ASHA American Speech-Language-Hearing Association

JSLHR

Research Article

Working Memory Performance in Children With Developmental Language Disorder: The Role of Domain

Caroline Larson[a,b] and **Susan Ellis Weismer**[a,b]

[a] Department of Communication Sciences and Disorders, University of Wisconsin–Madison [b] Waisman Center, University of Wisconsin–Madison

ARTICLE INFO

Article History:
Received August 2, 2021
Revision received December 6, 2021
Accepted January 14, 2022

Editor-in-Chief: Stephen M. Camarata
Editor: Susan Nittrouer

https://doi.org/10.1044/2022_JSLHR-21-00420

ABSTRACT

Purpose: This study examined working memory in children with developmental language disorder (DLD). The overarching goal of this work was to integrate three primary processing-based hypotheses of DLD, (a) limited verbal working memory, (b) slowed processing speed, and (c) inefficient inhibition of interference, by using the serial-order-in-a-box–complex span (SOB-CS) computational model as our theoretical framework. We also examined the role of domain in working memory performance by varying the domain of interference and recall (i.e., verbal vs. nonverbal) task demands.
Method: Participants were 55 school-age children, 21 children with DLD and 34 age-matched typically developing (TD) peers (9–13 years old).
Results: Findings indicated that verbal and nonverbal working memory performance was poorer in the DLD than TD group. There was a modest benefit of dispersing interference and recall task demands across domains relative to task demands being within one domain, yet verbal interference affected performance to a greater degree than nonverbal interference in the DLD group.
Conclusions: Overall findings supported a role for each of the processing-based hypotheses of DLD, albeit an incomplete role. In contrast, the SOB-CS model accounted for interrelationships among these processing-based factors and provided an explanation across patterns of findings. Thus, the SOB-CS model represents a useful step forward in explaining processing in children with DLD.
Supplemental Material: https://doi.org/10.23641/asha.19526179

School-age children with developmental language disorder (DLD) have verbal deficits relative to typically developing (TD) peers that are not explained by intellectual or biomedical conditions (Bishop et al., 2017; Norbury et al., 2016; Tomblin et al., 1997). The prevalence of DLD is approximately 7% (Norbury et al., 2016), and this disorder negatively impacts long-term academic, vocational, social–emotional, and health-related outcomes (Conti-Ramsden et al., 2012; Whitehouse et al., 2009). Although DLD is primarily characterized by deficits in verbal processes, these children also present with deficits in nonverbal processes, such as those important to working memory performance (e.g., processing speed, inhibition; Vugs et al., 2013). However, prior work suggests that children with DLD perform more similarly to TD peers on working memory tasks with both verbal and nonverbal task demands than performance on tasks with only verbal demands (Gillam et al., 1995; Hoffman & Gillam, 2004). This pattern may be due to poorer resistance to interference in children with DLD relative to TD peers (Marton et al., 2007; Pauls & Archibald, 2016) and due to a greater effect of interference on performance when task demands are limited to the verbal domain (Oberauer et al., 2012). Yet, no prior studies have systematically examined how dispersing task demands across verbal and nonverbal domains relates to interference during working memory performance in children with DLD relative to TD peers.

Correspondence to Caroline Larson, who is now with the Department of Psychological Services, University of Connecticut, Storrs: caroline.larson@uconn.edu. **Disclosure:** *The authors have declared that no competing financial or nonfinancial interests existed with the the time of publication.*

There are three primary hypotheses of processing-based factors that are important to working memory performance, which have been posited as factors underlying DLD in prior work. These hypotheses separately posit the following: (a) limitations in *verbal* aspects of working memory (e.g., verbal mediation; Archibald & Gathercole, 2007; Ellis Weismer et al., 1999), (b) slowed processing speed (Kail, 1994; Miller et al., 2001), and (c) inefficient inhibition of interference (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). One theoretical framework with the potential to unify these hypotheses and further describe working memory in DLD is the serial-order-in-a-box–complex span (SOB-CS) computational model (Oberauer et al., 2012). This interference-based model of working memory posits a key role for time, or *processing speed*, in *inhibiting interference* during *working memory*. The SOB-CS model also accounts for the effects of task demands in the verbal versus nonverbal domain based on interference between representations in working memory. Thus, it may provide an integrated framework for examining working memory in children with DLD.

It should be noted that the literature we discuss in this article adopted varied terms for developmental language impairment, with most of the studies using the terminology and criteria for specific language impairment (SLI). As typically defined, SLI entails the same language criteria as DLD but a more restricted range of nonverbal IQ that is within the average range of TD peers (standard score of at least 85). To meet criteria for DLD, nonverbal cognition is only required to be above the intellectual disability cutoff (standard score of at least 70). There is evidence that supports collapsing groups of children with language disorder who have average and below average nonverbal abilities (Bishop et al., 2016; Dennis et al., 2009; Gallinat & Spaulding, 2014; Norbury et al., 2017). In line with diagnostic criteria employed in this study and for the sake of consistency, we use the term *DLD* throughout this article. We would direct readers interested in a discussion of terminology and group classification to Volkers (2018).

Working Memory on Verbal and Nonverbal Tasks

Limitations in verbal working memory have been hypothesized to give rise to language deficits in DLD (Archibald & Gathercole, 2007; Ellis Weismer et al., 1999; Leonard et al., 2007), based on evidence of poorer performance on measures of verbal working memory for children with DLD relative to TD peers. Children with DLD are generally slower and less accurate than TD peers on verbal working memory tasks, which may lead to difficulty with language comprehension (e.g., with passive sentences which involve maintaining information about the object of the verb *prior to* hearing the verb and the subject; Archibald & Gathercole, 2007; Ellis Weismer et al., 1999; Mainela-Arnold et al., 2006; Montgomery & Evans, 2009), but also on working memory tasks that are nonverbal in nature, such as mental rotation tasks (Dispaldro et al., 2013; Smolak et al., 2020; but see Blom & Boerma, 2020). Vugs et al.'s (2013) meta-analysis on nonverbal working memory showed deficits in DLD relative to TD peers with a large effect size (d = .63).

Only two studies have contrasted performance on working memory tasks with varied verbal and nonverbal demands in children with DLD relative to TD peers (Gillam et al., 1995; Hoffman & Gillam, 2004). Gillam et al. (1995) examined performance accuracy on working memory tasks that varied the domain of recall items (e.g., verbal, verbal–visual) and response modality (i.e., verbal vs. pointing) whereas Hoffman and Gillam (2004) varied the domain of recall (e.g., verbal, nonverbal) and an interference processing task (e.g., pointing to a matching color). Both studies showed that the DLD and TD groups performed more poorly in the condition with demands within the verbal domain relative to the conditions with demands divided between verbal and nonverbal domains. Gillam et al. (1995) showed that the DLD group performed most similarly to TD peers when task demands were distributed across the verbal and nonverbal domains (e.g., verbal–visual items), suggesting a performance benefit when dispersing processing across domains during a working memory task for children with DLD (i.e., may also be viewed as a combined-cue condition). Hoffman and Gillam (2004) showed that children with DLD benefitted to a lesser degree than TD peers when processing was divided between domains relative to when processing was limited to a single domain (i.e., either verbal or nonverbal) during a working memory task.

Considering these two studies together, there may be a lesser performance benefit for dividing processing between domains than distributing processing across domains for children with DLD during working memory performance. However, Hoffman and Gillam (2004) did not include a distributed-domain condition and, although Gillam et al. (1995) did include a distributed-domain condition, it did not include an interference task. Rather, the design involved varying the domain of recall item and response modality. As a result, it is difficult to compare findings between these two studies in order to understand how different levels of interference relate to working memory performance in DLD.

Integrative Theoretical Framework

Beyond the relationship between domain (verbal/nonverbal) and working memory performance, it has been hypothesized that two other key factors thought to underlie DLD also share an important relationship with working memory performance. The generalized slowing hypothesis suggests that slowed response time on verbal or nonverbal tasks that draw on working memory (e.g., grammaticality judgment, mental rotation) leads to downstream effects on language in DLD (e.g., language unfolds over time and slowed processing may be associated with poor parsing of the speech stream; Kail, 1994; Miller et al., 2001) and the inefficient inhibition hypothesis suggests that slower and less accurate inhibition of interference leads to downstream effects on language in DLD (e.g., confusion between similar-sounding words or inaccurate interpretation of the object and subject in passive sentences; Bjorklund & Harnishfeger, 1990; Marton et al., 2007). Prior work shows slowed reaction time (RT) across verbal and nonverbal processing tasks, including working memory tasks, for children with DLD relative to TD peers, which is argued to lead to disproportionate difficulty with language (Kail, 1994; Leonard et al., 2007; Miller et al., 2001). Performance RT and accuracy on inhibition tasks has been linked to extant language abilities (Blom & Boerma, 2020; Dispaldro et al., 2013), later language outcomes (Kapa & Erikson, 2020; Larson et al., 2020), and to working memory in children with DLD (Marton et al., 2007). It is necessary, therefore, to examine the role of domain in working memory performance using a framework that captures domain effects and interrelationships among working memory, processing speed, and inhibition.

The SOB-CS model is an interference-based computational model of working memory that has the potential to capture the roles of factors thought to be important to working memory and thought to be important to DLD (i.e., verbal aspects of working memory, processing speed, inefficient inhibition; Oberauer et al., 2012). It involves a neural network with separate layers for item (e.g., a word) and serial position (e.g., first in a list), represented as distributed activation patterns. The item layer represents item features on a continuum, with the same processing units capable of representing either verbal (e.g., phonemes) or nonverbal (e.g., spatial location; also referred to as visuospatial) features depending on activation patterns. The position layer similarly represents temporal properties of input over the same set of processing units (e.g., first or last position in a list). Representations in working memory have item and position features as items are bound to context positions in a single weight matrix (Oberauer et al., 2012, 2016). Accordingly, interference may arise due to overlap in features or due to proximity in context positions. The degree to which representations interfere is also governed by a time-based active removal mechanism—*free time*. Free time occurs when there are unfilled intervals between cognitive operations, such as a pause between a processing task response and item recall. These unfilled intervals allow for items to be unbound from context positions and either forgotten or transferred to long-term memory, thus restoring working memory to a baseline state (Oberauer et al., 2012). Free time is necessarily related to processing speed as faster processing is likely to afford more time between cognitive operations relative to slower processing, and therefore, less interference between representations.

Under the SOB-CS model, items that are from the same domain are more likely to interfere than items from different domains per the degree to which they have similar features, whereby the relative role of verbal versus nonverbal encoding during performance is tested (e.g., verbal mediation vs. perceptual mediation; Oberauer et al., 2012). For instance, the word *frog* is more likely to interfere with the word *log* than the word *seven* for several reasons: (a) *frog* and *log* have more shared phonemic and syllabic features, (b) *frog* and *log* share a semantic relationship, and (c) *frog* and *log* are from the "word" category whereas *seven* is from the "digit" category. Relative strengths in a given domain may increase the representational distinctiveness of items from that domain and lead to a diminished likelihood of interference between those items (e.g., precise phonological and semantic representations of *frog* and *log* rather than confusion with an interfering word, such as *bog*; Oberauer et al., 2012). In children with DLD, for instance, nonverbal representations (e.g., shapes) may be less likely to interfere than verbal representations (e.g., words) due to relative strengths in representing nonverbal relative to verbal information. Accordingly, the SOB-CS model has the potential to capture interrelationships among processing speed, domain effects, and inhibition of interference in children with DLD.

This Study

This study examined the role of domain in working memory performance, similarly to Gillam et al. (1995) and Hoffman and Gillam (2004), but using a fully crossed design, unlike these two prior studies. Our working memory task structure was the same across conditions and was consistent with our theoretical framework of working memory, the SOB-CS model (Oberauer et al., 2012; see also Leonard et al., 2007). This model integrates key factors hypothesized to be important to working memory and hypothesized to underlie DLD. This framework is also a useful step forward, relative to prior related studies, in testing the role of domain in working memory because it captures how the domain of representations relates to working memory performance based on how representations interfere in working memory. Thus, this study is the first to clarify the degree to which dispersing processing across domains during working memory affects performance in school-age children with DLD relative to TD peers under a unified theoretical framework. We asked, how does working memory performance differ between school-age children with DLD and age-matched TD peers on tasks with: (Research Question [RQ] 1) demands within verbal or nonverbal domain, (RQ2) tasks with demands divided between verbal and nonverbal domains, and (RQ3) demands divided between verbal and nonverbal domains compared to tasks with demands distributed across both verbal and nonverbal domains?

Given that Gillam et al. (1995) and Hoffman and Gillam (2004) are closely related to the current work relative to other prior work, our hypotheses are based on their findings and specific predictions of the SOB-CS model (Oberauer et al., 2012). Our first prediction was that DLD and TD groups would perform better on tasks with demands divided between domains than tasks with demands within one domain, due to a lesser degree of interference when demands are divided between domains, but that the TD group would derive greater performance benefit. Our second prediction was that DLD and TD groups would perform better on tasks with demands distributed across domains than tasks with demands divided between domains, due to a lesser degree of interference when demands are distributed across domains at each phase of the task, but that the DLD group would derive greater performance benefit.

Method

Participants

This study was approved by the Education and Social/Behavioral Institutional Review Board at the University of Wisconsin–Madison. Participants were recruited from the Madison metropolitan area and nearby regions and school districts via the Waisman Center Clinical Translational Core, local contacts, and online outreach as part of a larger remote-based project on language and working memory in children with DLD (Larson, 2021). We administered assessments and experimental tasks remotely, due to this study taking place during the COVID-19 pandemic, over two visits that lasted approximately 2 hr each and were separated by 1 week or less. We used Zoom (i.e., a secure videoconferencing platform), and we provided a dedicated laptop computer (Dell Inspiron, Intel Core i5, Windows 10) to each participant for use during this study. We video-recorded parental verbal informed consent and child verbal assent. Parents received a written copy of the consent form prior to the first study session. Sixty-one participants were evaluated for the current study, and six were deemed ineligible due to the following reasons: history of traumatic brain injury (1), bilingualism (1), and history of speech-language or dyslexia services and not meeting criteria for the DLD group (4; e.g., history of speech-language services and all standardized language scores with the normal range). There were twenty-one 9- to 13-year-old children with DLD (M = 10.46 years, SD = 1.09 years) and 34 age-matched peers with typical development (M = 10.47 years, SD = 1.08 years; p = .95).

No participant had a history of failed hearing screening or hearing loss, had normal or corrected-to-normal vision, were monolingual, and had no known history of biomedical conditions associated with their language disorder based on parent report (e.g., autism spectrum disorder). Parents of participants provided maternal education information, a socioeconomic status (SES) proxy, as part of the background history questionnaire that also included developmental and medical history of the participant. Eligibility for the TD group was (a) no parental report of language delay or intervention, and (b) standard scores ≥ 85 on the Core Language, Expressive Language, or Language Content composite indices of the Clinical Evaluation of Language Fundamentals–Fifth Edition (CELF-5; Wiig et al., 2013). Note that all TD participants had nonverbal t-scores within the normal range (≥ 40) on the Matrix Reasoning subtest from the Wechsler Abbreviated Intelligence Scale–Second Edition (WASI-II; Wechsler, 2011), except one participant who had a t-score of 32 (i.e., above the intellectual disability cutoff of 30) and no history of developmental disability (see Supplemental Material S1 for additional participant information).

Eligibility for the DLD group was based on Bishop et al. (2017) and included (a) nonverbal t-scores > 30 on the Matrix Reasoning subtest from the WASI-II and (b) standard scores on the Core Language, Expressive Language, or Language Content composite index 1.2 *SD*s below the mean (≤ 82) on the CELF-5 (see Volkers, 2018, for a discussion on DLD). This CELF-5 criterion exceeds recommended sensitivity and specificity levels (e.g., .80 sensitivity and specificity; Nitido & Plante, 2020). See Table 1 for demographic information and standardized test scores for participants and see Supplemental Material S1 for two minor exceptions to these criteria. All assessments were conducted using videoconferencing and digitized forms of the stimulus materials.

We also administered the Conners-3 abbreviated parent interview (i.e., a screening for attention-deficit/hyperactivity disorder), a sustained attention task adapted with permission from Finneran et al. (2009), and a sentence comprehension task adapted with permission from Robertson and Gallant (2019) as part of the larger project. Participants did not differ significantly in Conners-3 t-scores (p = .34); however, both groups had mean t-scores indicating elevated symptoms, potentially related to COVID-19 conditions (e.g., home-based education, reduced child care resources). Participants also completed baseline visual and auditory RT tasks, and groups did not differ significantly on these measures when accounting for group differences in SES (DLD: M = 15.71 ms, SD = 1.45 ms; TD: M = 17.42 ms, SD = 2.53 ms; ps > .05). All assessments and

Table 1. Demographic information and standardized test scores for study participants.

Participant characteristics	TD (*n* = 34)	DLD (*n* = 21)	*p* value
Sex assigned at birth	F = 14 M = 20	F = 9 M = 12	
Race/ethnicity			
African American	1	0	
African American–Caucasian	0	2	
Asian American–Caucasian	5	1	
Caucasian/White	28	17	
Hispanic/Latino	0	1	
Age in years			
M	10.47	10.46	*p* = .95
SD	1.08	1.09	(r^2 = −.02)
Maternal education in years (SES)			
M	17.42	15.71	TD > DLD**
SD	2.53	1.45	(r^2 = .12)
WASI-II (matrix reasoning)			
M	58.00	46.05	TD > DLD***
SD	9.50	11.23	(r^2 = .24)
Conners t-score (attention)			
M	67.21	72.40	*p* = .34
SD	17.01	22.09	(r^2 = −.00)
Core Language (CELF-5)			
M	112.59	82.95	TD > DLD***
SD	12.14	10.39	(r^2 = .61)

Note. There was no change in statistical effects for TD-DLD comparisons when covarying socioeconomic status (SES) WASI-II = Wechsler Abbreviated Intelligence Scale–Second Edition, Matrix Reasoning subscale; Conners t-score = abbreviated parent interview for attention deficit/hyperactivity disorder (ADHD), note that higher scores reflect more ADHD symptoms; CELF-5 = Clinical Evaluation of Language Fundamentals–Fifth Edition; Standard scores are reported for the CELF-5 and t-scores are reported for the WASI-II; TD =typically developing; DLD = developmental language disorder. Standard scores are reported for the CELF-5, and t-scores are reported for the WASI-II. TD =typically developing; DLD = developmental language disorder; WASI-II = Wechsler Abbreviated Intelligence Scale–Second Edition, Matrix Reasoning subscale; Conners t-score = abbreviated parent interview for attention-deficit/hyperactivity disorder (ADHD) note that higher scores reflect more ADHD symptoms; CELF-5 = Clinical Evaluation of Language Fundamentals–Fifth Edition.

**$p < .01$. ***$p < .001$.

tasks were administered by the first author, a doctoral candidate with certification in speech-language pathology and training as a research assistant.

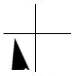
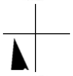
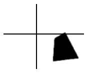
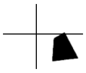
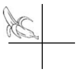
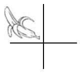
Experimental Tasks

The experimental task structure aligned with current views of working memory as a construct according to our theoretical framework and other prior work (Leonard et al., 2007; Oberauer et al., 2012, 2016). This structure involved presentation of potential recall items, an interference processing task, and recall of target items paired with serial information (i.e., not simple recognition). Our experimental paradigm was a fully crossed design with five conditions (see Table 2), and our dependent variables were recall test accuracy and RT. This paradigm was drawn from the Brown-Peterson design, which involves, for instance, presenting a string of letters, then an interference task involving counting backward by three, and finally testing recall of the string of letters in the correct sequence (e.g., Siffredi et al., 2017).

Stimuli

Stimuli included the following: auditorily presented words with associated images, visually presented abstract shapes (i.e., not easily labeled), visually presented faces/nonfaces, auditorily presented words/nonwords, and auditorily presented questions (see Table 2 for examples). The same speaker (not the examiner) produced all auditory stimuli and had a neutral Midwest accent. All auditory word/nonword stimuli were one to two syllables in length and were normalized to 65 dB and 650 ms. We selected words based on the most frequently occurring, readily depictable nouns from the CHILDES database (MacWhinney, 2000; Warren corpora; Warren-LeuBecker & Bohannon, 1984). These stimuli were supplemented with nouns selected from the MacArthur–Bates Communicative Development Inventories (Fensen et al., 2007; i.e., criterion assessment of early language ability), rather than selecting infrequently occurring words, under the assumption that all participants had already mastered these words. Nonwords were acquired from the ARC Nonword Database (Rastle et al., 2002) and generated with frequency statistics information. All

Table 2. Description of experimental conditions.

	Recall training phase		Interference processing phase		Recall test phase	
Task	**Stimulus**	**Example**	**Stimulus**	**Example**	**Stimulus**	**Example**
Within	Verbal (word–image)		Verbal (word/nonword judgment)	"Teeg"	Verbal (word–image)	
	Nonverbal (shape location)		Nonverbal (face/nonface judgment)		Nonverbal (shape location)	
Divided	Verbal (word–image)		Nonverbal (face/nonface judgment)		Verbal (word–image)	
	Nonverbal (shape location)		Verbal (word/nonword judgment)	"Glue"	Nonverbal (shape location)	
Distributed	Verbal nonverbal (word–image location)		Verbal nonverbal (auditory word location judgment)	"Door" ⇦	Verbal nonverbal (word–image location)	

Note. Nonverbal stimuli and distributed condition examples represent the item and the location of the item in one of four quadrants, indicated here via t-shaped lines (quadrant lines are not visible to participants for the experimental tasks).

auditory question stimuli were five words in length and normalized to 65 dB and 1,600 ms. All visual stimuli were black and white and normalized to 4 × 4 and 600 pixels. The word–images were prototypical exemplars edited in Adobe Photoshop CS (2004), the abstract shapes were four-sided shapes adapted with permission from Ceaser and Barch (2016; similar to the random shapes of Vanderplas and Garvin, 1959), and faces/nonfaces were adapted with permission from Siffredi et al. (2017). Verbal stimuli did not differ by condition on length, frequency, or category characteristics (ps > .31), and nonwords did not differ in length or frequency of phonological neighbors (ps > .07). See Supplemental Material S1 (Tables S1 and S2) for by-condition comparisons of stimuli features.

Task Design

Each trial had recall training, interference processing, and recall test phases across conditions, and brief unfilled intervals between each phase based on task piloting (150 ms). We will describe one condition in detail due to the task structure being the same across conditions, but see Supplemental Material S1 for detailed descriptions of other conditions and minor task timing differences (see also Table 2). The verbal-within domain condition involved three sequentially presented words and their associated images that appeared in the center of the screen for the recall training phase. The interference processing phase involved a word/nonword, followed by a question prompt ("Is that a real word?") and then a second presentation of the word/nonword. Participants had 3,300 ms after the word/nonword offset to respond, and the recall test phase did not begin until after the 3,300 ms had elapsed (i.e., rather than after the participant responded). For the recall test phase, two of the three recall training phase word–image pairs were presented again. The images appeared on the right or left side of the screen; image locations were pseudorandomized. Participants were to select the item that appeared earlier in the recall training phase sequence of presentation, thereby assessing item plus serial position. Auditory words were sequentially presented; and images appeared simultaneously at recall test. Participants had 5,050 ms after the offset of the second auditory word to respond prior to the offset of the trial (see the works of Hoffman & Gillam, 2004, and Siffredi et al., 2017, for similar task timing).

Procedure

Tasks were administered using Zoom and E-Prime Go (Psychology Software Tools, 2016)—a subprogram of E-Prime 3 designed for remote data collection. Instructions were provided using Zoom and a PowerPoint presentation, and Zoom was running during experimental task administration allowing the experimenter to monitor participation. E-Prime Go experiment files were saved locally, and the experiment ran identically to in-lab procedures.

Conditions were administered in blocks and counterbalanced across participants in two separate remote-based visits. Participants selected their response by clicking the mousepad for all experimental tasks. Each condition involved two complete instructional trials with experimenter verbal–visual instruction and feedback (e.g., "pick the winner," paired with highlighting the selection with the mouse icon), three practice trials with automated visual feedback (e.g., smiley face), and 15 experimental trials. Instructions were broadly balanced in having verbal and visual information, and children were able to ask questions at any time during instruction. The three practice trials had automatized visual feedback, and participants who indicated that they received sad faces were offered three additional practice trials. No participants failed the recall test for all three additional practice trials, and all participants demonstrated comprehension of instructions.

Analysis

We analyzed RT on correct response trials using linear mixed-effects models and accuracy (0,1) using generalized linear mixed-effects (GLM) models with random by-subject intercepts and random by-condition slopes in R (R Core Team, 2019; R Studio Team, 2020; Version 1.2.5033). We used gold standard generalized linear mixed-effects models due to the binomial distribution of our trial-level accuracy data (Brauer & Curtin, 2018), and we then converted b estimates from the GLM models to odds ratios for interpretability as the GLM b estimate is a logistic function of the odds (i.e., log-odds or linear function) of the association between the predictor and the outcome variables (note that we also report untransformed b estimates). We removed observations that exceeded acceptable levels of leverage and model influence (Judd et al., 2008), observations that were ≥ 3 *SD*s from each subject's mean (0.1% of the data) and RT observations that were < 150 ms (0.3% of the data). These data were treated as missing data in the next analysis step. We conducted follow up within-group analyses based on descriptive performance patterns (e.g., Table 3) and significant Group × Condition interactions using mixed-effects linear models (see Supplemental Material S2 for complete statistical output).

Covariates

Maternal education, our proxy for SES, was a covariate in all mixed-effects models with a group contrast due to evidence of significant group differences ($p < .01$). Nonverbal ability was not a covariate in statistical models due to the high overlap in working memory and fluid intelligence ability (Leonard et al., 2007) and nonverbal ability potentially being a key DLD-TD group differentiating characteristic (Kover & Atwood, 2013). We covaried interference task performance where groups differed significantly.

Missing Data

One participant from the DLD group had incomplete data due to completing only one of two study sessions, and we removed extreme observations (see above). These data were not missing completely at random; therefore, we used the gold standard approach to handling missing data—multiple imputation. Multiple imputation is a

Table 3. Descriptive statistics and by-group *t* tests for working memory experimental task conditions, recall reaction time and accuracy (see Interference Processing Task Descriptive Performance and *t* Tests section for interference processing task descriptive performance).

Condition	TD (n = 34)	DLD (n = 21)	p value
Verbal within			
Accuracy	M = 0.89	M = 0.67	TD > DLD***
	SD = 0.12	SD = 0.26	r^2 = .24
Reaction time	M = 1963.12	M = 2176.00	p = .12
	SD = 461.78	SD = 509.12	r^2 = .03
Verbal divided			
Accuracy	M = 0.91	M = 0.77	TD > DLD**
	SD = 0.12	SD = 0.20	r^2 = .15
Reaction time	M = 1793.02	M = 1930.52	p = .30
	SD = 430.74	SD = 510.12	r^2 = .00
Nonverbal within			
Accuracy	M = 0.87	M = 0.72	TD > DLD**
	SD = 0.14	SD = 0.21	r^2 = .14
Reaction time	M = 1942.82	M = 2161.63	p = .16
	SD = 516.19	SD = 599.74	r^2 = .02
Nonverbal divided			
Accuracy	M = 0.90	M = 0.67	TD > DLD***
	SD = 0.12	SD = 0.26	r^2 = .25
Reaction time	M = 2251.03	M = 2684.55	TD < DLD*
	SD = 684.68	SD = 879.77	r^2 = .05
Distributed			
Accuracy	M = 0.89	M = 0.76	TD > DLD**
	SD = 0.10	SD = 0.21	r^2 = .15
Reaction time	M = 2089.22	M = 2528.06	TD < DLD*
	SD = 531.30	SD = 829.71	r^2 = .08

Note. Reaction time values are reported only for correct trials. Outlier observations have been removed. M = mean; SD = standard deviation; TD = typically developing; DLD = developmental language disorder.

*$p < .05$. **$p < .01$. ***$p < .001$.

simulation-based approach where multiple complete datasets are generated (i.e., imputations), statistical analyses (e.g., mixed-effects models) are performed on each imputation, and then the multiple analyses are combined using Rubin's rules (Rubin, 1987; van Buuren & Groothuis-Oudshoorn, 2011). We used the mice package with predictive mean matching for continuous data (e.g., RT) and logistic regression imputation for binary data (e.g., accuracy; van Buuren & Groothuis-Oudshoorn, 2011) in R (R Core Team, 2019; R Studio Team, 2020; Version 1.2.5033). Data were imputed within subsets consistent with the substantive model (e.g., reflecting interaction terms; Bartlett et al., 2015), and all statistical results were based on multiple imputation statistical analyses. See Supplemental Material S2 for complete statistical output.

Results

Interference Processing Task Descriptive Performance and *t* Tests

Verbal Interference Task

Verbal-within accuracy was significantly poorer for the DLD (M = 0.82, SD = 0.16) than the TD group (M = 0.92, SD = 0.11; b = 0.08; t value = 2.19; $p < .05$), and RT did not differ significantly between groups (DLD: M = 1210.13, SD = 476.10; TD: M = 1027.46, SD = 323.14; p = .21), controlling for SES (ps > .25). Nonverbal-divided accuracy did not differ significantly between groups (DLD: M = 0.78, SD = 0.15; TD: M = 0.84, SD = 0.11; p = .14), but RT was significantly slower for the DLD group (M = 990.36, SD = 405.94) than the TD group (M = 1225.55, SD = 344.77; b = 260.28; t value = 2.35; $p < .05$), controlling for SES (ps > .50).

Nonverbal Interference Task

Nonverbal-within accuracy (DLD: M = 0.91, SD = 0.09; TD: M = 0.95, SD = 0.10; p = .25) and RT did not differ significantly between groups (DLD: M = 1942.71, SD = 394.95; TD: M = 2007.81, SD = 422.10; p = .36), controlling for SES (ps > .25). Similarly, verbal-divided accuracy (DLD: M = 0.91, SD = 0.10; TD: M = 0.94, SD = 0.09; p = .17) and RT did not differ significantly between groups (DLD: M = 1992.16, SD = 450.40; TD: M = 2089.71, SD = 445.28; p = .36), controlling for SES (ps > .24).

Distributed Interference Task

Distributed accuracy was significantly poorer for the DLD (M = 0.85, SD = 0.18) group than the TD group (M = 0.94, SD = .09; b = 0.08; t value = 2.12; $p < .05$), but RT was not significantly different between groups (DLD: M = 1141.36, SD = 371.6; TD: M = 1139.68, SD = 282.71; p = .92), controlling for SES (ps > .71).

Experimental Task Recall Accuracy

RQ1: Verbal Within Versus Nonverbal Within

There was a significant effect of group (b = −1.87; stat = −3.51; $p < .001$), indicating that the DLD group had worse odds of a correct response by a factor of 6.5 than the TD group, and there were no other significant effects (ps > .28). Follow up analyses showed that the DLD group had significantly worse odds of a correct response by a factor of 1.4 in the verbal-within than nonverbal-within condition (b = 0.34; stat = 3.84; $p < .001$), and the TD group had significantly better odds of a correct response by a factor of 1.3 in the verbal-within than nonverbal-within condition (b = −0.22; stat = −2.50; $p < .05$). See Figure 1.

RQ2: Verbal Within Versus Verbal Divided

There was a significant effect of group (b = −2.03; stat = −3.77; $p < .001$), indicating worse odds of a correct response by a factor of 7.6 for the DLD than TD group, and no other significant effects (ps > .30).

RQ2: Nonverbal Within Versus Nonverbal Divided

There was a significant effect of condition (b = 0.68; stat = 2.02; $p < .05$), indicating better odds of a correct response by a factor of 2.0 in the nonverbal-within than nonverbal-divided condition, and a significant effect of group (b = −1.19; stat = −2.48; $p < .05$), indicating that the DLD group had worse odds of a correct response by a factor of 3.3 than the TD group. There were no other significant effects (ps > .12). We conducted follow-up analyses based on descriptive performance patterns, which showed that the DLD group had significantly better odds of a correct response by a factor of 1.4 in the nonverbal-within than nonverbal-divided condition (b = −0.33; stat = −3.69; $p < .001$), and the TD group had significantly worse odds of a correct response by a factor of 1.5 in the nonverbal-within than nonverbal-divided condition (b = 0.42; stat = 4.36; $p < .001$).

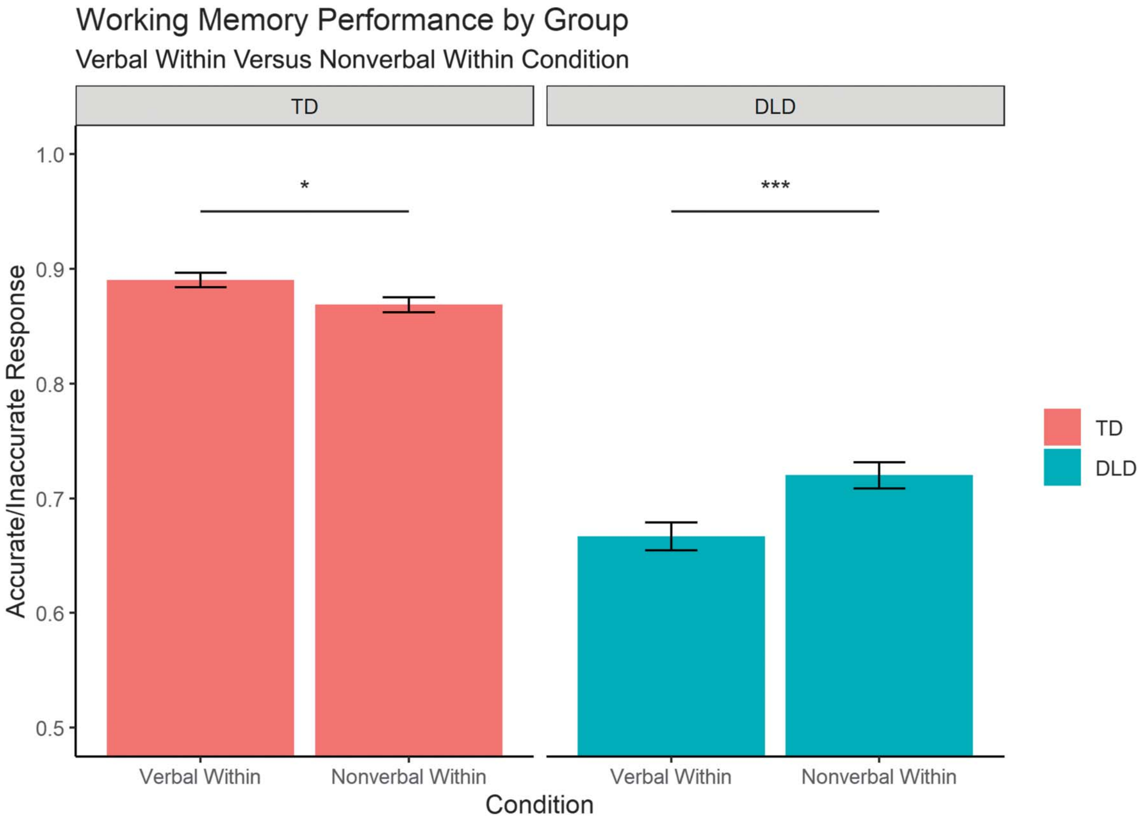
RQ3: Verbal Divided Versus Distributed

There was a significant effect of group (b = −1.44; stat = −3.05; $p < .01$), indicating that the DLD group had worse odds of a correct response by a factor of 4.2 than the TD group, and no other significant effects (ps > .06). We conducted follow up analyses based on descriptive performance patterns which showed no significant effect of condition for the DLD group (p = .36), whereas the TD group had significantly better odds of a correct response by a factor of 1.3 in the verbal-divided than distributed condition (b = −0.29; stat = −2.97; $p < .01$).

RQ3: Nonverbal Divided Versus Distributed

There was a significant effect of group (b = −1.81; stat = −3.23; $p < .01$), indicating that the DLD group had

Figure 1. Group differences in verbal-within versus nonverbal-within condition accuracy. *y*-axis range is 0.50–1.0. TD = typically developing; DLD = developmental language disorder. **p* < .05. ****p* < .001.



worse odds of a correct response by a factor of 6.1 than the TD group. There was a significant effect of distributed-condition interference accuracy (*b* = 2.26; stat = 3.18; *p* < .01), and there was a significant Group × Condition interaction (*b* = 0.94; stat = 2.33; *p* < .05). There were no other significant effects (*p*s > .06). Follow-up analyses showed that the DLD group had significantly worse odds of a correct response by a factor of 1.8 in the nonverbal-divided than distributed condition (*b* = 0.57; stat = 6.22; *p* < .001), and no significant effect of condition for the TD group (*p* = .10). See Figure 2.

Experimental Task Recall RT

RQ1: Verbal Within Versus Nonverbal Within

There were no significant effects (*p*s > .12).

RQ2: Verbal Within Versus Verbal Divided

There was a significant effect of condition (*b* = −180.54; stat = −2.38; *p* < .05), indicating that RT was slower in the verbal-within than verbal-divided condition, and no other significant effects (*p*s > .09).

RQ2: Nonverbal Within Versus Nonverbal Divided

There was a significant effect of condition (*b* = 442.57; stat = 4.51; *p* < .001), indicating that RT was faster in the nonverbal-within than nonverbal-divided condition, and group (*b* = 355.45; stat = 2.27; *p* < .05), indicating that the DLD group had slower RT than the TD group. There was a significant effect of nonverbal interference RT (*b* = 0.47; stat = 2.27; *p* < .05) and no other significant effects (*p*s > .44).

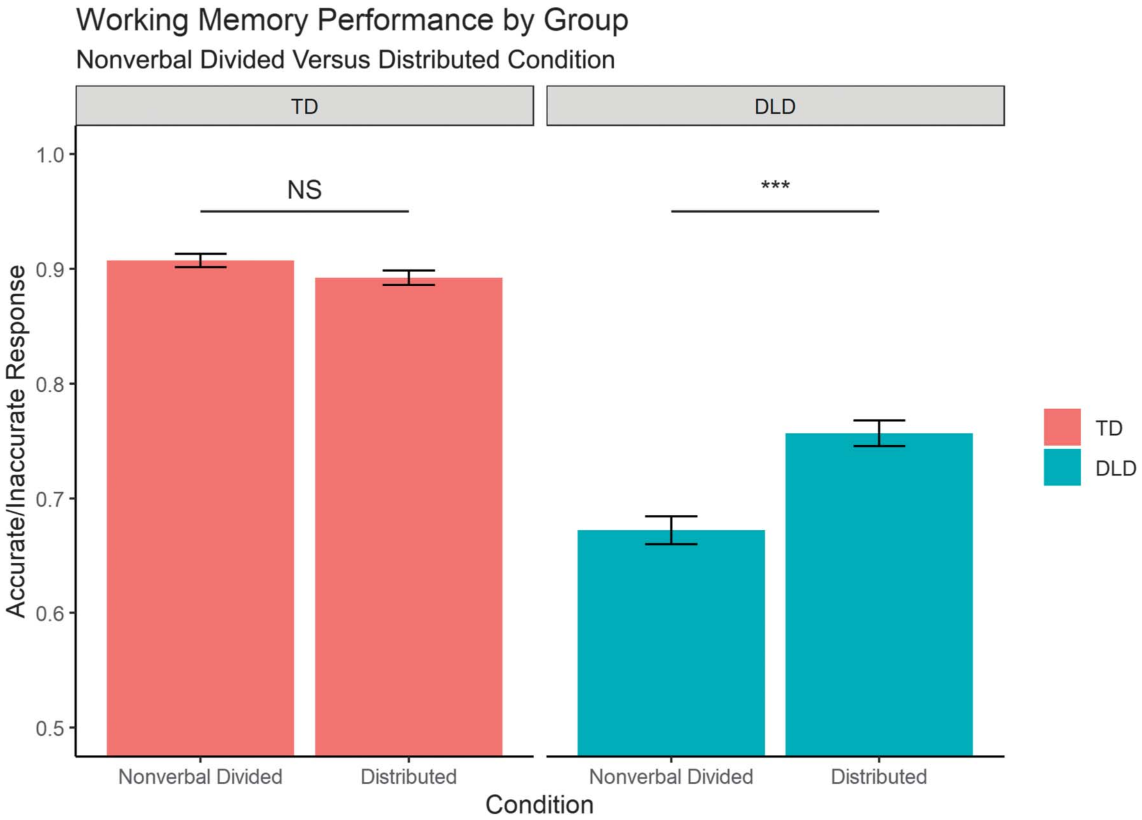
RQ3: Verbal Divided Versus Distributed

There was a significant effect of condition (*b* = 314.81; stat = 3.36; *p* < .001), indicating that RT was faster in the verbal-divided than distributed condition, and no other significant effects (*p*s > .08).

RQ3: Nonverbal Divided Versus Distributed

There was a significant effect of condition (*b* = −247.34; stat = −2.27; *p* < .05), indicating that RT was slower in the nonverbal-divided than distributed condition. There was a significant effect of nonverbal-divided

Figure 2. Group differences in nonverbal divided versus distributed condition accuracy. *y*-axis range is 0.50–1.0. NS = not significant; TD = typically developing; DLD = developmental language disorder. ***$p < .001$.



condition interference RT ($b = 0.49$; stat = 2.02; $p < .05$), and no other significant effects (*ps* > 05). See Supplemental Material S2 for complete statistical output.

Discussion

This study examined the role of domain in working memory performance in children with DLD relative to age-matched TD peers using a fully crossed design. We asked how working memory performance differs between children with DLD and TD peers on tasks with (RQ1) demands within the verbal or nonverbal domain, (RQ2) tasks with demands divided between verbal and nonverbal domains, and (RQ3) demands divided between domains compared to demands distributed across verbal and nonverbal domains. First, based on evidence of poor verbal working memory in DLD, we predicted that the DLD group would perform more poorly on the nonverbal-within than verbal-within domain tasks, but the TD group would perform better on verbal-within than nonverbal-within domain tasks, and this prediction was borne out in the data (RQ1). We also predicted that working memory performance would be better on tasks with demands divided between domains (e.g., word–image + face/nonface judgment; see Table 2) relative to tasks with demands within one domain for the DLD and TD group, and that this effect would be greater for the TD group (RQ2). Although this prediction was borne out with verbal RT, nonverbal recall RT was slower for both groups in the nonverbal-within than nonverbal-divided condition and these effects did not differ between groups. Finally, we predicted that working memory performance would be better on tasks with demands distributed across domains (i.e., word–image locations + auditory word location judgment) relative to tasks with demands divided between domains for the DLD and TD group, and that this effect would be greater for the DLD group (RQ3). This effect was borne out in the data for the distributed relative to nonverbal-divided condition, but not relative to the verbal-divided condition. Findings showed greater accuracy in the distributed condition than the nonverbal-divided condition for the DLD group, but not the TD group, and that both groups had faster RT in the distributed condition than nonverbal-divided condition. In contrast, both groups had faster RT in the verbal-divided condition than the distributed condition. Collectively, findings underscore a role for interference that differs per the domain of working memory task demands and DLD versus TD group status.

The Role of Domain

The current findings broadly align with prior related studies with key differences related to verbal versus nonverbal interference. Consistent with these prior studies, children with DLD and TD peers had faster RT when processing was divided between nonverbal interference (i.e., face/nonface judgment) and verbal recall (i.e., words) than when processing was limited to the verbal domain during working memory performance. Yet for nonverbal recall (i.e., shape location), both groups had faster RT when processing was limited to the nonverbal domain than when processing was divided between verbal interference and nonverbal recall during working memory performance. There were also model differences in within-group patterns for accuracy—better accuracy with processing within the nonverbal domain for the DLD group and better accuracy with processing divided between verbal interference and nonverbal recall for the TD group—but these patterns require further exploration. Prior work shows better accuracy across DLD and TD groups for divided-domain working memory conditions regardless of recall domain (Gillam et al., 1995; Hoffman & Gillam, 2004).

It is possible that our verbal interference (i.e., nonword judgment) task was more difficult than our nonverbal interference (i.e., face/nonface judgment) task, particularly for our DLD group. In contrast, Hoffman and Gillam's (2004) nonverbal interference task (i.e., pointing to matching colors) appears to have been more challenging than their verbal interference task (i.e., naming colors) based on recall accuracy values across groups and conditions, although performance on interference tasks was not reported in their study. The explanation that our verbal interference task was more challenging than our nonverbal interference task is consistent with our finding that both groups had faster RT, and the DLD group had better accuracy, in the distributed- than divided-domain condition. Interestingly, this finding is consistent with Gillam et al.'s (1995) finding of better performance in a distributed- than divided-domain condition, particularly for their DLD group.

If verbal interference drove results across conditions in our study, we would expect that the verbal-within condition would be substantially more difficult than the verbal-divided condition. We would also hypothesize a group difference in this effect given the DLD group's difficulty with our verbal interference task, and nonwords more generally, relative to TD peers (Deevy et al., 2010; Dollaghan & Campbell, 1998). Our findings showed that RT was faster for the verbal-divided than verbal-within condition for both groups, but there was no difference between these conditions in accuracy, nor a group difference in the condition effect. Additionally, if the verbal interference task drove the group difference in nonverbal-divided versus distributed condition accuracy, we may expect this effect to also be present for RT, but it was only evident for accuracy. Moreover, we controlled for group differences in interference task performance in order to remove this potential confound from our analysis of condition effects, an approach that is broadly consistent with prior work (Ellis Wesmer et al., 1999; Gaulin & Campbell, 1994; Montgomery & Evans, 2009). Nevertheless, we maintain that it is possible for group differences in interference task accuracy to have downstream effects on working memory performance (e.g., diminished engagement for nonverbal-divided recall).

Taken together, the role of interference differed depending on the domain manipulation. For the DLD group, there is not a clear benefit in dividing processing between verbal and nonverbal domains or distributing processing across verbal and nonverbal domains during working memory performance. Rather, the DLD group had better working memory performance across conditions in the absence of verbal interference, even after controlling for group differences in interference task performance. For the TD group, there was a greater benefit in dividing processing between verbal and nonverbal domains for nonverbal recall and, to a lesser degree, distributing processing across verbal and nonverbal domains during working memory performance. These group differences underscore the importance of inhibiting verbal interference during verbal processing and reveal the importance of inhibiting verbal interference during nonverbal working memory performance for the DLD group. Alternatively, the effect of nonverbal interference appears to be less important.

Theoretical and Clinical Implications

Prior work posits three primary processing-based hypotheses of DLD. These hypotheses separately suggest that deficit patterns observed in DLD are related to limitations in verbal aspects of working memory (Archibald & Gathercole, 2007; Ellis Weismer et al., 1999), processing speed (Kail, 1994; Miller et al., 2001), or inhibition of interference (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). These factors are also thought to be important to working memory performance. The SOB-CS computational model (Oberauer et al., 2012) is an interference-based model of working memory that accounts for the role of interference in working memory based on a processing speed mechanism. Thus, this model has the potential to integrate these key processing-based hypotheses of DLD to better explain working memory performance and provide a useful step forward in accounting for these processing-based factors in DLD and in working memory.

Our findings showed that children with DLD performed more poorly than TD peers across verbal and nonverbal working memory tasks. This finding is consistent with the limited verbal working memory hypothesis of DLD (Archibald & Gathercole, 2007; Ellis Weismer et al., 1999), but also with other evidence indicating that these limitations extend to working memory with nonverbal information (i.e., even though the limited verbal working memory hypothesis of DLD does not account for limitations in nonverbal working memory; Dispaldro et al., 2013; Smolak et al., 2020; Vugs et al., 2013). We also found that working memory deficits were present for RT (i.e., a measure of processing speed) with nonverbal item recall and verbal–nonverbal item (i.e., word–image location) recall for the DLD group, but not with verbal item recall. Overall, our findings indicated fewer group differences in the role of interference domain for processing speed than accuracy, suggesting that a processing speed account of DLD is insufficient (see also Ellis Weismer et al., 2005). Our DLD group had greater difficulty inhibiting interference from the verbal (i.e., nonword judgment) than nonverbal (i.e., face/nonface judgment) domain, and they demonstrated a larger effect of verbal interference than nonverbal interference regardless of recall item domain. These findings are consistent with work showing substantial difficulty inhibiting verbal interference in DLD (Hoffman & Gillam, 2004; Leonard et al., 2007; Marton et al., 2018), but are potentially inconsistent with a domain-general inefficient inhibition account of DLD (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). Thus, the three primary processing-based hypotheses of DLD are only partially supported in the current study when considered separately.

According to the SOB-CS model, item features are represented via a continuum (e.g., the same processing unit may represent verbal or nonverbal features), and working memory is restored to a baseline state during free time between cognitive operations (e.g., time between responding on an interference processing task and the presentation of recall test items; Oberauer et al., 2012). Given that children with DLD often have slower processing speed than TD peers on at least some verbal and nonverbal tasks (Kail, 1994; Miller et al., 2001), they may also have less free time available to reduce interference between items in working memory. The interplay of relative strengths in representing nonverbal relative to verbal item features and increased baseline interference (i.e., due to diminished free time) according to the SOB-CS could yield working memory performance patterns similar to those observed in our DLD group. Thus, this model may represent a useful account of verbal working memory, processing speed, and inefficient inhibition, as well as other patterns of limitations in DLD (e.g., greater difficulty inhibiting verbal than nonverbal interference).

Specifically, there was a lesser effect of within-domain interference for nonverbal than verbal recall for our DLD group, but not for the TD group, suggesting greater distinctiveness or diminished overlapping activation (or greater free time) for nonverbal than verbal items. These patterns may have also been evident in the distributed-domain condition as the DLD group could engage nonverbal processing at each phase of the distributed working memory task to a greater degree than at each phase of the divided-domain working memory task. Nevertheless, the only group difference in RT was found across nonverbal-within and divided domain conditions, so there is little evidence in this study that group differences in free time explain group differences in recall accuracy patterns. This interpretation, however, rests on the assumption that processing speed is directly related to free time, which requires further exploration.

Clinical Implications

Given the important role of verbal interference for the DLD group, to a greater extent than for TD peers, clinicians should be mindful of the rate and quantity of verbal information in therapy sessions and in the classroom. It may be beneficial to use nonverbal information to support language processing in therapy and in the classroom. For instance, when targeting tense morphology, pieces of paper with a verb (e.g., walk) and potential morphological markers (e.g., −*ed*, −*ing*) coupled with visual depictions (e.g., a person walking versus standing on a sidewalk) may be used to supplement verbal instruction. In this scenario, nonverbal visual (i.e., images) and spatial information (i.e., moving morphological marker pieces of paper to the verb) are used in concert with verbal information to target a morpheme (e.g., −*ed*).

Limitations and Future Directions

Prior work using experimental designs that include concurrent or secondary tasks often find that the relative difficulty between concurrent or secondary tasks differs, such as prior work on children with DLD (e.g., Hoffman & Gillam, 2004; Larson et al., 2019) and prior work with other clinical groups (e.g., Larson et al., 2021; but see Siffredi et al., 2017). The difference in difficulty of verbal interference relative to nonverbal and distributed interference, however, is a limitation of the current work. It is also important to note that our remote-based procedures may explain some differences between the current findings and prior research. Within the context of the current work, however, we were able to account for many of these variables (e.g., providing laptops, experimental tasks run identically to in-lab procedures). Nonetheless, future work should examine lab- versus remote-based administration of working memory tasks.

There are a couple of limitations related to our participant sample. Some prior work has focused on a more narrowly defined population, children with SLI who have normal-range nonverbal IQ, relative to our DLD participants who have nonverbal IQ above the intellectual disability cutoff. Because nonverbal IQ is correlated with working memory (Ellis Weismer et al., 2017; Fry & Hale, 1996), it may be important for future work to clarify the role of nonverbal ability criteria in working memory findings for SLI versus DLD groups. Although there is evidence that supports collapsing across groups of children with language disorder who have varied cognitive abilities (above the intellectual disability cutoff; Bishop et al., 2016; Dennis et al., 2009; Gallinat & Spaulding, 2014; Norbury et al., 2017), this evidence is more global in nature rather than being specific to working memory and cognitive ability. For instance, there is some mixed evidence on the relationship between nonverbal IQ and working memory in recent work on DLD. Smolak et al. (2020) found associations among attention, working memory, and language, but no associations between these variables and nonverbal IQ, in DLD. Blom and Boerma (2020) found that nonverbal IQ was associated with attention, inhibition, and working memory in their DLD group. The differences between these studies in the effect of nonverbal IQ suggest the need for future work to further examine the role of nonverbal IQ in relationships among inhibition, working memory, and language. However, *over and above* the effect of nonverbal IQ, Blom and Boerma (2020) showed that language was associated with inhibition and working memory, consistent with prior work on SLI (e.g., Kapa & Erikson, 2020; Leonard et al., 2007; Marton et al., 2007). Additionally, Leonard et al. (2007) suggests that nonverbal IQ was a minor contributing factor in their model of processing speed and working memory that predicted language ability in a combined sample of TD participants and participants meeting criteria for SLI or DLD. Thus, it is unlikely that working memory findings in SLI versus DLD groups differ substantively. See Volkers (2018) for further discussion of terminology and group classification.

Finally, future work would benefit from testing the role of verbal versus perceptual mediation more directly than our test of interference effects. Although our domain-based manipulation may represent a partial test of verbal versus perceptual strategy use (e.g., a verbal interference task is more likely to disrupt verbal mediation and verbal recall than a nonverbal interference task), we allowed individual differences in strategy use to vary given that our research questions were focused on domain effects related to working memory, processing speed, and inhibition. Future work may benefit from examining the relationship between working memory performance and individual differences in language versus perceptual abilities in order to determine the degree to which verbal versus perceptual mediation is deployed (e.g., Larson et al., 2019).

Conclusions

This study examined the role of domain in working memory performance using a design that varied the domain of interference and recall. We used the SOB-CS model as our theoretical framework in order to merge three key processing-based hypotheses of DLD and factors thought to be important to working memory under an integrated framework: limited verbal working memory (Archibald & Gathercole, 2007; Ellis Weismer et al., 1999), slowed processing speed (Kail, 1994; Miller et al., 2001), and inefficient inhibition (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). Findings supported a role for each processing-based hypothesis, albeit an incomplete role. The SOB-CS model, however, was able to account for overall findings from this study, suggesting that it represents a useful step forward in understanding processing-based factors and working memory performance in DLD. Yet, further examination of the free time mechanism is needed in order to better describe the relationship between processing speed and inhibition of interference, particularly for verbal items during working memory performance.

Acknowledgments

This research was supported by National Institutes of Health Grants F31 DC018704 (Larson, PI), T32 DC005359 (Ellis Weismer, PI), and U54 HD03352 core grant to the Waisman Center, and the American Speech-Language-Hearing Foundation New Century Scholars Doctoral Scholarship. This work is based on one study from the first author’s dissertation (Larson, 2021). The authors would like to thank the families who participated in this study as well as the school personnel who generously aided in participant recruitment. The authors are grateful to the members of the Language Processes Lab and Language Acquisition and Bilingualism Lab for their assistance.

References

Adobe Photoshop CS. (2004). Peachpit Press.

Archibald, L. M. D., & Gathercole, S. E. (2007). Nonword repetition in specific language impairment: More than a phonological short-term memory deficit. *Psychonomic Bulletin and Review, 14*(5), 919–924. https://doi.org/10.3758/BF03194122

Bartlett, J. W., Seaman, S. R., White, I. R., Carpenter, J. R., & Alzheimer’s Disease Neuroimaging Initiative. (2015). Multiple imputation of covariates by fully conditional specification: Accommodating the substantive model. *Statistical Methods in Medical Research, 24*(4), 462–487. https://doi.org/10.1177/0962280214521348

Bishop, D. V. M., Snowling, M. J., Thompson, P. A., Greenhalgh, T., & CATALISE Consortium. (2016). CATALISE: A multinational and multidisciplinary Delphi consensus study. Identifying language impairments in children. *PLOS ONE, 11*(7), e0158753. https://doi.org/10.1371/journal.pone.0158753

Bishop, D. V. M., Snowling, M. J., Thompson, P. A., Greenhalgh, T., & the CATALISE-2 Consortium. (2017). Phase 2 of CATALISE: A multinational and multidisciplinary Delphi consensus study of problems with language development: Terminology. *The Journal of Child Psychology and Psychiatry, 58*(10), 1068–1080. https://doi.org/10.1111/jcpp.12721

Bjorklund, D. F., & Harnishfeger, K. K. (1990). The resources construct in cognitive development: Diverse sources of evidence and a theory of inefficient inhibition. *Developmental Review, 10*(1), 48–71. https://doi.org/10.1016/0273-2297(90)90004-N

Blom, E., & Boerma, T. (2020). Do children with developmental language disorder (DLD) have difficulties with interference control, visuospatial working memory, and selective attention? Developmental patterns and the role of severity and persistence of DLD. *Journal of Speech, Language, and Hearing Research, 63*(9), 3036–3050. https://doi.org/10.1044/2020_JSLHR-20-00012

Brauer, M., & Curtin, J. J. (2018). Linear mixed-effects models and the analysis of nonindependent data: A unified framework to analyze categorical and continuous independent variables that vary within-subjects and/or within-items. *Psychological Methods, 23*(3), 389–411. https://doi.org/10.1037/met0000159

Ceaser, A. E., & Barch, D. M. (2016). Striatal activity is associated with deficits of cognitive control and aberrant salience for patients with schizophrenia. *Frontiers in Human Neuroscience, 9,* 687. https://doi.org/10.3389/fnhum.2015.00687

Conners, C. K. (2008). *Conners* (3rd ed.). Multi-Health Systems.

Conti-Ramsden, G., St. Clair, M. C., Pickles, A., & Durkin, K. (2012). Developmental trajectories of verbal and nonverbal skills in individuals with a history of specific language impairment: From childhood to adolescence. *Journal of Speech, Language, and Hearing Research, 55*(6), 1716–1735. https://doi.org/10.1044/1092-4388(2012/10-0182)

Deevy, P., Weil, L. W., Leonard, L. B., & Goffman, L. (2010). Extending use of the NRT to preschool-age children with and without specific language impairment. *Language, Speech, and Hearing Services in Schools, 41*(3), 277–288. https://doi.org/10.1044/0161-1461(2009/08-0096)

Dennis, M., Francis, D. J., Cirino, P. T., Schachar, R., Barnes, M. A., & Fletcher, J. M. (2009). Why IQ is not a covariate in cognitive studies of neurodevelopmental disorders. *Journal of the International Neuropsychological Society, 15*(3), 331–343. https://doi.org/10.1017/S1355617709090481

Dispaldro, M., Leonard, L. B., Corradi, N., Ruffino, M., Bronte, T., & Facoetti, A. (2013). Visual attentional engagement deficits in children with specific language impairment and their role in real-time language processing. *Cortex, 49*(8), 2126–2139. https://doi.org/10.1016/j.cortex.2012.09.012

Dollaghan, C., & Campbell, T. F. (1998). Nonword repetition and child language impairment. *Journal of Speech, Language, and Hearing Research, 41*(5), 1136–1146. https://doi.org/10.1044/jslhr.4105.1136

Ellis Weismer, S., Davidson, M. M., Gangopadhyay, I., Sindberg, H., Roebuck, H., & Kaushanskaya, M. (2017). The role of nonverbal working memory in morphosyntactic processing by children with specific language impairment and autism spectrum disorders. *Journal of Neurodevelopmental Disorders, 9*(1), 28. https://doi.org/10.1186/s11689-017-9209-6

Ellis Weismer, S., Evans, J., & Hesketh, L. J. (1999). An examination of verbal working memory capacity in children with specific language impairment. *Journal of Speech, Language, and Hearing Research, 42*(5), 1249–1260. https://doi.org/10.1044/jslhr.4205.1249

Ellis Weismer, S., Plante, E., Jones, M., & Tomblin, J. B. (2005). A functional magnetic resonance imaging investigation of verbal working memory in adolescents with specific language impairment. *Journal of Speech, Language, and Hearing Research, 48*(2), 405–425. https://doi.org/10.1044/1092-4388(2005/028)

Fensen, L., Marchman, V. A., Thal, D. J., Dale, P. S., Reznick, J. S., & Bates, E. (2007). *MacArthur–Bates Communication Development Inventories*. Brookes.

Fry, A. F., & Hale, S. (1996). Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. *Psychological Science, 7*(4), 237–241. http://www.jstor.org/stable/40062952

Finneran, D. A., Francis, A. L., & Leonard, L. B. (2009). Sustained attention in children with specific language impairment (SLI). *Journal of Speech, Language, and Hearing Research, 52*(4), 915–929. https://doi.org/10.1044/1092-4388(2009/07-0053)

Gallinat, E., & Spaulding, T. J. (2014). Differences in the performance of children with specific language impairment and their typically developing peers on nonverbal cognitive tests: A meta-analysis. *Journal of Speech, Language, and Hearing Research, 57*(4), 1363–1382. https://doi.org/10.1044/2014_JSLHR-L-12-0363

Gaulin, C. A., & Campbell, T. F. (1994). Procedure for assessing verbal working memory in normal school-age children: Some preliminary data. *Perceptual and Motor Skills, 79*(1), 55–64. https://doi.org/10.2466/pms.1994.79.1.55

Gillam, R. B., Cowan, N., & Day, L. S. (1995). Sequential memory in children with and without language impairment. *Journal of Speech and Hearing Research, 38*(2), 393–402. https://doi.org/10.1044/jshr.3802.393

Hoffman, L. M., & Gillam, R. B. (2004). Verbal and spatial information processing constraints in children with specific language impairment. *Journal of Speech, Language, and Hearing Research, 47*(1), 114–125. https://doi.org/10.1044/1092-4388(2004/011)

Judd, C. M., McClelland, G. H., & Ryan, C. (2008). *Data analysis: A model comparison approach* (2nd ed.). Routledge. https://doi.org/10.4324/9780203892053

Kail, R. (1994). A method for studying the generalized slowing hypothesis in children with specific language impairment. *Journal of Speech and Hearing Research, 37*(2), 418–421. https://doi.org/10.1044/jshr.3702.418

Kapa, L. L., & Erikson, J. A. (2020). The relationship between word learning and executive function in preschoolers with and without developmental language disorder. *Journal of Speech, Language, and Hearing Research, 63*(7), 2293–2307. https://doi.org/10.1044/2020_JSLHR-19-00342

Kover, S. T., & Atwood, A. K. (2013). Establishing equivalence: Methodological progress in group-matching design and analysis. *American Journal on Intellectual and Developmental Disabilities, 118*(1), 3–15. https://doi.org/10.1352/1944-7558-118.1.3

Larson, C. (2021). *Processing-based factors in child language impairment* [Doctoral dissertation, University of Wisconsin–Madison].

Larson, C., Gangopadhyay, I., Prescott, K., Kaushanskaya, M., & Ellis Weismer, S. (2021). Planning in children with autism spectrum disorder: The role of verbal mediation. *Journal of Autism and Developmental Disorders, 51*(7), 2200–2217. https://doi.org/10.1007/s10803-020-04639-5

Larson, C., Gangopadhyay, I., Kaushanskaya, M., & Weismer, S. E. (2019). The relationship between language and planning in children with language impairment. *Journal of Speech, Language, and Hearing Research, 62*(8), 2772–2784. https://doi.org/10.1044/2019_JSLHR-L-18-0367

Larson, C., Kaplan, D., Kaushanskaya, M., & Ellis Weismer, S. (2020). Language and inhibition: Predictive relationships in children with language impairment relative to typically developing peers. *Journal of Speech, Language, and Hearing Research, 63*(4), 1115–1127. https://doi.org/10.1044/2019_JSLHR-19-00210

Leonard, L. B., Ellis Weismer, S., Miller, C. A., Francis, D. J., Tomblin, B. J., & Kail, R. V. (2007). Speed of processing, working memory, and language impairment in children. *Journal of Speech, Language, and Hearing Research, 50*(2), 408–428. https://doi.org/10.1044/1092-4388(2007/029)

MacWhinney, B. (2000). *The CHILDES Project: Tools for analyzing talk* (3rd ed.). Erlbaum.

Mainela-Arnold, E., Evans, J. L., & Alibali, M. W. (2006). Understanding conservation delays in children with specific language impairment: Task representations revealed in speech and gesture. *Journal of Speech, Language, Hearing Research, 49*(6), 1267–1279. https://doi.org/10.1044/1092-4388(2006/091)

Marton, K., Kelmenson, L., & Pinkhasova, M. (2007). Inhibition control and working memory capacity in children with SLI. *Psychologia, 50*(2), 110–121. https://doi.org/10.2117/psysoc.2007.110

Marton, K., Kovi, Z., & Egri, T. (2018). Is interference control in children with specific language impairment similar to that of children with autistic spectrum disorder. *Research in Developmental Disabilities, 72,* 179–190. https://doi.org/10.1016/j.ridd.2017.11.007

Miller, C. A., Kail, R., Leonard, L. B., & Tomblin, J. B. (2001). Speed of processing in children with specific language impairment. *Journal of Speech, Language, and Hearing Research, 44*(2), 416–433. https://doi.org/10.1017/cbo9780511576164.023

Montgomery, J. W., & Evans, J. L. (2009). Complex sentence comprehension and working memory in children with specific language impairment. *Journal of Speech, Language, and Hearing Research, 52*(2), 269–288. https://doi.org/10.1044/1092-4388(2008/07-0116)

Nitido, H., & Plante, E. (2020). Diagnosis of developmental language disorder in research studies. *Journal of Speech, Language, and Hearing Research, 63*(8), 2777–2788. https://doi.org/10.1044/2020_JSLHR-20-00091

Norbury, C. F., Gooch, D., Wray, C., Baird, G., Charman, T., Simonoff, E., Vamvakas, G., & Pickles, A. (2016). The impact of nonverbal ability on prevalence and clinical presentation of language disorder: Evidence from a population study. *Journal of Child Psychology and Psychiatry and Allied Disciplines, 57*(11), 1247–1257. https://doi.org/10.1111/jcpp.12573

Norbury, C. F., Vamvakas, G., Gooch, D., Baird, G., Charman, T., Simonoff, E., & Pickles, A. (2017). Language growth in children with heterogeneous language disorders: A population study. *The Journal of Child Psychology and Psychiatry, 58*(10), 1092–1105. https://doi.org/10.1111/jcpp.12793

Oberauer, K., Farrell, S., Jarrold, C., & Lewandowsky, S. (2016). What limits working memory capacity. *Psychological Bulletin, 142*(7), 758–799. https://doi.org/10.1037/bul0000046

Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review, 19*(5), 779–819. https://doi.org/10.3758/s13423-012-0272-4

Pauls, L. J., & Archibald, L. M. D. (2016). Executive functions in children with specific language impairment: A meta-analysis. *Journal of Speech, Language, and Hearing Research, 59*(5), 1074–1086. https://doi.org/10.1044/2016_JSLHR-L-15-0174

Psychology Software Tools. (2016). *E-Prime (Version 3.0)*.

R Core Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

R Studio Team. (2020). *RStudio: Integrated development for R*. RStudio, Inc. http://www.rstudio.com/

Rastle, K., Harrington, J., & Coltheart, M. (2002). 358,534 Nonwords: The ARC nonword database. *Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology, 55*(4), 1339–1362. https://doi.org/10.1080/02724980244000099

Robertson, E. K., & Gallant, J. E. (2019). Eye tracking reveals subtle spoken sentence comprehension problems in children with dyslexia. *Lingua, 228,* 102708. https://doi.org/10.1016/j.lingua.2019.06.009

Rubin, D. B. (1987). The calculation of posterior distributions by data augmentation: Comment: A noniterative sampling/importance resampling alternative to the data augmentation algorithm for creating a few imputations when fractions of missing information are Modest: The SIR Algorithm. *Journal of the American Statistical Association, 82*(398), 543–546. https://doi.org/10.2307/2289460

Siffredi, V., Barrouillet, P., Spencer-Smith, M., Vaessen, M., Anderson, V., & Vuilleumier, P. (2017). Examining distinct working memory processes in children and adolescents using fMRI: Results and validation of a modified Brown-Peterson paradigm. *PLOS ONE, 12*(7), e0179959. https://doi.org/10.1371/journal.pone.0179959

Smolak, E., McGregor, K. K., Arbisi-Kelm, T., & Eden, N. (2020). Sustained attention in developmental language disorder and its relation to working memory and language. *Journal of Speech, Language, and Hearing Research, 63*(12), 4096–4108. https://doi.org/10.1044/2020_JSLHR-20-00265

Tomblin, J. B., Records, N. L., Buckwalter, P., Zhang, X., Smith, E., & O'Brien, M. (1997). Prevalence of specific language impairment in kindergarten children. *Journal of Speech, Language, and Hearing Research, 40*(6), 1245–1260. https://doi.org/10.1044/jslhr.4006.1245

van Buuren, K., & Groothuis-Oudshoorn, K. (2011). mice: Multivariate imputation by chained equations in R. *Journal of Statistical Software, 45*(3), 1–67. https://doi.org/10.18637/jss.v045.i03

Vanderplas, J. M., & Garvin, E. A. (1959). The association value of random shapes. *Journal of Experimental Psychology, 57*(3), 147–154. https://doi.org/10.1037/h0048723

Volkers, N. (2018). Diverging views on language disorders. *The ASHA Leader, 23*(12), 44–53. https://doi.org/10.1044/leader.FTR1.23122018.44

Vugs, B., Cuperus, J., Hendriks, M., & Verhoeven, L. (2013). Visuospatial working memory in specific language impairment: A meta-analysis. *Research in Developmental Disabilities, 34*(9), 2586–2597. https://doi.org/10.1016/j.ridd.2013.05.014

Warren-Leubecker, A., & Bohannon, J. N. (1984). Intonation patterns in child-directed speech: Mother–father differences. *Child Development, 55*(4), 1379–1385. https://doi.org/10.2307/1130007

Wechsler, D. (2011). *Wechsler Abbreviated Scale of Intelligence–Second Edition*. NCS Pearson.

Whitehouse, A. J. O., Watt, H. J., Line, E. A., & Bishop, D. V. M. (2009). Adult psychosocial outcomes of children with specific language impairment, pragmatic language impairment and autism. *International Journal of Language & Communication Disorders, 44*(4), 511–528. https://doi.org/10.1080/13682820802708098

Wiig, E. H., Semel, E., & Secord, W. A. (2013). *Clinical Evaluation of Language Fundamentals–Fifth Edition (CELF-5)*. Pearson.