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Research Article

Working Memory Profiles of Children With Dyslexia, Developmental Language Disorder, or Both

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Purpose: Compared to children with typical development, children with dyslexia, developmental language disorder (DLD), or both often demonstrate working memory deficits. It is unclear how pervasive the deficits are or whether the deficits align with diagnostic category. The purpose of this study was to determine whether different working memory profiles would emerge on a comprehensive battery of central executive, phonological, visuospatial, and binding working memory tasks and whether these profiles were associated with group membership.
Method: Three hundred two 2nd graders with typical development, dyslexia, DLD, or dyslexia/DLD completed 13 tasks from the Comprehensive Assessment Battery for Children–Working Memory (Gray, Alt, Hogan, Green, & Cowan, n.d.) that assessed central executive, phonological, and visuospatial/attention components of working memory.
Results: Latent class analyses yielded 4 distinct latent classes: low overall (21%), average with high number updating (30%), average with low number updating (12%), and high overall (37%). Children from each disability group and children from the typically developing group were present in each class.
Discussion: Findings highlight the importance of knowing an individual child's working memory profile because working memory profiles are not synonymous with learning disabilities diagnosis. Thus, working memory assessments could contribute important information about children's cognitive function over and above typical psychoeducational measures.

Working memory encompasses an individual's ability to process and store incoming information over short periods of time. It is a powerful predictor of learning (Alloway, 2009; Maehler & Schuchardt, 2016) and explains variance in reading and writing performance in elementary school children (Berninger et al., 2010; Swanson & Berninger, 1996). Therefore, working memory is suspect in children who have learning disabilities. We examined profiles of working memory performance in children with typical development, dyslexia, developmental language disorder (DLD),[1] and concomitant dyslexia and DLD to determine whether subgroups demonstrated a unique working memory profile and whether children with concomitant dyslexia and DLD demonstrated poorer working memory than their peers diagnosed with a single disorder.

Working Memory

In general, leading theories of working memory may be distinguished by their view on whether working memory is separable into distinct domain-specific components (e.g., Alloway, Gathercole, & Pickering, 2006; Baddeley, 2000; Baddeley & Hitch, 1974; Shah & Miyake, 1996) or whether

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[1] DLD has historically been referred to as *specific language impairment*. However, a recent consensus study concluded that the term *developmental language disorder* should be used instead (Bishop, Snowling, Thompson, Greenhalgh, & the CATALISE-2 Consortium, 2017). Thus, we use the term *developmental language disorder* throughout the article, except when referring to articles where authors used the term *specific language impairment* in their research.

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working memory is a more unitary construct influenced primarily by the focus of attention (e.g., Cowan, 2001; Engle, 2002). Baddeley and Hitch (1974) presented an early domain-specific working memory model with three distinct components—the central executive (CE), phonological loop, and visuospatial sketchpad. Later, Baddeley (2000) updated this model by adding a fourth component, the episodic buffer. Baddeley (2007) described the components of his working memory model as follows. The CE is viewed as the most important component of working memory, in charge of focusing, dividing, and switching attention and linking working and long-term memory, as well as determining the strategic use of the storage components. The phonological loop includes a phonological store and a mechanism for articulatory rehearsal. Because it is responsible for processing incoming verbal information, it is crucial for language learning. The visuospatial sketchpad functions for visual and spatial information like the phonological loop functions for phonological information, but unlike the phonological loop, the visuospatial sketchpad does not have a rehearsal mechanism. Finally, the episodic buffer serves as short-term storage for chunks of information, such as prose, and for binding information from two sources such as phonological and visuospatial information.

A more unitary view of working memory is represented by Cowan's (1988, 1999, 2005) embedded processes model that relies heavily on the focus of attention. This framework links memory and attention in a three-layer hierarchy. According to Cowan, working memory represents the portion of long-term memory that is activated, including newly learned associations. Within this pool of activated memory is a subset of working memory that is the focus of attention. This conception also includes a CE. Important differences from the multicomponent view include a greater emphasis on the use of attention during storage when verbal rehearsal is not possible and an unwillingness to be committed to a small number of storage components, given the large variety of stimuli that people actually encounter (e.g., tactile sensations, tastes and smells, spatially arranged and moving tones, semantic and orthographic features). In practice, the advent of the episodic buffer (Baddeley, 2000) greatly reduced the differences between the two types of models.

Working Memory Assessment

To determine whether distinct working memory profiles exist in children with dyslexia, DLD, or comorbid dyslexia and DLD, we administered a broad array of theoretically based working memory measures. This set of measures is more comprehensive than currently published studies with children. We used Baddeley and Hitch's (1974), Baddeley's (2000), and Cowan's (1995, 1999, 2001) well-tested theoretical models to define the scope of assessment. These model differences could present a dilemma when deciding which working memory skills to assess; however, Gray et al. (2017) tested the fit of these three models in young school-age children. They administered the Comprehensive Assessment Battery for Children–Working Memory (CABC-WM; Gray, Alt, Hogan, Green, & Cowan, n.d.) to 168 typically developing (TD) children of ages 7–9 years. Results suggested that the Baddeley and Hitch model and the Cowan model were quite close conceptually, but there was little evidence for Baddeley's episodic buffer component. Rather, a three-component hybrid model of working memory with CE, phonological, and focus of attention components fit the data well. In the hybrid model, tasks requiring processing of visuospatial information, verbal information that could not be rehearsed, and information that required feature binding (e.g., phonological and visual) all loaded on the focus of attention factor. Each of the 13 CABC-WM tasks were significantly related to one of the three factors, and no factor had fewer than three significant indicators. Based on these results, the CABC-WM offered a theoretically based set of working memory tasks to accomplish a comprehensive working memory assessment of children in this study.

To assess the CE component of working memory, we administered number updating, *n*-back auditory, and *n*-back visual tasks. The CABC-WM does not assess inhibition or set shifting because those tasks do not primarily test storage or manipulation of information, which is the primary function of working memory. For the focus of attention, component tasks included digit span running, location span, location span running, visual span, visual span running, visual–spatial binding, and cross-modal binding. Phonological component tasks included digit span, nonword repetition, and phonological binding. A detailed description of these tasks is included in the Method section.

Relationship Between Working Memory and Reading Decoding or Reading Fluency

Studies of elementary-age children generally report a positive relationship between verbal working memory and reading decoding or reading fluency, but few find a significant relationship between visuospatial working memory and reading decoding or reading fluency. Pham and Hasson (2014) studied the relationship between working memory and reading fluency in 157 fourth- and fifth-grade students with a wide variety of reading abilities. They found that verbal working memory measures were significant predictors of reading fluency, but visuospatial working memory measures were not. Similarly, Booth, Boyle, and Kelly (2014) studied a group of 21 ten-year-old children with word reading difficulties matched to chronological and reading-level groups. Verbal working memory predicted group membership, but nonverbal working memory did not. A longitudinal study of working memory and reading from kindergarten to fifth grade conducted in Hebrew found that verbal and visual–spatial working memory correlated significantly with word reading accuracy in first and second grades (except for phonological short-term memory), but none of the working memory measures were correlated with word reading accuracy in fifth grade (Nevo & Bar-Kochva, 2015). In contrast, a study of children with and without dyslexia in third to eighth grades found no relationship between phonological working memory and reading fluency in a dyslexic group but a positive relationship between reading fluency and phonological working memory in TD children (De Carvalho, Kida, Capellini, & de Avila, 2014).

A recent meta-analysis of reading and working memory by Peng et al. (2018) sheds some light on these findings. Overall, they found significant relations between working memory and measures of reading decoding/fluency and reading comprehension in children (r = .29), but this was influenced by working memory domain and grade level. Verbal working memory was more strongly related to reading than visuospatial working memory after third grade. The relationship between working memory and word recognition was stronger than that between working memory and nonword reading. Together, these studies provide strong evidence for a significant relationship between components of working memory and reading decoding/reading fluency.

Relationship Between Working Memory and Language Development

Research studies investigating the nature of the relationship between working memory and language development in children are limited. One study of preschoolers reported that, in children with specific language impairment (SLI), verbal CE function was moderately to strongly correlated with vocabulary, verbal comprehension, and syntax. Relationships between the verbal and visuospatial components of working memory and language measures in that study were not significant (Vugs, Knoors, Cuperus, Hendriks, & Verhoeven, 2016). It is important to note that this study did not assess children's phonological awareness or letter knowledge; therefore, it is not possible to say whether any of the children in the SLI group were also at risk for dyslexia, which could impact results.

Acheson and colleagues proposed a relationship between working memory and language production, but this has not been tested in children. According to Acheson and MacDonald (2009a, 2009b), serial ordering in verbal working memory is facilitated by the language production architecture. To plan, production people must maintain and order linguistic information over the word, phrase, and sentence levels using information from representations coded in long-term memory. The authors argue that the language production processes that support fluent language production also promote serial order maintenance in working memory tasks. They tested this hypothesis in a functional magnetic resonance imaging and transcranial magnetic stimulation study with 14 adults. They concluded that maintenance of information in verbal working memory depends directly on long-term representations and speech production processes rather than short-term memory alone. MacDonald (2016) went so far as to hypothesize that "utterance plans—the memory of what is to come in speaking—are also the arena of serial order and maintenance in verbal memory tasks, obviating the need for a dedicated short-term verbal store" (p. 47). This has implications for children with language impairment, who often have concomitant speech production problems (Eadie et al., 2014; Lewis et al., 2015) and smaller lexicons (Rice & Hoffman, 2015) than their TD peers. Together, this research suggests a plausible relationship between verbal aspects of working memory and language but provides less evidence for a relationship between visuospatial aspects of working memory and language.

Working Memory Profiles in Children With Dyslexia and DLD

If children within a particular diagnostic category demonstrate consistent working memory strengths or deficits, this is important for researchers, clinicians, and educators to know because it suggests particular approaches to instruction and provides testable hypotheses about the nature and direction of relations between language and working memory. On the other hand, if children within the same diagnostic category show different patterns of working memory strengths and deficits, this raises the possibility that working memory should be considered a separate cognitive ability where deficits may co-occur with other disorders, something that Archibald (2017) referred to as a "symbiotic" relationship. It is also possible that children who have not been diagnosed with a disorder, but who struggle to learn, could have working memory deficits (Archibald & Gathercole, 2006).

In general, researchers investigating working memory profiles in children with reading or language disorders have asked three types of questions. First, do working memory deficits consistently co-occur with dyslexia or DLD? Second, are specific patterns of deficits associated with different disorders? And third, are working memory deficits more severe in children with concomitant disorders such as dyslexia and DLD? Regarding the first question, Marton, Eichorn, Campanelli, and Zakarias (2016) proposed that working memory deficits do not just co-occur with DLD but represent an underlying cause of the disorder. According to this view, we should observe working memory deficits in each child with DLD. In contrast, Archibald and Joanisse (2009) administered language and working memory tests to school-age children and found a subgroup with DLD that did not appear to have working memory deficits. Consistent with this finding, Archibald (2017) suggested that every child with DLD may not have working memory deficits, but when they do and deficits are sufficiently severe, they may be an underlying cause of language impairment.

Regarding the question of whether specific types of working memory deficits may be associated with SLI and dyslexia, Alloway, Rajendran, and Archibald (2009) studied children with SLI and other disorders and reported different memory profiles for each disorder. They stated that "working memory appears to be a secondary deficit, possibly driven by core deficits in language, motor, behavior, or social difficulties" (Alloway et al., 2009, p. 378). According to this view, we should observe similar patterns of working memory deficits within DLD and dyslexic groups that differ from each other.

Maehler and Schuchardt (2016) proposed additive working memory deficits when children demonstrate comorbid conditions such as dyslexia and attention-deficit/hyperactivity disorder (ADHD). They concluded that "comorbidity leads to additive working memory deficits, i.e., children with both disorders must cope with broader deficits" (p. 341). This hypothesis differs from the double-deficit hypothesis in dyslexia that posits two core deficits in dyslexia, one in phonological awareness and one in rapid automatized naming, that result in more severe reading deficits when they co-occur (Wolf & Bowers, 1999, 2000). Instead, the proposal by Maehler and Schuchardt suggests that we should find more varied and perhaps more severe working memory deficits in children with concomitant dyslexia and DLD.

Three studies have gone beyond group comparisons to investigate whether individual children with SLI demonstrate working memory deficits. Archibald and Gathercole (2006) administered verbal and visuospatial short-term memory tasks to 20 children with SLI of ages 6–11 years. They defined a deficit as any score more than 1 *SD* below the standardization mean. Ninety-five percent of participants scored in the deficit range on the working memory composite. However, using language-adjusted scores (based on language age from the British Picture Vocabulary Test; Dunn, Dunn, Whetton, & Burley 1997), they found that the mean verbal short-term memory score was in the low average range (90.75) and the visuospatial short-term memory mean score was in the average range (101.05) with only half of participants showing a deficit in visuospatial short-term memory. In contrast, the mean score for nonword repetition was significantly below average (66.13).

Alloway et al. (2009) reported similar patterns of performance when they administered verbal and visuospatial short-term and working memory tasks to 15 children with SLI of ages 8–10 years. With nonverbal cognitive scores controlled statistically, 67%–80% of the children scored more than 1 *SD* below the mean on verbal tasks, and 20%–33%, on the visuospatial tasks. However, 7% scored within the normal range on verbal tasks, and 20%–40% scored within the normal range on visuospatial tasks. Freed, Lockton, and Adams (2012) also assessed verbal and visuospatial short-term and working memory skills in 12 children with SLI of ages 6–10 years. Forty-two percent to 58% of children scored 1 *SD* or more below the mean on phonological working memory tasks, and 42% scored 1 *SD* or more below the mean on the visuospatial working memory task.

Taken together, these studies suggest that working memory deficits do not always occur in children with DLD, but when they do, a pattern of performance emerges where phonological working memory deficits occur more often than visuospatial deficits. To date, no studies have examined the individual performance of children across all domains of working memory, and studies have not been conducted in children with concomitant dyslexia and DLD, leaving open the question of whether these children show consistent working memory deficits, whether they demonstrate particular patterns of deficits, and whether concomitant dyslexia and DLD result in additive working memory deficits.

Between-Groups Studies of Working Memory Deficits in Children With Dyslexia, DLD, or Both

Although between-groups comparisons cannot directly address questions regarding the co-occurrence of working memory and reading or language deficits or provide working memory profiles, group studies to date provide more detailed information about children's performance on a wider variety of working memory components than profile studies.

Dyslexia

Group studies of children with dyslexia show mixed evidence of CE function deficits. Schuchardt, Bockmann, Bornemann, and Maehler (2013) administered double span, backward span for words and digits, and counting span tasks to 9-year-olds with dyslexia and found that the TD group scored significantly higher on the backward digit span and counting span tasks. Unfortunately, they did not administer language assessments to the groups so it is not certain that the students with dyslexia did not have a concomitant language disorder. Nevertheless, the authors interpreted their findings as evidence that children with dyslexia do demonstrate CE function deficits, but they acknowledged that the CE tasks involved processing of phonological information (e.g., digits); therefore, results could be impacted by phonological loop deficits.

Jeffries and Everatt (2004) administered listening recall and backward digit recall to 8-year-olds with dyslexia and found that TD scores were significantly higher on both measures. They interpreted their findings as evidence suggestive of CE function deficits in the dyslexic group, even though they selected their participants to exclude those with attentional deficits, which could impact performance on CE tasks.

Evidence for phonological working memory deficits in children with dyslexia is strong. Groups of children with dyslexia score significantly lower than their TD peers on verbal span tasks (Menghini, Finzi, Carlesimo, & Vicari, 2011), forward digit recall (Jeffries & Everatt, 2004; Schuchardt et al., 2013), word recall (Schuchardt et al., 2013), and nonword repetition tasks (Jeffries & Everatt, 2004; Schuchardt et al., 2013). However, a recent study by Cowan et al. (2017) reported that, when children with dyslexia were matched to TD children using nonverbal IQ and oral language scores, significant between-groups differences on two nonword repetition tasks disappeared. Similarly, Rispens and Baker (2011) reported that 7- to 8-year-olds with reading impairment who did not have concomitant language impairment did not differ from age-matched peers on a test of nonword repetition.

Some evidence suggests that working memory deficits in children with dyslexia extend to visuospatial processing. Menghini et al. (2011) assessed children ages 8–14 years split into primary school (third to fifth grade) and middle school (fifth to seventh grade) groups. Assessments of visual–spatial and visual–object span showed significantly lower scores for the dyslexic group compared to the TD group at both ages. In contrast, Jeffries and Everatt (2004) showed no differences on block recall or maze memory task performance for 8-year-olds with dyslexia and typical development.

Given phonological and visuospatial deficits, it may not be surprising that, when children with dyslexia are asked to learn visual–phonological associations in cross-modal binding experiments, they perform lower than their peers. Albano, Garcia, and Cornoldi (2016) tested 10-year-olds' ability to bind nonwords and shapes presented in fixed or variable locations. The dyslexic group remembered significantly fewer pairs in both conditions than the TD group. In contrast, Alt et al. (2017) found that second graders with dyslexia did not differ from their TD peers in a word learning task that required children to associate phonological labels with visual referents.

DLD

Group studies of children with DLD provide limited evidence for CE function deficits, in part because CE tasks are often not included in working memory experiments. Two studies with 6- to 9-year-olds using backward digit recall and listening recall tasks as measures of CE function (Briscoe & Rankin, 2009; Hutchinson, Bavin, Efron, & Sciberras, 2012) and one study using listening recall with 10- to 12-year-olds (Henry, Messer, & Nash, 2012a) found that children with SLI scored significantly lower than their TD peers. We note that the listening recall tasks were linguistically based; therefore, results may not provide an accurate test of executive function alone because of language impairment in the DLD group. In contrast, a recent study with 5-year-olds using backward digit recall did not find significant between-groups differences for children with SLI and typical development (Petruccelli, Bavin, & Bretherton, 2012), and a second study that manipulated processing load while keeping storage demands constant and vice versa in 7- to 9-year-olds with and without low language found no CE deficits in the children with low language (Archibald & Griebeling, 2016).

In contrast, evidence for phonological working memory deficits in children with DLD is strong (e.g., Archibald & Gathercole, 2006; Archibald & Griebeling, 2016; Marton & Schwartz, 2003). Three studies using digit recall, word list recall, and nonword recall tasks with 5-year-olds (Petruccelli et al., 2012) and 6- to 9-year olds (Briscoe & Rankin, 2009; Hutchinson et al., 2012) found that the SLI group scored significantly lower than the TD group on every task. Botting, Psarou, Caplin, and Nevin (2013) were interested in determining whether phonological working memory deficits might be due to verbal output requirements so they manipulated the verbal content of tasks by administering a name recall task with nonverbal output and a nonword span task with verbal output to children ages 5;11–12;6 (years;months). The SLI group scored significantly lower than the TD group on both tasks, regardless of whether verbal output was required. One caveat is that SLI groups were not consistently tested for word reading, allowing the possibility that some children could have concomitant dyslexia. When Catts, Adlof, Hogan, and Weismer (2005) required that children with SLI have normal word reading, the SLI group did not differ from the TD group on nonword repetition, a commonly used measure of phonological working memory. Similarly, Rispens and Parigger (2010) and Rispens and Baker (2011) reported that 7- to 8-year-olds with SLI who did not have concomitant reading impairment did not differ from age-matched peers on a test of nonword repetition. These findings suggest that the phonological working memory deficits reported in children with language impairment may be called into question if reading was not assessed; a concomitant reading disorder such as dyslexia could account for between-groups differences in these studies.

Evidence for visuospatial working memory deficits in DLD is mixed. Three studies assessing children's visuospatial working memory using block recall, maze memory, or both found no between-groups differences in children ranging from 5 to 9 years of age (Botting et al., 2013; Briscoe & Rankin, 2009; Hutchinson et al., 2012; Petruccelli et al., 2012). Henry, Messer, and Nash (2012b) administered a spatial span task to children ages 8–14 years and found no between-groups differences. Botting et al. (2013) administered a block recall task and a picture sequence recall task to children ages 5;11–12 and found no between-groups differences on the block recall task, but the SLI group scored significantly lower on the picture sequence recall task. The authors attributed lower scores on the picture sequence recall task to verbal encoding requirements.

Others have found evidence of visuospatial working memory deficits in this population. Alt (2013) engaged 7- and 8-year-olds in a visual fast-mapping game that required them to recall visual features of novel dinosaurs and their actions in the face of interference, thus testing their visuospatial working memory skills. The children with SLI showed impaired working memory when compared to peers, but only in certain conditions. Alt concluded that children with SLI were likely susceptible to interference, leading to poorer visual working memory skills. However, those deficits were less severe than verbal working memory deficits. This finding was in line with the results of a meta-analysis of visuospatial working memory of children with SLI (ages 4–13 years) by Vugs, Cuperus, Hendriks, and Verhoeven (2013). They found that children with SLI had visuospatial storage deficits with effect sizes of roughly $d = 0.49$ compared to TD peers.

Bavin, Wilson, Maruff, and Sleeman (2005) reported that 4-year-olds with SLI scored significantly lower than their TD peers on "spatiovisual" tasks assessing pattern recognition, paired associate learning, and spatial span, but not on tasks assessing spatial recognition or spatial working memory searches. Hick, Botting, and Conti-Ramsden (2005) followed children from ages 3;9 for 1 year, administering pattern recall and block construction tasks three times during the year. Performance did not differ for the SLI and TD groups on either task.

Together, these research studies suggest that DLD groups sometimes perform lower than TD groups on CE tasks and often perform lower than TD groups on phonological and visuospatial working memory tasks. Evidence is strongest for deficits in phonological working memory, in part perhaps because more studies have examined performance in this area.

Concomitant Dyslexia and DLD

Dyslexia and DLD commonly co-occur (Catts et al., 2005; McArthur, Hogben, Edwards, Heath, & Mengler, 2000; Tomblin, Zhang, Buckwalter, & Catts, 2000). With substantial evidence that children with dyslexia and DLD demonstrate working memory deficits in CE, phonological, and visuospatial functions, it is logical to ask whether a child with both disorders may have more pervasive working memory deficits than children with a single disorder. Although few studies have investigated this group of children, recent work shows that this may be the case. Rispens and Baker (2011) reported that 7- to 8-year-olds with SLI and reading impairment scored significantly lower on a nonword repetition task than age-matched peers. Schuchardt et al. (2013) administered double span, backward span for words and digits, and counting span tasks to 9-year-olds with concomitant SLI and dyslexia and found that the TD group scored significantly higher on all of the CE tasks. Cowan et al. (2017) found that 9- to 11-year-olds with concomitant SLI and dyslexia scored similarly to their peers with dyslexia only on serial order recall tasks of phonological, lexical, spatial, and visual items, but both groups scored lower than their TD peers. The concomitant group did score lower than the dyslexia-only group on two nonword repetition measures.

Purpose

The purpose of this study was to determine whether different profiles of working memory strengths and weaknesses were evident in second-grade children when the sample included children with typical development, dyslexia, DLD, and concomitant dyslexia/DLD. One advantage of latent profile analysis (LPA) is that it does not take diagnostic group into account when determining the number of latent profiles observed. The profiles are based entirely on performance on the working memory tasks. Only after statistically determining the number of profiles do we examine the descriptive characteristics of children in each of the profiles. Thus, the aim of the study was to enrich our understanding of children with dyslexia and/or DLD by showing how working memory, a type of mental ability of known special importance to cognition, intersects with indices of these learning disorders.

Based on results from previous working memory profile and between-groups studies showing different working memory strengths and weaknesses among children with language learning disabilities, our hypothesis was that distinct profiles would emerge but that profiles would not be synonymous with group. As with any cognitive skill, we expected children to demonstrate a range of performance on working memory tasks. Because of their language-based disorders, however, we expected that more children with DLD, dyslexia, and concomitant DLD and dyslexia would be present in profiles with lower scores on phonological storage and rehearsal/phonological loop component tasks. Furthermore, if working memory deficits are additive for DLD and dyslexia, we hypothesized that this group would be prevalent in the lowest working memory profile.

Method

Participants

We recruited second-grade children from schools in metropolitan and rural areas of Arizona, Massachusetts, and Nebraska. Teachers sent home consent packets to all children. If parents wished to consent, they returned their information to their child's teacher or to researchers via mail. We sampled 302 second graders (ages 7;0–9;1) classified into four groups based on the inclusionary criteria described below. The TD group in this study was the same group studied in Gray et al. (2017). All of the children in this study were part of a larger study on working memory and word learning.[2] The sample sizes for children with typical development, dyslexia, DLD, and concomitant dyslexia and DLD were 167, 82, 9, and 44, respectively. There were 161 girls and 141 boys. For ethnicity, 81% reported non-Hispanic, 17% reported Hispanic, and 2% provided no report. For race, 3% reported American Indian or Alaska Native, 1% reported Asian, 4% reported Black, 76% reported White, 12% reported more than one race, and 4% did not report. Table 1 provides additional descriptive information.

Inclusionary criteria for all children included (a) passing a bilateral hearing screening, (b) passing a color vision screening, (c) passing a near vision acuity screening, (d) enrolled in or just completed second grade, (e) no history of neuropsychiatric disorders (e.g., ADHD, autism spectrum disorder) by parent report, (f) spoke monolingual English by parent report, and (g) standard score of ≥ 75 on the Nonverbal Index of the Kaufman Assessment Battery for Children–Second Edition (Kaufman & Kaufman, 2004).

Children in the TD group met the following additional inclusionary criteria: (a) no history of special education services, (b) no repeating of a grade, (c) a standard

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[2] Participants in this study represent a portion of the participants in a larger sample from the Profiles of Working Memory and Word Learning for Educational Research (POWWER) study funded by National Institute on Deafness and Other Communication Disorders Grant R01 DC010784. Working memory data from POWWER have also been published in Cowan et al. (2017), Gray et al. (2017), and Green et al. (2016).

Table 1. Participant characteristics and test scores.

	Group							
	TD		Dyslexia		DLD		Dyslexia/DLD	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age in months	92.82	4.97	94.19	5.39	96.44	6.21	94.61	5.66
Mother's education in years	15.38	1.66	14.84	1.90	14.55	2.79	14.19	2.12
GFTA-2 Articulation Accuracy percentile	50.89	8.54	41.37	15.97	38.11	17.05	33.50	18.53
KABC-II Nonverbal Index standard score	117.60	15.53	106.80	13.40	103.33	13.68	97.20	14.46
TOWRE-2 Word/Nonword standard score	109.45	8.40	80.61	6.23	103.11	6.83	79.27	7.09
CELF-4 Core Language standard score	108.75	9.58	100.30	8.61	74.11	10.13	73.30	8.33
EVT-2 standard score	112.39	10.95	103.34	10.85	93.22	8.90	89.18	9.57
WRMT-III PC standard score	108.23	9.85	93.89	10.66	98.11	8.25	82.11	11.78
ADHD raw score	10.19	8.77	13.02	9.02	7.17	7.6	15.47	12.15

Note. TD = typical development; DLD = developmental language disorder; GFTA-2 = Goldman-Fristoe Test of Articulation–Second Edition (Goldman & Fristoe, 2000); KABC-II = Kaufman Assessment Battery for Children–Second Edition (Kaufman & Kaufman, 2004); TOWRE-2 = Test of Word Reading Efficiency–Second Edition (Torgesen, Wagner, & Rashotte, 2012); CELF-4 = Clinical Evaluation of Language Fundamentals–Fourth Edition (Semel, Wiig, & Secord, 2003); EVT-2 = Expressive Vocabulary Test–Second Edition (Williams, 2007); WRMT-III PC = Woodcock Reading Mastery Tests–Third Edition Passage Comprehension (Woodcock, 2011); ADHD = ADHD Rating Scale–IV: Home Version (DuPaul et al., 1998).

score of > 30th percentile on the Goldman-Fristoe Test of Articulation–Second Edition (GFTA-2; Goldman & Fristoe, 2000) unless scores below that percentile were due to consonant errors on a single sound, (d) a standard score of > 87 on the Core Language Composite of the Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003), and (e) a second-grade composite standard score of > 95 on the Test of Word Reading Efficiency–Second Edition (TOWRE-2; Torgesen, Wagner, & Rashotte, 2012).

Children in the dyslexia group met the same inclusionary criteria as the TD group, except they were required to score 88 or below on the TOWRE-2. This cut score is similar to recently published studies of children with dyslexia using TOWRE-2 scores (e.g., 80–86; Goswami, Barnes, Mead, Power, & Leong, 2016; Power, Colling, Mead, Barnes, & Goswami, 2016). Children in the DLD group met the same inclusionary criteria as the TD group, except they were required to score 82 (1 *SD* below the mean plus 1 *SEM*) or lower on the CELF-4 to reflect language impairment. Children in the concomitant dyslexia and DLD group met the same inclusionary criteria as the TD group, except they were required to score 88 or below on the TOWRE-2 and 82 or lower on the CELF-4. In addition, children in the dyslexia, DLD, and concomitant groups could score lower than the 31st percentile on the GFTA-2 as long as they could correctly produce all phonemes on experimental measures, and they were not excluded if they had repeated a grade. Note that our criteria for dyslexia and DLD are simple enough to be objectively applied, unlike practical educational criteria that have to consider clinical judgment; yet, our testing was more extensive than in most studies of these disorders (see Table 1).

We were not able to enroll many children with DLD only (without dyslexia). We undertook several steps to find children with DLD, including speaking directly with more than 40 speech-language pathologists to recruit students. We also instituted classroom screenings using the Test of Silent Word Reading Fluency–Second Edition (Mather, Hammill, Allen, & Roberts, 2004) in 105 second-grade classrooms because a colleague used this procedure to recruit children with DLD in another state (Adlof, Scoggins, Brazendale, Babb, & Petscher, 2017). Despite these efforts and more, most children with language impairment qualified for the comorbid DLD/dyslexia group. We applied stringent inclusionary criteria for the DLD, dyslexic, and comorbid groups because we wished to avoid a confound that often occurs in the literature when children classified as DLD never have their reading tested or children with dyslexia never have their oral language tested. We do not conclude that children with DLD only (without dyslexia) are rare, but we do know that concomitant DLD and dyslexia are common (Catts et al., 2005). It is important to note that the LPA conducted in this study does not depend on diagnostic groups, however, and we felt it was important to include the children who did qualify as having DLD so that important information about those children was not lost.

Table 1 also includes raw scores on the 18-item ADHD Rating Scale–IV (Home Version; DuPaul, Power, Anastopoulos, & Reid, 1998), which asks parents to rate their child's behavior over the past 6 months. The scale items were adapted from the *Diagnostic and Statistical-Manual of Mental Disorders, Fourth Edition* diagnostic criteria for ADHD. The highest possible score is 54, which would be indicative of a high level of concern about attention and/or hyperactivity. Although children with a diagnosis of ADHD were excluded from the study because studying children with three concomitant disorders (e.g., dyslexia, DLD, and ADHD) could make it difficult to interpret our results, we know that functional attention varies in children without a formal diagnosis of ADHD; thus, we documented that variation in children who met inclusionary criteria. For descriptive purposes, we also report standard scores on the Woodcock Reading Mastery Tests–Third Edition for the Passage Comprehension subtest (Woodcock, 2011).

Procedure

After completing assessments, children participated in 13 experimental working memory tasks from the Comprehensive Assessment Battery for Children–Working Memory (CABC-WM; Cabbage et al., 2017; Gray et al., n.d.). A video showing examples of the tasks is available at https://www.jove.com/video/55121 in the *Journal of Visualized Experiments*.

The CABC-WM includes some executive function tasks that do not require working memory and thus are not included in this article. Children also completed word learning tasks not included in this article. Together, the standardized assessments, working memory, and word learning games required about six 2-hr sessions completed over a period of 1–2 weeks.

Each child was seen individually by a trained research assistant (RA) in a quiet location, such as a library, school, or their home. Both were seated side by side, 52 cm from a touch-screen computer monitor, and wore headsets with an integrated microphone. Children rested their dominant response hand on a circle placed 4 in. in front of the computer monitor.

Working Memory Tasks and Scoring

The context of the working memory games is an engaging, computer-based, pirate-themed game where children travel from island to island helping an animated pirate solve problems. Children receive motivational feedback in the form of gold coins or rocks at the end of each game, but they do not receive feedback on individual responses. They spend their gold coins on their personal pirate avatar at a virtual pirate supply store. The computer randomizes the order of task administration across research sessions and within each session. Each game begins with computerized instructions from the guide pirate paired with a demonstration of how to play the game. Training trials follow the demonstration. If the child does not pass training, they do not complete the game. If they do pass training, the game begins.

The percentage of children passing training trials varied from task to task and from group to group (see Table 2). To ensure that the low performance of children who could not pass training was included in the data analyses, we assigned scores for these children. We calculated the level of chance performance on each task. For the *n*-back auditory and *n*-back visual tasks, children responded yes or no for each trial giving them a .50 chance of giving the correct answer; however, we found that some children who passed training averaged lower than .50 on these two tasks. For this reason, we assigned the lowest average score achieved by any student who passed training on these two tasks. All of the other tasks required correct responses on multiple items within a single trial to score a point. Because the odds of earning a point on these tasks by chance were very low, we assigned an average score of 0 on these tasks for any child who did not pass training (see Table 2).

CE Tasks

Each CE task assessed working memory using visual or auditory stimuli requiring storage and manipulation of information. Children were required to maintain an active memory representation of the stimuli while also processing incoming information.

n-Back auditory. A robot band played different instruments that produced pure tones that varied in frequency (1000, 1250, 1500, 1750, and 2000 Hz). Children saw the still image of a robot band and listened to the series of tones. Their task was to decide whether a new tone was the same or different from the previous tone in the sequence. After each tone presentation, the robot band image disappeared and was replaced by a green rectangle response cue that remained on the screen for 3,000 ms. Children responded by pressing a designated key on the keyboard labeled with a green sticker for “same” or a red sticker for “different.” The next trial began immediately after the child’s response or after the 3,000-ms response period ended. Accuracy was recorded by the computer. Children were required to pass four of six training trials, after which they completed three blocks of 18 trials each, nine same and nine different. The dependent variable was the mean accuracy for same and different trials combined.

n-Back visual. Robots played a game with square black game pieces, each with a different pattern of white dots. After each piece was shown, children indicated whether the pattern was the same or different from the preceding game piece. Each game piece remained in the center of the screen for 1,000 ms and then disappeared. A blank response cue screen followed. Children pressed a key with a green sticker to indicate that the piece was the same or a key with a red sticker to indicate that the piece was different. The child’s response triggered the next presentation. If the child did not make a choice after 3,000 ms, the game proceeded to the next screen. The computer recorded the accuracy of each response. Children were required to pass four of six training trials, after which they completed three blocks of 18 trials each, nine same and nine different. The dependent variable was the mean accuracy for same and different trials combined.

Number updating. A toy factory appeared on the screen where yoyos and bears were being made. The child’s job was to keep track of how many of each type of toy was produced. To begin, two black-rimmed squares appeared on the screen, one with a yoyo icon in the background and one with a teddy bear icon in the background. In the foreground of each square, a single digit appeared that remained on the screen for 2,000 ms. Next, the black-rimmed squares were replaced by red-rimmed operation squares showing an addition operation (e.g., + 1) for either the yoyos or teddy bears, indicating that the child should add that many yoyos or teddy bears to the running total. The operation

Table 2. Percentage of children passing training by group, assigned scores for those who did not pass training, and number of assigned scores per task.

Task	Percentage of children passing training by group: TD	Dyslexia	DLD	Dyslexia/DLD	Assigned score for nonpass	Total *n*	*n* With assigned score
n-Back auditory	99	96	88	88	0.37	282	11
n-Back visual	96	89	75	81	0.26	288	25
Number updating	91	79	75	34	0.0	293	61
Digit span	100	99	100	98	0.0	294	2
Digit span running	70	74	50	42	0.0	292	98
Nonword repetition	100	100	100	100	0.0	283	0
Location span	100	99	100	100	0.0	292	1
Location span running	94	90	88	66	0.0	292	34
Visual span	90	91	100	81	0.0	286	31
Visual span running	78	81	83	65	0.0	249	58
Phonological binding	99	100	100	100	0.0	281	1
Visual–spatial binding	93	92	100	86	0.0	290	23
Cross-modal binding	99	100	100	100	0.0	289	1

Note. TD = typical development; DLD = developmental language disorder.

squares remained on the screen for 500 ms. Following this blank, green-rimmed squares with yoyo or teddy bear icons appeared, cueing the child to tell the RA the running total for each type of toy. The computer recorded the verbal response, and the RA entered the two numbers into the computer via keyboard. The next trial began 50 ms after the keyboard response. To score a 1 for the trial, the child had to report correct running totals for both toys. If the child responded with an incorrect number but used that number from that trial forward to correctly report the running total, they scored a 0 for the initial incorrect trial but received credit for subsequent correct trials. Children were required to pass five of five training trials for two blocks, after which they completed three blocks of five trials. The dependent variable was the mean accuracy for all trials.

Short-Term Phonological Memory Tasks

Short-term phonological memory tasks assessed working memory with minimal reliance on lexical knowledge. In running versions, the child could not anticipate the number of items that would be presented before they were asked to recall them. This reduces the likelihood of covert verbal rehearsal (Cowan et al., 2005) and is thought to necessitate the use of attention for storage (Gray et al., 2017).

Digit span. The child played copycat with a robot who read lists of numbers from one to nine (excluding the two-syllable number *seven*) in random order. Spans were from two to eight digits in length. After the presentation of each series, a green rectangle appeared on the screen to cue the child to say as many of the numbers remembered as possible in sequence. The computer recorded verbal responses, and the RA wrote down the child's responses and then entered them into the computer via keyboard. Children were required to pass two of two training trials, after which they completed 14 blocks of two trials at each span length from two to eight. The dependent variable was the sum of the number of trials correct at each span length × the span length.

Digit span running. The child played copycat with sea monsters who spoke lists of seven to 10 numbers. Procedures were similar to digit span, but children did not know how many numbers would be presented, and rather than recall numbers in forward sequence, they were asked to recall as many as they could from the end of the list in forward order. Children were required to remember at least one digit on three trials to pass training, after which they completed 12 blocks with three trials at each span length from seven to 10 digits. The dependent variable was the mean number of digits recalled in the correct order.

Nonword repetition. Children repeated nonwords to help a pirate build a bridge over a river. Each repetition provided one additional piece. Children heard the auditory presentation of a nonword and then repeated it. The computer recorded the response for later scoring in the lab by trained transcribers. The RA advanced the program after each response. The 16 nonwords (four each at two-, three-, four-, and five-syllable lengths) contained low-frequency biphones and had no phonological neighbors. Nonwords of the same syllable length did not differ statistically in spoken duration. Children were required to pass one of three training trials by attempting to repeat 3 two-syllable words. Children scored 1 point for each nonword with all consonant sounds repeated correctly. Articulatory substitutions (e.g., /s/ for /z/) also produced on the GFTA-2 were not scored as incorrect. The dependent variable was the sum of the number of nonwords with all consonant sounds repeated correctly.

Short-Term Visuospatial Memory Tasks

Shapes and locations difficult to associate with verbal labels were used to assess children's short-term memory for visual information. In running versions, the child could not anticipate the number of items that would be presented before they were asked to recall them.

Location span. The child helped the pirate locate buried treasure by remembering where a series of arrows pointed on the screen. First, a black dot appeared at the center of the screen, followed by a series of arrows appearing one at a time for 1,000 ms each. Each arrow pointed to a different location radiating out from the black dot at eight equidistant angles. Following the arrow sequence, eight red dots appeared in a circular pattern around the screen to show all of the possible locations where arrows pointed. These locations were not typical of locations of numbers on the face of a clock. Children touch a red dot, in the correct order, for each location where an arrow had pointed. The red dots remained until the child had touched the correct number of locations, and then the next trial began. Children were required to pass three of three training trials correctly choosing one location on one trial and two locations on two trials, after which they completed 12 blocks with two trials at each span length from two to six. The dependent variable was the sum of the correct number of trials at span length × the span length.

Location span running. The child played the same game as location span but did not know the number of locations that would appear before they were asked to recall as many as they could from the end of the list in forward order. When they finished pointing to all of the locations, they touched a "NEXT" button to start the next trial. Children were required to pass three training trials by correctly pointing to at least one location in spans of six, seven, and eight locations, after which they completed 12 blocks of two trials at each span length from two to six. The dependent variable was the mean number of locations correctly identified across all trials.

Visual span. The child helped the pirate remember, in the correct order, which gems (black polygon shapes) had appeared on the screen. Each gem in the series appeared alone in the center of the screen for 1,000 ms and then was replaced by the next gem. After the last gem, a selection screen with empty response boxes and six gems appeared on the screen. The number of boxes matched the number of gems seen in that trial. As the child selected each gem, they had seen it moved into a box in left to right order, indicating the order seen during the trials. After the final gem was moved, the next trial began. Children were required to pass three of three training trials correctly identifying one gem on one trial and two gems on two trials, after which they completed 12 blocks of two trials at each span length from one to six. To score a 1, gems had to be recalled in the correct order. The dependent variable was the sum of the correct number of trials at each span length × the span length.

Visual span running. The child played the same game as visual span but did not know how many gems would appear before they were prompted to recall them. At the end of the series, six gems appeared on the screen, and children touched them in order to indicate as many as they could recall from the end of the list in forward order. Children were required to pass two of two training trials correctly identifying one gem on each trial of three and four lengths, after which they completed 12 blocks of three trials at each span length from three to six. To score a 1, gems had to be recalled in the correct order. The dependent variable was the mean number of gems correctly identified in order across all trials.

Binding Tasks

Correct responses to binding tasks required children to see or hear two types of stimuli (phonological–phonological, visual–spatial, phonological–visual) and remember them as pairs.

Phonological binding span. The child helped robots remember nonword–sound (e.g., beeps and mechanical noises) pairings to order candy at a candy store. One to four nonword–speech pairings occurred in each series. Nonwords and sounds were not repeated within a series, and nonword–sound pairings differed for each series. The computer drew nonwords at random from a pool of 11 single-syllable consonant–vowel–consonant words with low phonotactic probability (seven to 13 neighbors each). For each trial, a robot appeared on the screen and remained while a nonspeech sound was presented. After 500 ms elapsed, a nonword was presented in the presence of the same robot. At the end of the series, a speaker icon appeared in the center of the screen that played a nonspeech sound. A green rectangle then appeared to prompt the child to say the nonword that had been paired with that nonspeech sound in that series. The computer recorded the child's verbal response for later scoring in the lab by trained transcribers. The RA advanced the computer to the next trial after the child spoke the nonword. A nonword was considered correct if all consonants were produced correctly. Consistent articulatory substitutions were not scored incorrect. Children were required to pass two of two training trials by attempting to produce nonwords on one and two span lengths, after which they completed 20 trials, two trials each of one to four pairs per trial. The dependent variable was the sum of the correct number of trials at each span length × the span length.

Visual–spatial binding span. The child remembered where a shape (black polygon) appeared on a 4 × 4 grid. First, a polygon appeared on the grid for 1,000 ms, followed by a blank grid for 500 ms, and then a new polygon appeared in a different location for 1,000 ms. Up to six polygons appeared, depending on the span length for that trial. After the final polygon in the sequence disappeared, a blank grid appeared next to the six polygons. Children selected polygons and dragged them to the location where they appeared in the grid in correct sequence. A score of 1 was assigned if the entire span length was recreated in the correct order. Children were required to pass two of two training trials by correctly identifying the location on one and two span lengths, after which they completed 12 blocks of two trials at each span length from one to six gems. The dependent variable was the sum of the correct number of trials at each span length × the span length.

Cross-modal binding. The child remembered nonword names for black polygon game pieces. Nonwords contained different vowel sounds and were low in phonotactic probability and neighborhood density. Spans ranged from one to six polygons in length. A polygon appeared on the screen simultaneously with its nonword name. After the last nonword–polygon pair was presented, a selection screen with all six polygons appeared. Children heard each nonword and touched the associated polygon to indicate its correct polygon. Nonwords were not assessed in their presentation order. A score of 1 was assigned if the entire span length was correct. Children were required to pass two of two training trials by identifying the correct polygons on one and two span lengths, after which they completed 12 blocks with two trials at each span length from one to six. The dependent variable was the sum of the correct number of trials at each span length × the span length.

Reliability of Working Memory Tasks

We calculated split-half and split-third coefficients for each working memory task using TD group means or weighted sums. Reliability ranged from a low of .38 for cross-modal binding to .95 for number updating. Other reliabilities include *n*-back visual (.86), *n*-back auditory (.82), location span (.70), location span running (.93), visual span (.73), visual span running (.84), digit span (.67), digit span running (.85), nonword repetition (.60), phonological binding (.53), and visual–spatial binding (.51). We report detailed results in Gray et al. (2017). Discussion regarding the use of internal consistency coefficients in experimental tasks is in Green et al. (2016).

Statistical Analyses

We conducted LPAs in Mplus Version 8.0 (Muthén & Muthén, 2017) using scores on the 13 CABC-WM tasks. LPA is a person-centered analytic approach that classifies individuals into distinct groups (i.e., latent "profiles" or "classes") based on their response patterns for a given set of variables. LPA is a type of finite mixture model, analogous to latent class analysis, but with continuous instead of categorical indicators. LPAs are estimated similar to first-order factor confirmatory factor analyses, where the latent construct is indicated by the observed variables (e.g., Foorman, Petscher, Stanley, & Truckenmiller, 2017) and the profiles are reflective of performance on the observed measures.

The percentage of missing data on the CABC-WM tasks was generally small (ranging from 2.0% to 7.5%), with the exception of the visual span running task, which had 17.5% missing. Overall, 68.5% of the sample did not have any missing data, and 95.4% of the sample had three or less missing data values. There were no differences between diagnostic groups on the amount of missing data. To determine the missing data mechanism for the CABC-WM tasks, we used Little's missing completely at random test (Little, 1988). This test was not significant, $\chi^2(300) = 305.56$, $p = .40$, indicating missing data could be treated as missing completely at random. To address missing data when running the models, we used maximum likelihood with robust standard errors. Maximum likelihood estimation uses all available data to estimate model parameters.

Variables were standardized prior to analyses. We tested models containing between two and six classes. To determine which model solution best fit the data, we used a combination of model fit statistics, entropy, and interpretability of classes. Model fit statistics included the Akaike and adjusted Bayesian information criteria (AIC and aBIC, respectively), Vuong-Lo-Mendell-Rubin likelihood ratio test (VLMR), and adjusted Lo-Mendell-Rubin test (aLMR). The AIC and aBIC statistics are used to compare models where lower values are preferred; Raftery (1995) found that information criteria differences of at least six provide strong evidence of distinguished models. The VLMR and aLMR are used to test whether model c should be selected over model $c - 1$, where c denotes the number of classes estimated. Entropy is a statistic that assesses the degree that individuals are correctly classified into latent classes. A higher value of entropy represents higher certainty in classification, and values greater than .80 indicate that classes are discriminating (Muthén & Muthén, 2017).

External Correlates of Latent Profiles

Following the LPAs, we evaluated whether the working memory profiles were synonymous with disorder group, as they would be if individuals in each disorder demonstrated a similar pattern of working memory deficits. Furthermore, if working memory deficits are additive for DLD and dyslexia, we hypothesized that we should observe a latent profile for individuals with both DLD and dyslexia that is in the lowest scoring range of performance.

Results

LPA Findings

Table 3 contains the means, standard deviations, and correlation matrix for the CABC-WM tasks. Results of the LPAs are presented in Table 4. For the five- and six-class solutions, we were not able to replicate the best log-likelihood, and thus, parameters from these models are untrustworthy, are not included in Table 4, and are not discussed further. Based on the model fit statistics and the interpretability of the classes, we selected the four-class solution as having the best fit. Although the VLMR and aLMR were nonsignificant for the four-class model (indicating that the one cannot conclude that the four-class solution improves fit over and above a three-class solution), the AIC, aBIC, and entropy statistics favored the four-class model. In addition, although the three-class model seemed to separate individuals into high, low, and average performances across the tasks, the four-class model included an additional class ($n = 36$) that performed poorly on the number updating task but average on other tasks.

Table 3. Correlation matrix for Comprehensive Assessment Battery for Children–Working Memory tasks.

	M	*SD*	1	2	3	4	5	6	7	8	9	10	11	12
1. Number updating	0.73	0.39	—											
2. *n*-Back auditory	0.78	0.17	.349**	—										
3. *n*-Back visual	0.69	0.22	.352**	.500**	—									
4. Digit span	17.36	6.96	.196**	.228**	.209**	—								
5. Digit span running	1.52	1.25	.312**	.195**	.277**	.296**	—							
6. Location span	10.19	5.91	.226**	.238**	.334**	.169**	.195**	—						
7. Location span running	1.13	0.69	.357**	.233**	.393**	.221**	.315**	.394**	—					
8. Visual span	6.11	5.06	.271**	.286**	.410**	.145*	.189**	.354**	.326**	—				
9. Visual span running	0.71	0.63	.286**	.191**	.371**	.177**	.386**	.255**	.398**	.332**	—			
10. Nonword repetition	9.58	6.40	.230**	.270**	.239**	.363**	.257**	.119*	.177**	.237**	.232**	—		
11. Cross-modal binding	4.04	2.63	.184**	.210**	.246**	.087	.100	.238**	.152*	.314**	.300**	.136*	—	
12. Phonological binding	11.07	6.73	.131*	.212**	.144*	.238**	.209**	.190**	.180**	.161**	.195**	.342**	.135*	—
13. Visual binding span	4.06	3.07	.169**	.220**	.314**	.045	.205**	.292**	.305**	.432**	.428**	.109	.234**	.120*

*p < .05. **p < .001.

In Figure 1, we plot the standardized means on working memory tasks for the four latent classes. We labeled the four classes low overall ($n = 65$), average with low number updating ($n = 36$), average with high number updating ($n = 90$), and high overall ($n = 111$).

External Correlates of Latent Classes

We next examined the relation between the latent classes and the diagnostic groups. If working memory performance is synonymous with diagnostic group, we should observe similar within-group performance and differing between-groups performance; however, as shown in Table 5 and Figure 2, this was not the case. Children from each of the four diagnostic groups were found in each of the four classes. If working memory deficits are additive, we would expect children with concomitant dyslexia and DLD to be found primarily in the lowest classes. Although the majority of the group (66%) were in the low overall class, 27% were in one of the average classes and 7% were in the high overall class.

Nonverbal IQ, Reading, and Oral Language Scores for Each Working Memory Latent Class

We calculated mean nonverbal IQ, reading, and oral language scores to determine whether there were different patterns of performance for each latent class. We conducted one-way analyses of variance using standard scores from the Kaufman Assessment Battery for Children–Second Edition, the TOWRE-2, and the CELF-4 as dependent variables with latent class as the between-groups factor. Post hoc comparisons utilized a Bonferroni correction, and we report Cohen's *d* effect sizes. Results are illustrated in Figure 3.

There were significant between-groups differences for nonverbal IQ, $F(3, 301) = 39.37$, $p < .001$; reading, $F(3, 301) = 28.46$, $p < .001$; and oral language, $F(3, 301) = 29.48$, $p < .001$, scores. As shown in Figure 3, post hoc analyses for nonverbal IQ indicated that the low overall class scored significantly lower than the average class with high number updating ($p < .001$, $d = 0.86$), the average class with low number updating ($p = .003$, $d = 0.79$), and the high overall class ($p < .001$, $d = 1.48$). The average class with high number updating scored significantly lower than the high overall class ($p = .001$, $d = 0.75$) but was not significantly different from the average class with low number updating. Finally, the average class with low number updating scored significantly lower than the high overall class ($p = .001$, $d = 0.83$).

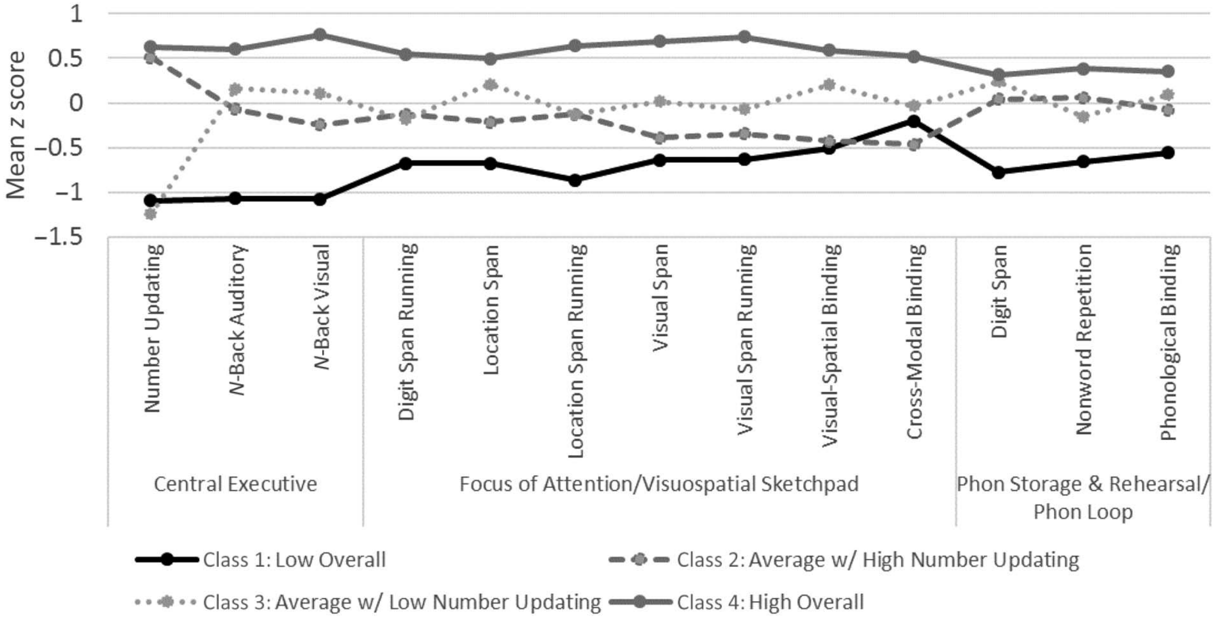
For reading, post hoc analyses indicated that the low overall class scored significantly lower than the average class with high number updating ($p < .001$, $d = 0.80$) and the high overall class ($p < .001$, $d = 1.48$) but did not differ from the average class with low number updating. The average class with high number updating scored significantly lower than the high overall class ($p = .008$, $d = 0.40$) but was not significantly different from the average class with

Table 4. Model fit indices for the two-, three-, and four-class solutions.

Classes	Log likelihood	Parameters	AIC	aBIC	Entropy	VLMR	aLMR
Two	–4707.89	53	9521.771	9550.336	0.89	< .001	< .001
Three	–4602.69	80	9365.375	9408.492	0.84	.04	.04
Four	–4512.90	107	9239.795	9297.466	0.86	.16	.16

Note. AIC = Akaike information criterion; aBIC = adjusted Bayesian information criterion; VLMR = *p* value for the Vuong-Lo-Mendell-Rubin test; aLMR = *p* value for the Lo-Mendell-Rubin test.

Figure 1. Mean *z* scores on the working memory tasks for each of the four latent classes. Phon = phonological.



low number updating. Finally, the average class with low number updating scored significantly lower than the high overall class (p = .001, d = 0.86).

For oral language, post hoc analyses indicated that the low overall class scored significantly lower than the average class with high number updating (p < .001, d = 0.52), the average class with low number updating (p = .020, d = 0.52), and the high overall class (p < .001, d = 1.32). The average class with high number updating scored significantly lower than the high overall class (p = .003, d = 0.52) but was not significantly different from the average class with low number updating. Finally, the average class with low number updating scored significantly lower than the high overall class (p = .001, d = 1.32).

Overall, very large Cohen's d between-groups effect sizes were observed between the low overall and high overall classes (1.32–1.48) on nonverbal IQ, reading, and oral language measures, with the two average classes scoring between the low and high classes. This shows a positive relationship between working memory performance and these measures. However, in Figure 4, we show box and whisker plots for each of the measures for each latent class. These illustrate considerable overlap among scores for each latent profile on each measure. It is important to note that children in the low overall class could not be readily distinguished from those in the average profiles using any of these measures.

Discussion

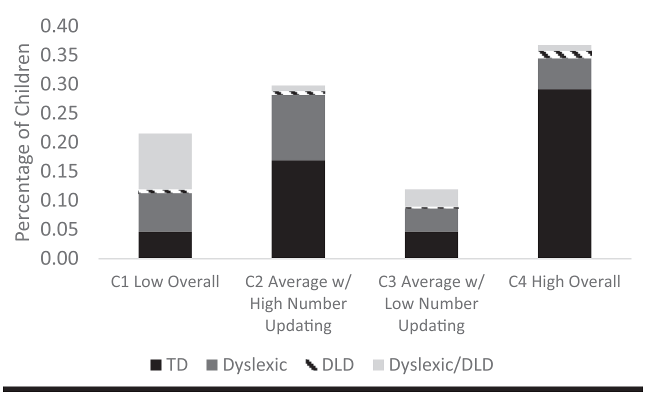
Because working memory is integral to learning, researchers and clinicians would like to know whether children in a particular diagnostic group have similar working memory profiles. If so, this would mitigate the need to include working memory assessments in educational test batteries because working memory scores would add no new information—knowing a child's diagnostic category would also tell you about their working memory strengths and weaknesses. However, our results show that working memory profiles are not synonymous with diagnostic

Table 5. Number (%) of children in each diagnostic group in each latent class.

Group	C1 low overall	C2 average with high number updating	C3 average with low number updating	C4 high overall	Total
TD	14 (8)	51 (31)	14 (8)	88 (53)	167 (55)
Dyslexia	20 (24)	34 (41)	12 (15)	16 (20)	82 (27)
DLD	2 (22)	2 (22)	1 (11)	4 (44)	9 (3)
DLD/dyslexia	29 (66)	3 (7)	9 (20)	3 (7)	44 (15)
Total	65 (21)	90 (30)	36 (12)	111 (37)	302 (100)

Note. C = Class; TD = typical development; DLD = developmental language disorder.

Figure 2. Percentage of children with typical development, dyslexia, developmental language disorder, or concomitant dyslexia and developmental language disorder in each latent class. TD = typically developing; DLD = developmental language disorder.



categories and that working memory deficits do not always co-occur with DLD or dyslexia. To the contrary, children from each learning disability category in our study, as well as TD children, were distributed across working memory classes. This establishes the point that working memory and learning disorders do not coincide but rather intersect. Our data provide estimates of the distribution of working memory skills among children of each diagnostic category.

The most interesting difference among the groups was number updating performance, in which children in Classes 1 and 2 averaged 0.5 *SD* above the mean and children in Classes 3 and 4 averaged 1 *SD* or more below the mean. The CE tasks required children to maintain an active memory representation of auditory or visual stimuli while also processing incoming information, making the tasks very challenging. In fact, Table 2 shows that a lower percentage of children with concomitant dyslexia/DLD passed training for number updating than any other task in the battery. We assigned scores to the children who did not pass training so that their data were included in the profile analysis. However, it is clear from Table 2 that, in relation to other CE tasks and to most other tasks in the battery, maintaining and concurrently updating information may be particularly difficult for second graders and especially for those with concomitant dyslexia/DLD. The pronounced difficulty with number updating in some children may be explained, in part, by how it differed from our auditory and visual *n*-back tasks also used to assess CE function. Ecker, Lewandowsky, Oberauer, and Chee (2010) proposed that, in adults, tasks requiring information retrieval and transformation (e.g., as in number updating in which a child had to add one more number to the last number presented) may be more difficult than tasks requiring only retrieval, such as our *n*-back tasks.

Our results may help explain mixed CE findings in the literature for children with learning disabilities. Studies testing for mean differences are more likely to find them if participants from the TD group come primarily from high-profile working memory classes and participants with learning disabilities come primarily from lower profile classes. The reverse would be true for studies enrolling participants with the opposite patterns.

Our findings highlight the importance of knowing an individual child's working memory profile. CE updating is a significant predictor of academic achievement in children with low reading skills (e.g., Borella, Carretti, & Pelegrina, 2010; Cornoldi, Drusi, Tencati, Giofrè, & Mirandola, 2012) and low mathematical skills (Kolkman, Hoijtink, Kroesbergen, & Leseman, 2013; Van der Ven, Kroesbergen, Boom, & Leseman, 2012). Working memory updating also predicts reading and math achievement in TD children (Lechuga, Pelegrina, Pelaez, Martin-Puga, & Justicia, 2016; St. Clair-

Figure 3. Mean standard scores on tests of nonverbal IQ, reading, and oral language for each latent class. Horizontal bars indicate no significant difference between classes. KABC = Kaufman Assessment Battery for Children; TOWRE = Test of Word Reading Efficiency; CELF-4 = Clinical.

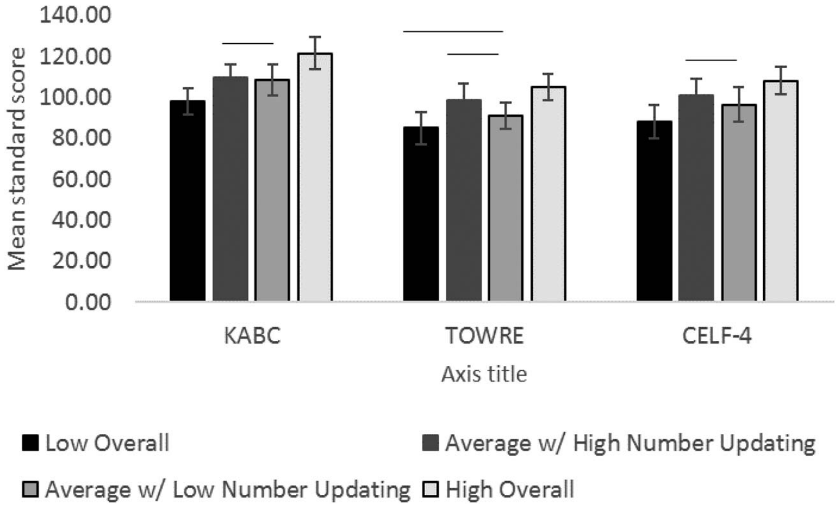
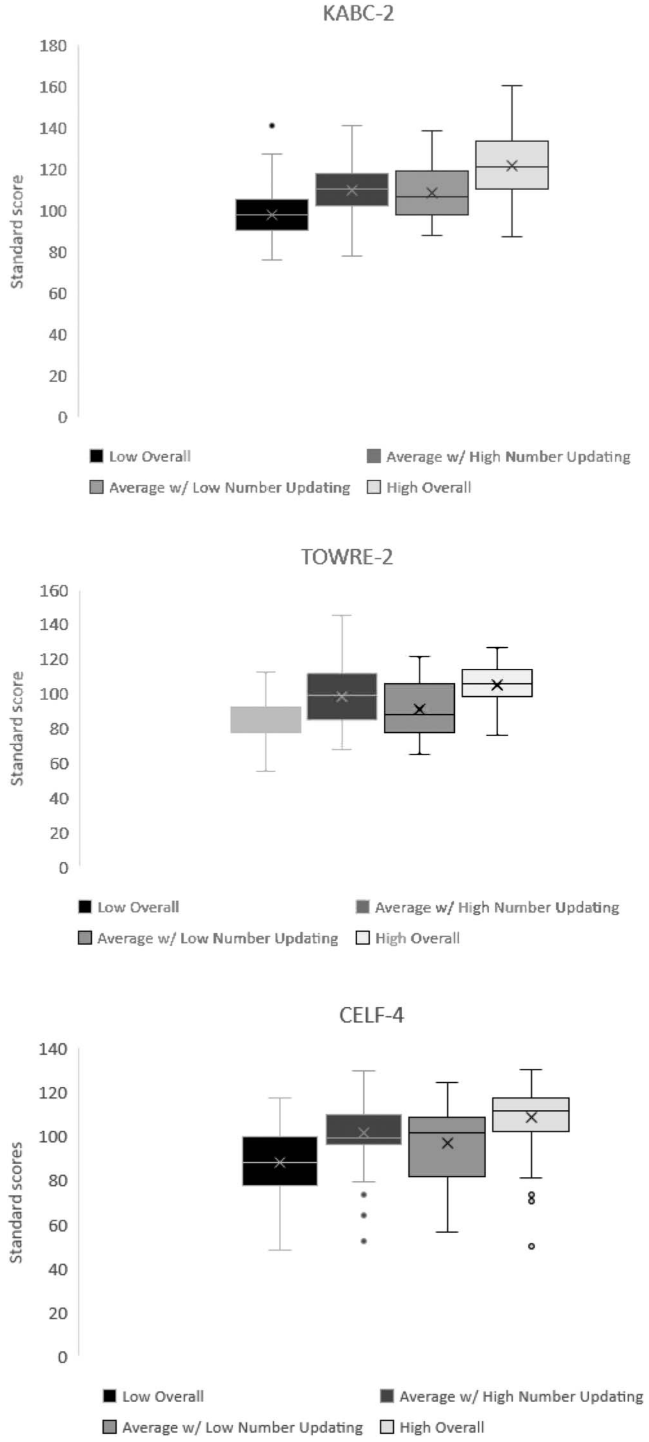


Figure 4. Box and whisker plots for standard scores on tests of nonverbal IQ (Kaufman Assessment Battery for Children–Second Edition [KABC-2]), reading (Test of Word Reading Efficiency–Second Edition [TOWRE-2]), and oral language (Clinical Evaluation of Language Fundamentals–Fourth Edition [CELF-4]) for each latent class. Bottom box represents Quartile 1, top box represents Quartile 3, line represents median, X represents mean, and whiskers represent minimum and maximum scores exclusive of outliers.



Thompson & Gathercole, 2006). Therefore, if teachers and parents knew that their child had particular difficulty with updating or other CE functions, it would be possible for them to adjust instruction accordingly.

We did not include a listening span task (e.g., Daneman & Carpenter, 1980) in our CE battery, although it has been used in many other studies (e.g., Fung & Swanson, 2017; Jeffries & Everatt, 2004; Kail, 2007; Swanson & Sachse-Lee, 2001). Typically, this task requires participants to listen to a series of sentences, answer a question about a topic in one of the sentences, and then recall the last word of each sentence in order. For children with language learning disabilities, this presents a possible confound between language ability, stored background knowledge, and CE function; thus, we do not view this task solely as a working memory measure.

Previously, Maehler and Schuchardt (2016) proposed that children with comorbid conditions, such as dyslexia and ADHD, might experience additive working memory deficits. This is a reasonable assumption given evidence that children with dyslexia (Beneventi, Tønnessen, & Ersland, 2009; Ma et al., 2015; Xu, Yang, Siok, & Tan, 2015) and SLI (Ellis Weismer, Plante, Jones, & Tomblin, 2005) demonstrate differences in brain structure and function compared to their TD peers. If each disability involves different brain structures or functions, having both disabilities could result in more severe deficits. However, we do not yet have brain studies designed to tease apart brain structure or functional differences in children with dyslexia, DLD, or both; therefore, currently, we rely on behavioral research. Some research suggests additive effects on working memory (Schuchardt et al., 2013), but other research finds similar effects for both groups (Alloway, Tewolde, Skipper, & Hijar, 2017; Wong et al., 2017). Our results showed that 66% of the dyslexia/DLD group was in the lowest working memory class, but the remaining 34% was represented in each of the higher classes. This suggests that children with comorbid DLD and dyslexia may be more likely than children with either diagnosis alone to have working memory deficits. Our examination of nonverbal IQ, reading, and oral language scores by working memory class suggests that a child with comorbid DLD and dyslexia, who also has lower nonverbal IQ scores than their peers from other classes, is most at risk for also having working memory deficits.

We did not anticipate finding TD children in the lowest working memory profile, but 8% of the TD group appeared to have working memory deficits. However, this is comparable to findings by Archibald and Gathercole (2006), who reported a likelihood ratio of .11 that children with no history of special education from the standardization sample of the Working Memory Test Battery for Children (Pickering & Gathercole 2001) would be classified as having a working memory deficit. The incidence of children with no reported developmental disorder exhibiting working memory deficits requires further investigation to determine whether children with this profile show concomitant learning difficulties in school.

Recent longitudinal research suggests that working memory development varies considerably between first and third grades and that children with typical development who have low working memory scores in first grade look much more similar to their peers with higher working memory scores by third grade (Nicolaou et al., 2017). Therefore, it may be that children with typical development in the low overall class will “catch up” with their peers as they progress through school. Because this study included only second graders, we do not know whether these classes are stable over time or whether children change classes as they age, but this question is a focus of our ongoing research.

Limitations

To answer our research questions, we used LPA, which is an exploratory statistical technique. To further bolster confidence in our findings, future research should cross-validate these profiles in larger samples. With larger samples in each group, it would be possible to determine whether there is a statistical relationship between class and diagnostic group. In addition, although profile analysis is not based on diagnostic groups, it is unlikely that the small number of students classified as having DLD represents the larger population of those children. Future studies with larger DLD groups are clearly needed. Studies that evaluate the working memory profiles of children who are diagnosed using inclusionary criteria for special education services are also needed, although these criteria may be more dependent on clinical judgment than is ideal for experimental research.

Summary

Working memory is a powerful predictor of learning (Alloway, 2009; Maehler & Schuchardt, 2016). Because many between-groups studies show that children with DLD and dyslexia score lower than their TD peers on working memory tasks, working memory is often assumed to be a concomitant deficit in these children. Our study, which employed a comprehensive, theoretically based set of working memory measures, showed that working memory profiles were not synonymous with learning disabilities group and, in fact, that a small percentage of TD children also appeared to have working memory deficits. These results suggest that working memory assessments could contribute important information about children’s cognitive function over and above typical psychoeducational measures. Given that working memory correlates with cognitive aptitude (e.g., Cowan et al., 2005; Gray et al., 2017), working memory scores provide information that may prove relevant for how well a child can adjust to, or sometimes even overcome, challenges presented by dyslexia or DLD. Future studies assessing the relationship between working memory and specific academic skills are needed, especially research testing whether instructional approaches informed by working memory profiles can improve learning.

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