012) found that the children with and without DLD performed comparably on the SRT task. Given the small sample size, these null findings may have resulted from individual variation in memory impairment in children with DLD, and the fact that the sampled children had impairments only in expressive language (whereas other studies sampled children with severe deficits across expressive and receptive domains; Lum et al, 2010; Lum et al., 2012). These findings form an important foundation for exploring the relationships between the working, declarative, and procedural memory systems, and provide a strong motivation for further research.

The current study

The aims of the current research were to replicate and extend findings of Lum and colleagues by exploring the working, declarative, and procedural memory systems in a large cohort of children with and without DLD (Lum et al., 2010; Lum et al., 2012; Lum & Bleses, 2012). In line with the

Procedural Deficit Hypothesis and with the findings of previous literature, we predicted that children with DLD would demonstrate significant deficits on the measures of verbal short-term memory, verbal working memory, and visual-spatial short-term memory. Additionally, we expected that children with DLD would perform poorly on a measure of procedural memory (an audiovisual SRT task), even after controlling for working memory abilities, which would indicate a deficit in procedural memory that cannot be accounted for by working memory problems. Furthermore, we predicted that children with DLD would demonstrate unimpaired declarative memory skills in the visual-spatial domain. Based on extant literature, we predicted that verbal declarative memory performance would be poor in the DLD group, but that a deficit would no longer be apparent after controlling for verbal short-term memory and verbal working memory (which would indicate that the declarative memory system itself is intact).

Method

Procedure

Following ethics approval, the researcher met with head teachers at two specialist language schools and three mainstream schools to discuss the research and obtain consent. Teachers for Year 1 and 2 classrooms distributed letters and consent forms to the parent or caregiver of eligible students. General eligibility criteria included that the child spoke English as a dominant language and had no significant problems with articulation or behaviour. Additionally, children with a biomedical diagnosis such as Autism Spectrum Disorder, Down syndrome, or sensori-neural hearing loss were not eligible to participate in the current study (Bishop et al., 2017). Informed consent was obtained from each participant's parent or caregiver prior to testing.

Participant Selection Measures

Participants were individually assessed on a range of measures to confirm inclusion in the study. A hearing screen was conducted using a Grason-Stadler GSI 39 (Version 3) Pure Tone portable audiometer with a cut-off level set at 25dB at 250, 500, 1000, 2000, 4000, and 8000Hz (Doyle, 1998). The DEAP Diagnostic Screen (which has high test-retest reliability, $r = .94$ and strong content and concurrent validity; Dodd et al., 2002) was individually administered to participants to briefly evaluate the presence of difficulties in the areas of articulation, phonology, and oro-motor ability. The task involves labelling pictures, and any errors in phoneme production were identified. The Core Language subtests from the Clinical Evaluation of Language Fundamentals, fourth edition (CELF-IV; Semel et al., 2006b) were administered to evaluate overall oral language ability and to confirm inclusion in the study. The Core Language Score is derived from performance across four subtests: Concepts and Following Directions, Word Structure, Recalling Sentences, and Formulated Sentences. This composite score is used to make decisions about the presence or absence of a language disorder. It provides a measure of a range of oral language abilities, including interpreting oral directions, recalling and imitating sentences, using morphological rules, and formulating grammatically and semantically correct sentences (Semel et al., 2006b). The Primary Test of Nonverbal Intelligence (PTONI) was administered to evaluate nonverbal intelligence (IQ), and has strong reliability (e.g., internal consistency of r = .90 to .95) and validity (Ehrler & McGhee, 2008). The task was designed for use with young children and requires them to examine a series of pictures and point to the item that does not belong in the series (Ehrler & McGhee, 2008).

Participants

One hundred and four children participated in the present study: 50 with DLD (36 boys, 14 girls) and 54 with typically developing (TD) language (30 boys, 24 girls). The mean age for the DLD group was 6 years, 11 months and for the TD group was 6 years, 10 months. Demographic information and performances on the participant selection measures for each group are presented in Table 1.

Table 1 about here

DLD Group

The participants for the DLD group were recruited from two publicly-funded specialist language development schools in the metropolitan area of Perth, Western Australia. These children had already been clinically diagnosed as having DLD six to 24 months prior to participation in the current study. This clinical diagnosis process involved assessment from a speech-language pathologist with evidence of the following criteria: scores of at least 1.25 standard deviations below the mean on the Core Language Score, Receptive Language Index, and/or Expressive Language Index on the CELF (either the Preschool or Fourth Edition, depending on the age of the child); and poor performance on norm-referenced measures of expressive grammar and narrative retell (e.g., the Bus Story; Renfew, 2010). At the time of initial diagnosis, informal teacher and parent developmental and behavioural questionnaires were also completed to gather information about each child's functional communication and social/emotional development. A diagnosis was supported by evidence that the child's language difficulties were having a functional impact on communicative success and academic progress (Bishop et al., 2017). To confirm diagnosis, the children were also assessed by a registered psychologist and did not fall within the 'intellectual disability' range, as indicated by a standard score of above 70 on the Wechsler Intelligence Scale for Children (Wechsler, 2016).

Upon their recruitment to the current study, each child was re-evaluated on a small battery of measures by the primary investigator to confirm their current suitability for inclusion in the DLD group. The criteria outlined by Bishop et al. (2017)[1] were used: each child was required to attain a composite standard score of 85 or less on the Core Language subtests of the CELF-IV (see Table 1 for descriptive statistics, aggregated by group). This criterion has high sensitivity (1.00) and specificity (0.82) for identifying the presence of a language disorder (Semel et al., 2006b). As part of their enrolment at the language school, the children with DLD were subject to routine oral language assessments. Thus, if participants had been assessed using the CELF-IV within 12 months prior to the study, their Core Language Score was obtained and this assessment was not re-administered. Additionally, participants were not excluded based on low-range nonverbal IQ scores; however, in line with Bishop et al.'s (2017) criteria for DLD classification, there were no participants who achieved a standard score of 70 or below on the PTONI (Ehrler & McGhee, 2008).

TD Group

The children participating in the TD group were recruited from three mainstream schools in the same region and with similar demographic profiles as the specialist language schools. Participation in the TD group was confirmed by demonstrating test scores consistent with typical language development,

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[1] At the commencement of the current study, the publication of the CATALISE research had recently become available (Bishop et al., 2017). As such, these updated criteria were followed to ensure the children selected as participants would suitably represent DLD in the context of the literature on this population.

as indicated by a Core Language Score of 86 or above. TD participants were also required to score above 70 on the PTONI. The application of these selection criteria resulted in groups that were comparable in age but significantly different in oral language skills (see Table 1 for results of independent sample *t*-tests). Of note, the groups were also significantly different on the PTONI; therefore, these scores were controlled for in statistical analyses to ensure group effects on the memory analyses were not a result of differences in nonverbal IQ.

Experimental Measures

Aspects of the working, declarative, and procedural memory systems were assessed using well-validated measures.

The Working Memory System

Three subtests from the Working Memory Test Battery for Children (WMTB-C; Gathercole & Pickering, 2001) were administered. These subtests have high reliability and validity (e.g., inter-tester reliability: $r = .86 – .90$; Gathercole & Pickering, 2001). Verbal short-term memory was assessed using the ‘Digit Recall’ task, which involves hearing, temporarily storing, and repeating random strings of digits that increase in length. Verbal working memory was evaluated using ‘Backwards Digit Recall’, in which the child listens to a string of digits and repeats them in reverse order. Visual-spatial short-term memory was tested using the ‘Block Recall’ subtest, which involves the child sitting in front of an array of randomly-placed blocks. The examiner taps the blocks (an increasing number of blocks are tapped as the test progresses) and then child taps the blocks in the same order (Gathercole & Pickering, 2001). Standard scores (standardised to a mean of 100 and standard deviation of 15) were used in the analyses.

In addition, verbal short-term memory was evaluated using the Nonword Repetition Test (Dollaghan & Campbell, 1998). This task involves the child hearing, encoding, temporarily storing, and then recalling nonwords that increase in length. The stimuli were pre-recorded in accordance with the guidelines for pronunciation outlined by Dollaghan and Campbell (1998) and were played to participants via noise-cancelling head phones. Participant responses were scored on-line using the Percentage of Phonemes Correct (PPC) method, and were audio recorded for later checking and re-scoring. Scoring procedures outlined by Dollaghan and Campbell (1998) were followed. A trained research assistant (a speech-language pathologist and PhD student) independently re-scored 20% of the nonword repetition tasks and high reliability between scorers was found (*r* = .96).

Procedural Memory

Procedural memory was evaluated using an audio-visual SRT task developed by Kuppuraj et al. (2018). This SRT task was designed to measure implicit sequence learning in procedural memory, and it tests learning of two types of statistical dependencies: adjacent deterministic (i.e., patterns that follow the same, fixed sequence) and adjacent probabilistic (i.e., where certain sequences of trials occur more frequently than others, but do not follow a fixed sequence; Hsu & Bishop, 2014). In the 2018 study, the task was administered to adult participants, and high reliability and validity was demonstrated (full details regarding task design and administration with adults can be viewed in Kuppuraj et al., 2018). Subsequently, the task was adapted for use with young children with and without DLD (Kuppuraj, 2018).

The task was administered individually through the MATLAB program (Higham & Higham, 2010) and took approximately 30 minutes. The participant sat in front of a Microsoft Surface Pro 4 and held the accompanying stylus pen. Drawing from a bank of 61 monosyllabic common nouns (see Appendix), six triplet sequences were created to use as stimuli for the learning task. Two of the triplets were adjacent deterministic sequences, two triplets were adjacent probabilistic sequences, and two were random (i.e., control) sequences (which did not follow a sequence). Full details regarding the construction of task sequences are presented in Kuppuraj et al. (2018).

The SRT task involved eight blocks of testing. The first six blocks of testing involved presentation of the six triplet sequences in pseudorandomised order. The participant listened as the first two items in a triplet were presented singly on the screen and named (using a synthesised British English voice). Then, the third item (the target) in the triplet sequence was presented in an array of four images, with the voiceover saying the name of the target noun. The participant was required to select the target from the array as quickly as possible using the stylus pen on the screen. Learning was indexed by measuring reaction times (i.e., how quickly the target item was selected in each triplet sequence). For adjacent deterministic and probabilistic sequences, reaction times were expected to decrease across the six learning blocks in comparison to the reaction times for random triplets, indicating that the patterns had been implicitly learned. In the seventh and eighth blocks of testing, the deterministic and probabilistic patterns were interrupted: the first two nouns in a previously-patterned sequence were followed by a new noun. Reaction times were expected to increase to reflect the break in anticipated sequence (Kuppuraj et al., 2018).

The top left corner of the screen displayed visual rewards (coloured pictures) for faster responses to the target stimuli. A practice set with 20 items was presented prior to the eight blocks of training to familiarise participants with the image-name pairs and the method of selecting the target image using the stylus pen. Participants were not informed that patterns would occur but were encouraged to select the stimuli as quickly as possible (see Appendix for task script). Participants were allowed a break of up to two minutes at a time between blocks.

Data extraction for the SRT task involved the following procedure (Kuppuraj, 2018). At the individual level, two slopes were extracted for both the deterministic and probabilistic sequences: 1) the reaction time slope for the initial learning phase (i.e. across the first six testing blocks); 2) the reaction time slope for the phase when the pattern was broken (i.e., the seventh and eighth blocks). For both of these sequence types, the regression discontinuity method was used to yield a *t*-statistic[2] which indicated if there was a significant difference in the two slopes. It was expected that the slope would decrease across the initial learning phase, with a rebound in the slope for the phase when the pattern was broken. This pattern was interpreted as evidence that learning had occurred. A *t*-statistic was calculated for each child for the deterministic and probabilistic conditions to quantify evidence of learning. A higher *t*-statistic suggested that the participant's reaction time increased in the phase where the pattern was broken, relative to the initial patterned phase. Two scores (a deterministic *t*-statistic and probabilistic *t*-statistic) were yielded for use in the analyses.

There were significant technological issues that impacted the administration of the SRT; namely, the program crashed when administering the task to 25 of the participants. After the program crashed, it was not possible to resume the task from the point where testing was interrupted. To avoid practice effects and the risk of collecting invalid data, the task was not re-administered in these cases,

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[2] The *t*-statistic demonstrates the ratio of difference between the slope for the learning phase and the slope for the phase when the pattern was broken.

and partial data could not be used in the analyses. As such, we report the SRT results for a subset of the sample. SRT data were available for 79 cases (38 for the DLD group, and 41 for the TD group). Descriptive statistics on relevant measures for the group of children whose SRT data were analysed are presented in Supplementary Materials. There were no significant differences between the group of children whose data were included versus the group of children whose SRT data were excluded in age (t[102] = 0.30, p = .77), oral language skills (t[102] = 0.84, p = .41), nonverbal IQ skills (t[102] = -0.03, p = .98), Nonword Repetition (t[102] = 0.01, p = .99), Digit Recall (t[102] = 0.80, p = .43), Backwards Digit Recall (t[102] = 1.65, p = .56), or Block Recall (t[102] = -0.58, p = .49).

Declarative Memory

Declarative memory for verbal and visual information was tested using two subtests on the Children's Memory Scale (CMS), which has high reliabilty and validity (e.g., reliabiltiy coefficients: *r*s = .76 to .91; Cohen, 1997). The Word Pairs subtest evaluates declarative memory for verbal information, and involves the child hearing a list of 14 semantically-unrelated word pairs (e.g., nurse-fire). The first word in a pair is provided, and the child is required to recall the second word. This process is repeated across three trials and the total number of correctly recalled words summed across the trials provides a *Learning* score. The child then recalls as many word pairs as possible without prompting (this score is summed with the *Learning* score to create a *Short Recall* score). After approximately 30 minutes, the child is asked again to recall all word pairs (*Delayed Recall*). Finally, they are presented with the 14 word pairs alongside 14 distractor pairs and indicate whether they recognise the word pair from the initial learning session (*Delayed Recognition*).

The Dot Locations subtest was used to measure visual-spatial (nonverbal) declarative memory (Cohen, 1997). This task involves the child looking at a picture of randomly placed dots three times. After each exposure, the picture is removed and the child recreates the picture using small tokens (*Learning*). After a distractor picture, the child is asked to recreate the initial picture (that they had seen three times) from memory. This score is summed with the *Learning* score to create a *Total Score*. Approximately 30 minutes later, the child recreates the same picture using the tokens (*Long Delay*). Standard scores (standardised to a mean of 10 and standard deviation of 3) were calculated for each of the Word Pairs and Dot Locations scores and were used in the analyses (Cohen, 1997).

Results

A series of MANOVA procedures were conducted to examine between-group differences across measures of working, procedural, and declarative memory. As noted in the Method, nonverbal IQ significantly differed between the groups. Furthermore, there were significant correlations between nonverbal IQ and each of the memory constructs (correlations are reported in Supplementary Materials). As such, each MANOVA was re-run as a MANCOVA (with nonverbal IQ entered as a covariate), in order to ensure group differences were due to language status and not nonverbal IQ abilities. Further exploratory MANCOVAs were run to explore the relationships between the memory systems, and are detailed below. The main effects of the MANOVA and MANCOVAs are reported in Table 2. Summary scores (aggregated by group) for the memory measures and post-hoc tests for each analysis are included in Tables 3, 4, and 5. Full tables including the effects of the covariate factors are included in Supplementary Materials.

Working Memory

Four measures of the working memory system were included in the MANOVA: Nonword Repetition, Digit Recall, Backwards Digit Recall, and Block Recall. A significant multivariate effect of group was obtained for working memory; Wilks' $\lambda = .42$, $F(4, 99) = 33.79$, $p < .001$, partial $\eta^2 = 0.58$. Critical α level was set at .0125 for univariate analyses. Children with DLD performed significantly worse across all four measures of working memory, all with large effect sizes (see Table 3; Cohen, 1988). This analysis was re-run with the inclusion of nonverbal IQ as a covariate. The MANCOVA showed a significant multivariate group effect with a large effect size, Wilks' $\lambda = .49$, $F(4, 98) = 25.40$, $p = .001$, partial $\eta^2 = 0.51$ (see Table 2). Post-hoc univariate tests revealed significant differences on all subtests after controlling for nonverbal IQ, with a small-to-medium effect for visual-spatial short-term memory and large effects for the verbal measures (see Table 3).

Finally, to further explore the presence of a 'dual deficit' in both verbal short-term and working memory abilities (Archibald & Gathercole, 2006b), an ANCOVA was conducted to test whether children with DLD demonstrated significantly impaired Backwards Digit Recall performance (i.e., verbal working memory) after controlling for Nonword Repetition and Digit Recall scores (verbal short-term memory). The results showed a significant main effect for group, $F(1, 100) = 9.43$, $p = .003$, partial $\eta^2 = 0.09$.

Table 2 about here

Table 3 about here

Procedural Memory

A MANOVA was run to determine the effect of group on SRT performance. Two measures of procedural memory were included in the analysis: the deterministic pattern learning *t*-statistic and probabilistic pattern learning *t*-statistic. A significant multivariate effect of group was obtained with a large effect size; Wilks' $\lambda = .87$, $F(2, 76) = 5.59$, $p = .005$, partial $\eta^2 = 0.13$ (see Table 4). Follow-up univariate post-hoc tests, with a critical α level set at .025, revealed significant group differences for deterministic learning with a large effect size. No significant group difference was found for probabilistic learning. Examination of the group means indicates that both groups performed close to floor level on this aspect of the SRT task; therefore, these non-significant group differences must be interpreted with caution as they may result from a lack of variability in performance due to task demands being too high for both groups of children.

In a follow-up MANCOVA, nonverbal IQ was included as a covariate. There was a significant multivariate group difference; Wilks' $\lambda = .92$, $F(2, 75) = 3.34$, $p = .041$, partial $\eta^2 = 0.08$. Post-hoc univariate tests showed a significant group difference for deterministic, but not for probabilistic, pattern learning (see Table 4). Given that procedural memory may rely on working memory (Ullman & Pierpont, 2005), and given the significant correlations between working and procedural memory scores (*r*s ranged from .20 to .66; see Supplementary Materials), a single composite variable of all working memory scores was created ('General WM') using principle components analysis. This lead to the creation of a single factor for use in the analysis. The solution explained 59.54% of the total variance. The factor loadings were: Nonword Repetition = .68, Digit Recall = .71, Backwards Digit Recall = .65, and Block Recall = .34. The MANCOVA with the General WM factor included as a covariate yielded no significant multivariate group effect; Wilks' $\lambda = .98$, $F(2, 75) = 0.81$, $p = .449$, partial $\eta^2 = 0.02$ (see Table 2). A final MANCOVA with nonverbal IQ and the General WM as covariates also yielded a non-significant main effect.

Table 4 about here

Declarative Memory

Visual Declarative Memory

Three scores for the Dot Locations subtest were included in the analysis: *Total*, *Learning*, and *Long Delay*. The MANOVA showed no statistically significant multivariate group effect; Wilks' $\lambda = .96$, $F(3, 100) = 1.46$, $p = .23$, partial $\eta^2 = 0.04$. Critical α level was set at .017 (to account for the three dependent variables) for univariate analyses. There were no significant group differences for any of the three aspects of visual declarative memory (see Table 5). These differences remained non-significant when controlling for nonverbal IQ.

Verbal Declarative Memory

Four Word Pairs scores were included in the MANOVA: *Total*, *Learning*, *Delayed Recall*, and *Delayed Recognition*. There was a significant multivariate effect of group; Wilks' $\lambda = .63$, $F(4, 99) = 14.46$, $p < .001$, partial $\eta^2 = 0.37$. Critical α level was set at .0125 for univariate analyses. The post-hoc univariate tests yielded significant group differences, with large effect sizes, on all aspects of the verbal declarative memory task (see Table 5).

In a follow-up analysis, nonverbal IQ was included as a covariate to account for the potential influence of nonverbal IQ differences on verbal declarative memory performance. There was a significant multivariate group difference; Wilks' $\lambda = 0.74$, $F(4, 98) = 8.58$, $p < .001$, partial $\eta^2 = 0.26$. Post-hoc univariate analyses showed significant between-group differences for Word Pairs *Total*, *Delayed Recall*, and *Delayed Recognition* (all with large effect sizes); however, there was no significant difference for *Learning* (see Table 5).

The Word Pairs subtest involves the temporary storage of verbal information, and so observed group differences may be accounted for by verbal short-term and working memory deficits (Lum et al., 2015). There were significant correlations (*r*s ranged from .28 to .66) between each aspect of Word Pairs performance and verbal short-term memory and working memory measures (Nonword Repetition, Digit Recall, and Backwards Digit Recall). As such, a single composite variable of verbal short-term and working memory ('Verbal ST/WM') was computed using principal components analysis, which lead to the extraction of a single factor. The three measures accounted for 71.70% of the variance in the Verbal ST/WM factor. The factor loadings were: Nonword Repetition = .77, Digit Recall = .71, and Backwards Digit Recall = .68. The MANCOVA with the inclusion of the Verbal ST/WM factor included as a covariate yielded a significant multivariate group effect, though with a smaller effect size than the analogous model (see Table 5). Results of the post-hoc testing revealed that there was only a significant group difference for Delayed Recognition after controlling for the Verbal ST/WM factor (partial $\eta^2 = 0.09$). Finally, both nonverbal IQ and Verbal ST/WM factors were included in the model and the group effect was no longer significant.

Table 5 about here

Discussion

This study aimed to investigate the working, declarative, and procedural memory systems in a cohort of five to eight-year-old children with and without DLD. Collectively, the results show a complex profile of impairment across the memory systems, with working memory abilities largely accounting for the observed deficits on the declarative and procedural memory tasks.

Working Memory

The group of children with DLD exhibited impaired verbal short-term memory and verbal working memory in comparison to the TD group, even when controlling for nonverbal IQ. This is consistent with evidence from a range of studies indicating that children with DLD often exhibit impaired processing for verbal information in the working memory system (Estes et al., 2007; Henry & Botting, 2016; Montgomery et al., 2010). Groups of children with DLD have consistently exhibited significant impairments in the simple storage of verbal information, as evidenced by poor performance on tasks such as nonword repetition and digit span (Alloway et al., 2009; Archibald & Griebeling, 2016; Archibald & Gathercole, 2007b; Baird et al., 2010; Duinmeijer et al., 2012; Lum et al., 2012). Evidence for deficits in verbal working memory, however, has been less clear. While many studies have identified impaired verbal working memory (e.g., backwards digit recall) performance in children with DLD (e.g., Alloway et al., 2009; Baird et al., 2010; Hutchinson et al., 2012; Marini et al., 2014), others found performance to be in the average range (Archibald & Griebeling, 2016; Freed et al., 2012; Lum et al., 2015). The results of the current study showed that children with DLD exhibited a verbal working memory deficit even after controlling for scores on verbal short-term memory tasks, providing support for the notion of a dual deficit in both the phonological loop capacity and the secondary processing requirements of the central executive (Archibald & Gathercole, 2006a; Baddeley, 2012). Of note, while verbal short-term and working memory impairments are often emblematic of children with DLD, some children (i.e., approximately one quarter; Archibald & Joanisse, 2009) may not demonstrate a deficit in this area. The current research, along with the body of previous research, examined performance according to group averages, and further work should explore individual variation in working memory performance (Bishop, 2006).

Notably, the results revealed large effect sizes for all three verbal short-term and working memory measures; however, the effect size for Nonword Repetition was considerably greater (partial $\eta^2 = 0.48$) than for Digit Recall (partial $\eta^2 = 0.19$) and Backwards Digit Recall (partial $\eta^2 = 0.05$). This likely reflects the bidirectional relationship between long-term memory (in this case, existing vocabulary knowledge) and working memory (Munson et al., 2005), and further supports the use of nonword repetition as a sensitive clinical marker of DLD (Conti-Ramsden et al., 2001). While nonword repetition reflects verbal short-term memory capacity and the influence of long-term memory, additional phonological processes are likely involved, such as phonological sensitivity and analysis (Bishop et al., 1996; Duinmeijer et al., 2012); however, specific measures of these processing skills were not included in the current study and should be further investigated.

In the current study, children with DLD also demonstrated significant impairment in visual-spatial short-term memory after controlling for nonverbal IQ. This is consistent with a body of research evidencing impaired visual-spatial storage capacity in children with DLD (Vugs et al., 2013; Yim et al., 2016); however, these impairments have not always been found (Archibald & Gathercole, 2006b; Ellis Weismer et al., 2017; Henry et al., 2012; Hutchinson et al., 2012; Lum et al., 2012; Petruccelli et al., 2012). The current study had a relatively large sample size, and was therefore sufficiently powered to yield a significant group difference. Many previous studies have been more limited in sample size, and so issues with power may have led to non-significant findings (Vugs et al., 2013). This is an issue that may be compounded when sampling children from a population with inherently heterogeneous cognitive development (Pennington, 2006). The disparity among previous findings may also reflect participant factors, with Vugs et al. (2013) highlighting the relationship between oral language severity and deficits in the visual-spatial domain of the working memory system. Given the severity of the oral language deficits in the group of children with DLD in the current study, it is possible that we sampled a ‘subgroup’ of this heterogeneous population that are more likely to exhibit both verbal and visual-spatial storage problems (Nickisch & Von Kries, 2009).

Evidence suggests that there may not be a meaningful difference between performance on tasks measuring simple visual-spatial processing in working memory (such as Block Recall as in the current study) and tasks that include a secondary component that engages additional processing or manipulation (i.e., ‘visual-spatial working memory’; Archibald, 2018; Gray et al., 2017). Therefore, we did not specifically include a task that might tap visual-spatial working memory. Additionally, the task battery already involved a substantial time commitment for each child. However, further research should explicitly examine performance on these tasks in order to further develop an understanding of the cognitive profile of children with DLD, such as whether there may be a ‘dual deficit’ for visual-spatial skills (Vugs et al., 2013). Our findings lend support to a domain-general deficit account for DLD, which proposes that children with DLD tend to demonstrate deficits within the working memory system that affect processing of both verbal and visual-spatial information (Archibald, 2017; Henry & Botting, 2016).

Procedural memory

The children with DLD were impaired at the audio-visual SRT procedural memory task, even after removing the variance associated with nonverbal IQ. This finding is consistent with a body of research highlighting impaired procedural memory in groups of children with DLD (Desmottes et al., 2016; Lum et al., 2014; Obeid et al., 2016). Of note, in the current study the group difference was found to be significant only when learning deterministic patterns, but not probabilistic patterns. This aligns with previous research showing that children may perform differently depending on whether they are learning deterministic or probabilistic sequences (Gabriel et al., 2011); however, it is important to note that in the current study, the groups of children likely performed similarly for probabilistic sequences as a result of the task demands being too high (i.e., both groups performed close to floor level, as detailed in the Results). Further refinement of this version of the SRT task is needed to reduce task demands and potentially unmask group differences, and to improve issues related to task administration that resulted in the loss of data for this task.

Neurological evidence links procedural memory with working memory via shared neural structures (e.g., the basal ganglia; Squire & Dede, 2015), yet there is little behavioural evidence of the relationship between these two systems in children with DLD (Conti-Ramsden et al., 2015). In the current study, the group difference for procedural memory was no longer significant after controlling for the working memory factor. This suggests that an apparent procedural learning deficit for children with DLD could be accounted for by working memory impairments, and challenges the notion of a core procedural memory deficit in DLD, as per the Procedural Deficit Hypothesis (Ullman, 2013). However, we are cautious of over-interpreting these results given that our SRT task measured learning over a relatively short timeframe (i.e. 30 minutes). As such, while this SRT task was designed to reflect learning in the procedural memory system, performance in this group of children appears to more strongly reflect processing of the verbal and visual-spatial stimuli in working memory, rather than long-term retention and retrieval of information from procedural memory (Lum et al., 2010; others). It is also possible that this version of the SRT task afforded children the opportunity to use working memory strategies to bolster performance. That is, the child was instructed to select the third item in the patterned triplet as quickly as possible. If children became aware of repeated and predictable patterns, this may have resulted in the sequenced patterns being called into explicit awareness, thus engaging the working memory system (Ashby & Maddox, 2011; Ullman, 2013).

Notably, a handful of studies have also examined procedural memory while controlling for working memory (Conti-Ramsden et al., 2015; Hedenius, 2013; Lum et al., 2012). Contrary to the current findings, these studies identified impaired procedural memory performance in the children with DLD, even after accounting for working memory. Individual variation in cognitive abilities likely contributes to variation in findings across studies (Bishop, 2006; Pennington, 2006). Additionally, the use of different versions of the SRT task may account for these inconsistencies. Specifically, the version of the SRT used in the current study involved an auditory-verbal component, whereas the previous studies used an SRT task limited to the visuo-motor domain (Conti-Ramsden et al., 2015; Hedenius, 2013; Lum et al., 2012). It is likely that the auditory component of our task resulted in higher engagement of the working memory system to support performance (Karuza et al., 2013). Future studies should aim to use measures of procedural memory that include training over longer learning intervals in order to further unpack the complex interactions between working and procedural memory in children with DLD.

Declarative memory

Children with DLD demonstrated intact visual declarative memory. These results are supportive of the PDH (Ullman & Pierpont, 2005), and are consistent with a body of research showing intact declarative memory for visual-spatial information in groups of children with DLD (e.g., Baird et al., 2010; Bavin et al., 2005; Lum & Conti-Ramsden, 2013; Lum et al., 2012; Lum et al., 2010; Riccio et al., 2007). In contrast, the children with DLD exhibited impaired verbal declarative memory compared with their peers, and this pattern remained after controlling for nonverbal IQ. However, these group differences were no longer apparent after controlling for the verbal short-term/working memory factor and nonverbal IQ. This is consistent with Ullman and Pierpont's (2005) model, which posits that observable verbal declarative memory deficits are secondary to verbal working memory impairments.

A small body of research has explored the relationship between the verbal working and declarative memory systems in children with DLD. The current results were consistent with Lum and Bleses (2012), who found that group differences on a verbal paired associates task were no longer significant after accounting for verbal working memory. Similarly, Lum et al. (2015) found that verbal declarative memory was only significantly impaired in a group of children with DLD who had low verbal working memory. These findings are also consistent with Bishop and Hsu's (2015) suggestions that verbal declarative learning in children with DLD is impacted by deficits in the initial encoding of verbal information in the working memory system, but that retention in declarative memory itself remains intact. However, the results are inconsistent with those of Lum et al. (2010) who found significant group differences on verbal declarative memory remained after controlling for verbal short-term memory abilities (nonword repetition skills), receptive vocabulary, and nonverbal IQ scores. It is not clear the relative contribution of these varied factors on verbal declarative memory performance, and further should systematically examine the unique impact of each of these variables on verbal declarative memory.

The current findings shed light on the relationship between the working and declarative memory systems for verbal learning, and provides further evidence that working memory supports the initial encoding of information, as well as recall of information from declarative memory (Blumenfeld & Ranganath, 2006; Cabeza et al., 2002). The relationship between declarative and working memory should be systematically explored in further research. Specifically, most research has evaluated declarative learning using relatively short learning and retrieval tasks (e.g., involving a 30-minute delay; Cohen, 1997); however, further research should explore whether children with DLD also experience deficits in the later stages of declarative learning (Lukacs et al., 2017; McGregor et al., 2013).

Conclusions

Overall, the findings of the current study highlight deficits in the working memory system for young children with DLD in both the verbal and visual-spatial domains. Additionally, the findings are somewhat supportive of the Procedural Deficit Hypothesis; visual declarative memory appears to be intact in children with DLD, and verbal declarative memory impairments appear to be accounted for by verbal short-term and working memory and nonverbal IQ. However, the results show that working memory accounted for procedural memory performance, which offers a potential challenge to the notion of a core deficit in procedural memory for children with DLD.

This study is one of a small number of studies that has simultaneously investigated working, declarative, and procedural memory systems in a group of children with DLD (Lum et al., 2010; Lum et al., 2012; Lum & Bleses, 2012). We acknowledge that a potential limitation arises from sampling the children with DLD from a specialist language school. As a result, these children may have had a more severe presentation of DLD than those attending mainstream schools. Previous research suggests that memory impairments may be related to the severity of oral language deficits (e.g., see Archibald, 2017), and so further research could further explore this in order to build understanding of cognitive variation in the disorder. Future research is also required to substantiate the pattern of findings from the current study using a more comprehensive battery of tasks (e.g., including tasks that tap visual-spatial working memory). Further research should also explore the implications of these findings for teaching and intervention programmes. While the impact of verbal short-term and working memory deficits on language development are well-documented, particularly for vocabulary acquisition (e.g. see Montgomery et al., 2010 for a review), problems with visual-spatial storage in the working memory system may further compound language learning difficulties (Archibald & Gathercole, 2006b; Vugs et al., 2016). For instance, visual-spatial storage may contribute to success in vocabulary development, especially when the novel words can be linked with a visual referent (e.g., when learning the name of a new object). That is, mapping the physical features of the visual referent to the phonological form of new words is likely facilitated by visual-spatial processing within the working memory system (Gray et al., 2020). Functionally, a combination of deficits in short-term and working memory for verbal and visual-spatial information may therefore have a significant impact on the ability to learn language (Gathercole, 2006).

While working memory intervention is the subject of controversy (Melby-Lervag et al., 2016; Sala & Gobet, 2017), it is crucial that further research evaluate methods for effectively teaching and training children with DLD using strategies that minimise the demands on the working memory system, such as presenting fewer pieces of new information in learning tasks (Gillam et al., 2019). Given the apparent sparing of declarative memory, it might be the case that tasks such as vocabulary learning could be supported in children with DLD through the use of strategies that capitalise on declarative learning (e.g., explicit teaching and the provision of exposures over multiple days; McGregor et al., 2013) and reduce working memory demands (e.g., first targeting shorter and less phonologically-complex words; reducing competing attentional demands; Lum et al., 2015). The development and use of these strategies holds potential for improving language outcomes for children with DLD.

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Table 1

Participants' Demographic Features and Means and Standard Deviations on Participant Selection Measures

Variable	TD, *n* = 54			DLD, *n* = 50			Comparison of means	
	M	*SD*	*R*	*M*	*SD*	*R*	*t*	*d*
Age in months	82.04	7.61	70 – 98	83.54	7.64	71 – 104	1.00	0.23
CLS[a]	101.26	11.86	86 – 134	64.16	11.55	40 – 85	-16.14**	3.16
PTONI[a]	102.93	18.96	76 – 140	87.40	15.20	70 – 141	-4.62**	0.90

Note: CLS = Core Language Score on the CELF-IV; *t* = independent samples *t*-test statistic; *d* = Cohen's *d* effect size.

[a]Standard scores are provided (tests standardised to a mean of 100 and standard deviation of 15).

$^{**}p < .001$

Table 2

MANOVAs and MANCOVAs for Working, Declarative, and Procedural Memory

Memory system	Adjusting for	Wilks' Lambda	*F*	*p*	*partial* η^2	Observed power
Working memory	No covariates	.42	33.79	< .001	0.58	1.00
	NVIQ	.49	25.40	< .001	0.51	1.00
Procedural Memory	None	.87	5.59	.005	0.13	0.84
	NVIQ	.92	3.34	.041	0.08	0.62
	General WM	.98	0.81	.449	0.02	0.18
	NVIQ & General WM	.98	0.72	.492	0.02	0.17
Verbal declarative memory	None	.63	14.46	< .001	0.37	1.00
	NVIQ	.74	8.58	< .001	0.26	0.99
	Verbal ST/WM	.90	2.76	.032	0.10	0.74
	NVIQ & Verbal STM/WM	.97	0.87	.488	0.03	0.27
Visual declarative memory	None	.96	1.46	.231	0.04	0.38
	NVIQ	.99	0.30	.829	0.01	0.11

Note. NVIQ = nonverbal IQ (as measured using the PTONI); the 'Verbal ST/WM' factor was created using principle components analysis of three individual subtest scores (Nonword Repetition, Digit Recall, and Backwards Digit Recall); the 'General WM' factor was created using principle components analysis of four individual subtest scores (Nonword Repetition, Digit Recall, Backwards Digit Recall, and Block Recall).

Table 3

Summary Scores for Measures of Working Memory

Dependent variable	Group means	DLD, n = 50			TD, n = 54			
		M	*SE*	95% CI	*M*	*SE*	95% CI	*partial* η^2
Nonword Repetition[a]	Unadjusted	72.45	1.60	70.14 – 74.76	89.83	1.12	87.61 – 92.05	0.53*
	Adjusted (NVIQ)	72.59	1.23	70.15 – 75.03	89.79	1.18	87.36 – 92.04	0.48*
Digit Recall[b]	Unadjusted	84.26	2.30	79.70 – 88.82	102.63	2.21	98.25 – 107.01	0.25*
	Adjusted (NVIQ)	84.93	2.42	80.13 – 89.73	102.01	2.32	97.41 – 106.61	0.19*
Backwards Digit Recall[b]	Unadjusted	73.84	2.08	69.72 – 77.97	95.61	2.00	91.64 – 99.58	0.07*
	Adjusted (NVIQ)	75.66	2.12	71.46 – 79.87	92.92	2.03	89.89 – 97.96	0.05*
Block Recall[b]	Unadjusted	86.10	2.60	80.94 – 91.26	96.28	2.08	91.31 – 101.24	0.36*
	Adjusted (NVIQ)	86.61	2.75	81.16 – 92.06	95.81	2.63	90.58 – 101.03	0.26*

Note. Adjusted group means were obtained while controlling for NVIQ (nonverbal IQ).

[a] Percentage of Phonemes Correct score reported.

[b] Standard scores reported (standardised to a mean of 10 and standard deviation of 3).

**p* < .0125 (using Bonferroni adjustment for four dependent variables).

Table 4

Summary Scores (t-statistics) for Measures of Procedural Memory

Dependent variable	Group means	DLD, n = 38			TD, n = 41			
		M	*SE*	95% CI	*M*	*SE*	95% CI	partial η^2
Deterministic pattern	Unadjusted	0.95	0.37	0.21 – 1.70	2.69	0.36	1.98 – 3.41	0.13*
	Adjusted (NVIQ)	1.15	0.38	0.40 – 1.90	2.51	0.36	1.79 – 3.23	0.08*
	Adjusted (General WM)	1.40	0.45	0.51 – 2.30	2.28	0.43	1.43 – 3.13	0.03
	Adjusted (NVIQ & General WM)	1.46	0.45	0.57 – 2.34	2.23	0.43	1.39 – 3.07	0.02
Probabilistic pattern	Unadjusted	-0.83	0.24	-1.31 – -0.34	-0.63	0.23	-1.10 – -0.17	0.004
	Adjusted (NVIQ)	-0.94	0.25	-1.43 – -0.45	-0.53	0.24	-1.00 – -0.45	0.02
	Adjusted (General WM)	-0.86	0.30	-1.46 – -0.27	-0.60	0.28	-1.16 – 0.03	0.004
	Adjusted (NVIQ & General WM)	-0.90	0.30	-1.49 – -0.31	-0.56	0.28	-1.12 – 0.01	0.01

Note. The *t*-statistic demonstrates the ratio of difference between the slope for the learning phase and the slope for the phase when the pattern was broken. A higher *t*-statistic suggested that the participant's reaction time increased in the phase where the pattern was broken, relative to the initial patterned phase. Adjusted group means were obtained while controlling for NVIQ (nonverbal IQ) and/or the General WM (working memory) factor.

*p < .025 (using Bonferroni adjustment for two dependent variables).

Table 5

Summary Scores for Measures of Declarative Memory

Dependent variable	Group means	DLD, *n* = 50			TD, *n* = 54			
		M	*SE*	95% CI	*M*	*SE*	95% CI	*partial* η^2
Verbal								
Learning	Unadjusted	6.94	0.43	6.09 – 7.79	8.78	0.41	7.96 – 9.60	0.09*
	Adjusted (NVIQ)	7.22	0.45	6.34 – 8.11	8.52	0.43	7.67 – 9.37	0.04
	Adjusted (Verbal ST/WM)	7.46	0.49	6.49 – 8.43	8.30	0.47	7.37 – 9.22	0.01
	Adjusted (NVIQ & Verbal ST/WM)	7.95	0.53	6.89 – 9.00	7.85	0.50	6.85 – 8.85	< .001
Total	Unadjusted	7.14	0.40	6.35 – 7.93	9.54	0.38	8.78 – 10.30	0.16*
	Adjusted (NVIQ)	7.47	0.41	6.67 – 8.28	9.23	0.39	8.46 – 10.01	0.08*
	Adjusted (Verbal ST/WM)	7.83	0.44	6.95 – 8.71	8.90	0.42	8.07 – 9.74	0.02
	Adjusted (NVIQ & Verbal ST/WM)	8.20	0.48	7.25 – 9.16	8.56	0.46	7.65 – 9.47	0.002
Delayed Recall	Unadjusted	7.30	0.43	6.46 – 8.14	9.69	0.41	8.88 – 10.50	0.14*
	Adjusted (NVIQ)	7.56	0.44	6.68 – 8.43	9.46	0.42	8.62 – 10.30	0.08*
	Adjusted (Verbal ST/WM)	8.01	0.47	7.07 – 8.95	9.04	0.45	8.14 – 9.93	0.02
	Adjusted (NVIQ & Verbal ST/WM)	8.20	0.53	7.16 – 9.25	8.86	0.51	7.86 – 9.85	0.006
Delayed Recognition	Unadjusted	7.40	0.41	6.60 – 8.20	11.30	0.39	10.52 – 12.07	0.32*
	Adjusted (NVIQ)	7.79	0.41	6.98 – 8.60	10.94	0.39	10.16 –11.72	0.22*
	Adjusted (Verbal ST/WM)	8.36	0.43	7.51 – 9.22	10.40	0.41	9.59 – 11.22	0.09*
	Adjusted (NVIQ & Verbal ST/WM)	9.03	0.45	8.13 – 9.92	9.79	0.43	8.94 – 10.64	0.01
Visual-spatial								
Learning	Unadjusted	9.92	0.39	9.13 – 10.71	10.82	0.41	10.00 – 11.64	0.02
	Adjusted (NVIQ)	10.33	0.41	9.51 – 11.15	10.45	0.40	9.66 – 11.54	0.003

Total	Unadjusted	10.32	0.37	9.57 – 11.07	11.37	0.41	10.55 – 12.18	0.03
	Adjusted (NVIQ)	10.74	0.41	9.95 – 11.54	10.98	0.39	10.21 – 11.74	0.00
Long Delay	Unadjusted	11.18	0.32	10.54 – 11.82	11.92	0.26	11.40 – 12.44	0.03
	Adjusted (NVIQ)	11.39	0.30	10.78 – 11.99	11.73	0.29	11.15 0 12.31	0.01

Note. Standard scores reported (standardised to a mean of 10 and standard deviation of 3). Adjusted group means were obtained while controlling for NVIQ (nonverbal IQ), the Verbal Short-Term/Working Memory (ST/WM) factor, and/or the General Working Memory (WM) factor.

**p* < .0125 (using Bonferroni adjustment for four dependent variables).

Appendix

Methodological Details for the Serial Reaction Time Task

SRT Task Instructions

“We are going to play a game on this computer. You will see pictures and hear a lady say their names. When you see four pictures, I want you to touch the picture that you hear named with this pen [show stylus]. Remember to go as fast as you can. If you think you know what comes next, you can press the picture before you hear the lady name it. This will give you more points. Try to get the right one.”

Table 1

List of Noun Stimuli in SRT Task

Drum	Scarf	Plug	Clock
Bread	Fox	Fly	Bow
Flag	Leaf	Van	Fan
Pen	Car	Horn	Watch
Crab	Pond	Chest	Tie
Bell	Mask	Shed	Box
Desk	Bin	Bed	Moon
Boat	Cup	Arm	Sledge
Swing	Wall	Heart	Train
Witch	Clown	Hen	Lamp
Door	Vase	Eye	Bat
Jug	Wheel	Snow	Sheep
Kite	Leg	Sword	Shirt
Whale	Snail	Toad	Tree
Thief	Chain	Pie	Chair
Ring			

Note: An electronic .gif motion graphic of two consecutive triplet sequences can be viewed at https://osf.io/x4td6/.

Supplementary Materials

Table S1

Groups of Children with and Without SRT Data (Demographic Features and Means and Standard Deviations on Participant Selection Measures)

Variable	SRT_{AV}, *n* = 79			$\text{SRT}_{\text{N/A}}$, *n* = 25			Comparison of means	
	M	*SD*	*R*	*M*	*SD*	*R*	*t*	*p*
Age in months	82.89	7.70	70 – 104	82.36	7.53	72 – 96	0.30	.765
CLS[a]	84.39	22.27	40 – 134	80.36	21.16		0.80	.427
PTONI[a]	95.43	19.41	70 – 141	95.56	17.37		-0.03	.976
NWR	81.47	11.61		81.47	13.25		0.00	.999
DR[a]	94.62	18.59		91.20	18.83		0.80	.426
BDR[a]	86.80	18.74		79.92	15.91		1.66	.101
BDR[a]	90.77	19.97		93.32	15.69		-0.58	.562
General WM[b]	0.04	1.02		-0.12	0.94		0.69	.491

Note: SRT_{AV}, = Children for whom SRT data was available; $\text{SRT}_{\text{N/A}}$ = children for whom SRT data was unavailable; CLS = Core Language Score on the CELF-IV; PTONI = Primary Test of Nonverbal Intelligence; NWR = nonword repetition (percentage of phonemes correct score); DR = digit recall; BDR = backwards digit recall; *t* = independent samples *t*-test statistic.

[a] Standard scores are provided (tests standardised to a mean of 100 and standard deviation of 15).

[b] General working memory factor created through factor analysis of four working memory subtests (Nonword Repetition, Digit Recall, Backwards Digit Recall, Block Recall).

Table S2

Results of Bivariate Correlations Between All Variables

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Age (months)	–																
2. Gender[a]	.12	–															
3. Nonverbal IQ	-.15	.05	–														
4. General language	-.15	-.21*	.47**	–													
5. Nonword repetition (PPC)	.07	-.07	.36**	.78**	–												
6. Digit span	-.15	.01	.24*	.62**	.61**	–											
7. Block recall	-.16	.13	.18	.36**	.26**	.40**	–										
8. Backward digit span	-.10	-.08	.36**	.69**	.61**	.52**	.33**	–									
9. DL Learning	-.07	.03	.31**	.28**	.17	.17	.16	.26**	–								
10. DL Total	-.07	.06	.31**	.28*	.18	.16	.16	.25**	.94**	–							
11. DL Long Delay	-.06	.19	.27**	.27**	.22**	.33**	.21*	.26**	.69**	.70**	–						
12. WP Learning	.02	.03	.29**	.34**	.33**	.29**	.14	.29**	.27**	.26**	.34**	–					
13. WP Total	-.12	.03	.37**	.46**	.39**	.36**	.20*	.39**	.33**	.33**	.39**	.94**	–				
14. WP Long Delay	-.04	-.15	.31**	.43**	.28**	.39**	.34**	.37**	.34**	.32**	.38**	.54**	.59**	–			
15. WP Del Recognition	.02	-.05	.44**	.64**	.59**	.38**	.20*	.66**	.34**	.36**	.37**	.42**	.51**	.43**	–		
16. Deterministic *t*-test[b]	.01	-.08	.23*	.35*	.35*	.36*	.30*	.22	.16	.10	.19	.04	.12	.13	.32*	–	
17. Probabilistic *t*-test	.11	.02	-.17	.01	.06	-.03	-.06	.06	.10	.12	.05	.08	.06	.06	.07	.14	–

Note. Values reported are Pearson's correlation coefficients (*r*). All values reported are standard scores, unless otherwise stated. PPC = percentage of phonemes correct; DL = Dot Locations (Cohen, 1997); WP = Word Pairs (Cohen, 1997).

[a]Point-biserial correlation used to determine the strength of a linear relationship between continuous variable and nominal variable with two categories (i.e., gender).

[b]Spearman's rho correlation used due to violations in the assumption of normality, linearity, or homoscedasticity.

*$p < .05$.

**$p < .001$

Table S3

Covariate Factors in MANCOVAs for Working, Declarative, and Procedural Memory Analyses

Memory system	Adjusting for	Wilks' Lambda	*F*	*p*	*partial* η^2	Observed power
Working memory	Nonverbal IQ	0.93	1.92	.114	0.07	0.56
Procedural Memory	Nonverbal IQ	0.89	4.50	.014	0.11	0.75
	General WM	0.96	1.63	.203	0.04	0.33
Verbal declarative memory	Nonverbal IQ	0.88	3.32	.014	0.12	0.83
	Verbal ST/WM	0.77	7.46	< .001	0.23	0.99
Visual declarative memory	Nonverbal IQ	0.90	3.75	.013	0.10	0.80

Note. General WM = General working memory factor created through factor analysis of four working memory subtests; Verbal ST/WM = Verbal short-term and working memory factor created through factor analysis of three individual subtest scores (Nonword Repetition, Digit Recall, and Backwards Digit Recall).