Processing-based Factors in Child Language Impairment

By

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Dedication

For all my former clients and their families

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Abstract

The current dissertation examined working memory in children with Developmental Language Disorder (DLD). The goal of this work was to integrate three primary processing-based hypotheses of DLD, 1) limited verbal working memory, 2) slowed processing speed, and 3) inefficient inhibition of interference, by using the serial-order-in-a-box – complex span (SOB-CS) computational model as my theoretical framework. I tested the role of domain in working memory performance by varying the domain of interference and recall (i.e., verbal versus nonverbal) task demands, and the relationship between working memory performance and a key time-based mechanism posited by the SOB-CS model, *free time*. Finally, I examined how individual differences in child factors related to working memory performance. Participants were 55 school-age children, 21 children with DLD and 34 age-matched TD peers (9-13 years). Findings indicated that 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. Second, I demonstrated a link between *free time* and working memory performance, suggesting that unfilled pauses are beneficial to performance. However, when verbal recall was paired with verbal interference, there appeared to be a detrimental effect of *free time* for the DLD group, and a facilitative effect of *free time* for the TD group. This finding may have been related to diminished attention to verbal interference in the DLD group, potentially reflecting a contributing factor in verbal processing difficulty. Finally, the DLD group appeared to recruit language and nonverbal skills adaptively to facilitate working memory performance whereas the TD group appeared to recruit language regardless of whether language facilitated performance. Together, findings support 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 in the current work. Thus, the SOB-CS model represents a useful step forward in explaining processing in children with DLD.

Chapter 1: Introduction

Developmental Language Disorder versus Specific Language Impairment

The current literature on children with language impairment largely focuses on children who have deficits in language relative to typically developing peers in the absence of comorbid intellectual, medical, or developmental disability (e.g., Down syndrome). This group of children is referred to as having Specific Language Impairment (SLI; Tomblin et al., 1997; Leonard, 2014). A large-scale epidemiological study has guided much of the research on children with SLI for the last 20 years (Tomblin, Records, & Zhang, 1996), though SLI had been identified and studied previously (e.g., "developmental aphasia," Ingram & Reid, 1956; "grammatical specifically language impaired," van der Lely, 1994). Tomblin et al. (1996) developed the EpiSLI system for diagnosing children with SLI. This system involves obtaining composite scores in five areas of language: receptive and expressive vocabulary, grammar, and narrative, and general comprehension (i.e., receptive vocabulary, grammar, and narrative), and general expression (i.e., expressive receptive vocabulary, grammar, and narrative; Tomblin et al., 1996). In order to receive a diagnosis of SLI, a child must have at least 2 composite scores (e.g., receptive narrative and expressive grammar) falling at least 1.25 SDs below the mean of same-age peers. The child must also have nonverbal IQ (NVIQ) standard scores >87, pass a hearing screening, have normal or corrected-to-normal vision, be monolingual, and have no other medical or developmental disability. Using the EpiSLI system, Tomblin et al. (1997) found a prevalence of 7.4% for SLI in children 5 years of age.

Motivated in part by disagreement related to the role of NVIQ criteria, Norbury et al. (2016) examined how differences in criteria affect prevalence at school entry for children with

language impairment. Their criteria for an SLI diagnosis were: at least 2 composite scores (e.g., expressive vocabulary and receptive grammar) falling at least 1.5 SDs below the mean of same-age peers, NVIQ standard scores ≥85, and no developmental disability or hearing impairment. These criteria yielded a prevalence of 7.58% (Norbury et al., 2016). Children who met the language criteria, but who also had intellectual or medical disability, were found to represent a prevalence of 2.34%. When using Tomblin et al.'s (1996) criteria plus extending the NVIQ cutoff to the low-average range (i.e., >70), Norbury et al. (2016) found a prevalence of 11.11%.

Our current knowledge of child language impairment primarily comes from studies of children with SLI as defined by Tomblin et al. (1996) or Norbury et al. (2016; i.e., the group with NVIQ standard scores ≥85). Contrary to prior research trends, there is a recent movement in the field to examine children with language impairment using broader diagnostic criteria that are focused on functional impact and poor prognosis rather than exclusionary criteria (Bishop, Snowling, Thompson, Greenhalgh, & CATALISE-2 Consortium, 2017; Norbury et at., 2017). This perspective, based on a Delphi consensus study (Bishop et al., 2017), focuses on individuals with significant deficits in language, but allows for varied nonverbal abilities (e.g., standard scores ≥ 70, the low-average range) while also including children with SLI (i.e., standard scores ≥ 85, the average range). This perspective allows for co-occurring impairments in cognitive, sensory-motor, or behavioral domains, such as Attention-Deficit/Hyperactivity Disorder and dyslexia, but proposes a different classification for co-occurring biomedical conditions, such as Autism Spectrum Disorder or brain injury (i.e., differentiating conditions; Bishop et al., 2017; see also Language Disorder in the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, American Psychiatric Association, 2013 for similar classification). The former group is viewed as having Developmental Language Disorder (DLD; also referred to as Language

Disorder of unknown origin; Norbury et al., 2016) and the latter group is viewed as having Language Disorder associated with *X* (e.g., Language disorder associated with Autism Spectrum Disorder; Bishop et al., 2017). This DLD group may better represent clinical populations in research and allow for a greater understanding of relationships between language and other cognitive abilities (Bishop et al., 2017; Leonard et al., 2007; Leonard et al., 2014; Norbury et at., 2017; see Rice, Taylor, & Zubrick, 2008 for additional evidence and McGregor, Goffman, van Horne, Hogan, & Finestack, 2020 and Volkers, 2018 for further discussion). Accordingly, Bishop et al. (2017) and others (e.g., McGregor et al., 2020) have highlighted the importance of considering children with DLD in research.

Although they are less well studied than their SLI counterparts, children with DLD have been shown to present with significant deficits in language relative to TD peers which negatively affect their long-term academic, vocational, and social emotional outcomes (Conti-Ramsden, Durkin, Toseeb, Botting, & Pickles, 2018; Norbury et al., 2017; Ponari, Norbury, Rotaru, Lenci, & Vigliocco, 2018; Snowling, Nash, Gooch, Hyiou-Thomas, & Hulme, 2019). Norbury et al. (2017) found no differences in severity of language impairment or social and academic outcomes between groups of children with DLD and average (i.e., ≥85) versus low-average (i.e., 70-84) NVIQ standard scores. Norbury et al. (2017) did, however, find more severe language impairment and worse outcomes for children with comorbid biomedical (e.g., Autism Spectrum Disorder) or intellectual impairment (i.e., NVIQ standard scores ≤70). Similarly, other work shows that even where omnibus comparisons reveal poorer levels of performance between DLD groups with average versus low-average NVIQ (i.e., without developmental or intellectual disability) on a given skill (e.g., past-tense *-ed* production) at a given timepoint, the direction and magnitude of acquisition over time may be highly similar (Rice, Tomblin, Hoffman, Richman, &

Marquis, 2004). In contrast, Rice, Taylor, Zubrick, Hoffman, & Earnest's (2020) twin study revealed different patterns of heritability in children belonging to SLI versus DLD groups, as well as nonoverlapping causal pathways for language and nonverbal ability. Thus, this study provides evidence against collapsing SLI and DLD groups, especially when examining change over time. However, Rice et al. (2020) also found little evidence of quantitative differences in concurrent language ability between these groups. It follows that there may not be important differences in relationships between language and other cognitive skills in groups of children with language deficits who have average versus low-average NVIQ and no comorbid developmental or intellectual disability, particularly when examining concurrent relationships. One group from the Netherlands is conducting a large-scale multi-year study on a population of children with DLD and NVIQ in the low-average range and above, focusing on relationships between executive function and language over time. Their findings show patterns broadly consistent with prior literature on children with DLD and NVIQ in the average and above average range (Blom & Boerma, 2019, 2020). Beyond this group's line of research, few studies have examined specific linguistic and cognitive profiles of the DLD group with low-average NVIQ (see Smolak, McGregor, Arbisi-Kelm, & Eden, 2020 for another example). Thus, I will review evidence on children with SLI, using the currently preferred term "DLD," yet examine children with DLD who have low-average or better NVIQ and no comorbid biomedical or intellectual disability in the experimental work associated with this dissertation.

Hypotheses of Factors Underlying DLD

Children with DLD, especially those speaking Germanic languages, have pervasive deficits in language with disproportionate weakness in morphosyntax during the pre-school and school years (Leonard, 2014; Rice & Wexler, 1996). This morphosyntactic weakness, which is

not explained by general intellectual deficits, medical factors, or developmental disability, has led some researchers to develop linguistic explanations of DLD, such as the Extended Optional Infinitive Hypothesis (Rice & Wexler, 1996; Rice, Wexler, & Cleave, 1995). This hypothesis argues that DLD involves a prolonged lack of obligatory tense-marking on verbs, such as the *-ed* in the past-tense verb clos*ed*. Although this pattern is observed in typical language development, children with DLD remain in this stage of development for a longer period of time than their TD peers. The Extended Optional Infinitive account argues that children with DLD have difficulty consistently representing tense-marking grammatical morphemes because they do not recognize obligatory contexts. That is, the grammar of children with DLD is underspecified as it does not represent grammatical properties at a maturational level congruent with their age. This hypothesis also argues that this deficit is not attributable to surface-level factors (e.g., phonetic salience; Leonard, McGregor, & Allen, 1992; Rice & Wexler, 1996; Rice et al., 1995).

Another linguistic explanation of DLD is the Representational Deficit for Dependent Relationships (van der Lely, 1994). This hypothesis suggests that the grammatical deficits seen in SLI, such as marking obligatory tense, are explained by an underlying deficit in representing structural relationships in syntactic frames (van der Lely, 1994). Specifically, van der Lely (1994) suggests that syntactic errors are explained by an impaired ability to represent the semantics of a verb about which children with DLD have syntactic information, but intact ability to represent the arguments of a verb about which they have semantic information. For instance, in the sentence "The dog *mooped* the cat," the meaning of the nonword *mooped* must be derived from the syntactic frame. Typically developing children are better able to understand that *the dog* did something to *the cat* and that this action has reached an endpoint than children with DLD. Their errors may reflect incorrect interpretations of sentences, such as a semantic rather syntactic

interpretation of an ambiguous passive sentence (van der Lely, 1996). These relationships are referred to as forward (i.e., semantics first) and reverse (i.e., syntax first) linking rules, and are thought to facilitate language through bootstrapping – using the semantic or syntactic cues to learn previously unknown linguistic information (van der Lely, 1994; van der Lely, 1996). Thus, the Representational Deficit for Dependent Relationships posits an underspecified grammatical system in children with DLD, similar to the Extended Optional Infinitive Account, based on their difficulty in representing the relationships communicated via syntactic frames.

Clahsen (1989) posits a somewhat more specific linguistic explanation of DLD, suggesting that deficits in subject-verb agreement underlie their grammatical deficits. This hypothesis is based on findings of poor case, gender, and auxiliary agreement in German-speaking children with DLD (Clahsen, 1989). In German, an underlying difficulty in subject-verb agreement should affect word order, but spare plural nouns. This prediction was borne out in Clahsen, Rothweiler, Woest, and Marcus (1992), thus providing support for an agreement-based linguistic deficit in DLD while other grammatical skills remain relatively intact. However, these linguistic explanations do not capture difficulties children with DLD have in other language and cognitive areas, such as pragmatics (Gibson, Adams, Lockton, & Green, 2013; Rice, Warren, & Betz, 2005), attention (Ebert & Kohnert, 2011; Marton & Schwartz, 2003; Redmond & Ash, 2014), and general processing (Kail, 1994; Miller, Kail, Leonard, & Tomblin, 2001; Tallal et al., 1996).

Processing-based Hypotheses

Beyond linguistic explanations of DLD, there are three primary processing-based hypotheses of factors that underlie DLD. First, limited verbal working memory is a processing-

based hypothesis which suggests that deficits in verbal working memory are associated with language processing difficulty and downstream effects on language acquisition in children with DLD (Archibald & Gathercole, 2006, 2007; Ellis Weismer, Evans, & Hesketh, 1999; Leonard, Ellis Weismer, Weber-Fox, & Miller, 2014; Leonard et al., 2007; Marton, Eichorn, Campanelli, & Zakarias, 2016; Tallal et al., 1996; see also Alloway, Rajendran, & Archibald, 2009 for discussion of working memory difficulty being secondary to language deficits). Second, the Generalized Slowing Hypothesis is a cross-domain processing hypothesis that is based on evidence of slowed reaction times across verbal and nonverbal domains for children with DLD relative to TD peers (Kail, 1994; Leonard et al., 2014; Leonard et al., 2007; Miller et al., 2001; Tallal et al., 1996). This slowed reaction time is thought to lead to disproportionate difficulty with language relative to other cognitive processes because language is particularly dependent on timescales (e.g., incremental processing, serial recall). Finally, the Inefficient Inhibition Hypothesis is also a cross-domain processing hypothesis positing that slow and inaccurate resistance to interference in children with DLD leads to poor encoding and retrieval of information, particularly in the verbal domain (Bjorklund & Harnishfeger, 1990; Marton, Kelmenson, & Pinkhasova, 2007).

There is ample evidence that children with DLD present with difficulties on verbal processing-based tasks (Archibald & Gathercole, 2006, 2007; Dollaghan & Campbell, 1998; Ellis Weismer et al., 1999; Montgomery, Magimairaj, & Finney, 2010; Vugs, Hendriks, Cuperus, Knoors, & Verhoeven, 2017). These patterns underscore processing difficulty with verbal information, namely, that deficits in verbal working memory underlie the language deficits characteristic of DLD (Archibald & Gathercole, 2006, 2007; Ellis Weismer et al., 1999). Children with DLD perform more poorly than TD peers on verbal working memory tasks, such

as a class of tasks purported to measure working memory capacity – span tasks (Baddeley, Allen, & Hitch, 2011; Bayliss, Jarrold, Gunn, & Baddeley, 2003). Examples of verbal span tasks include backward word span (e.g., Kapa & Erikson, 2020), reading span (Daneman & Carpenter, 1980), and sentence span (e.g., the competing language processing task; Gaulin & Campbell, 1994). A backward word span task, for instance, requires the participant to recall a sequence of words in reverse order relative to their presentation sequence. The length of the word sequence varies (e.g., 4 words versus 8 words) and the greatest length of sequence accurately recalled by the participant provides one measure of that participant's working memory capacity (Baddeley et al., 2011; Kapa & Erikson, 2020). Performance on verbal span tasks has been shown to be related to individual differences in language ability (Ellis Weismer et al., 1999; Montgomery et al., 2010; Thordardottir, 2008), such as verbal working memory performance on a sentence span task predicting language ability (i.e., a language factor including measures of vocabulary and syntax) at a later timepoint in children with DLD.

However, there is evidence that children with DLD have deficits in processing beyond the verbal domain compared to same-age TD peers (e.g., simple reaction time, picture matching, and mental rotation). For instance, children with DLD perform more poorly on spatial span tasks than TD peers, like pattern recall (Windsor, Kohnert, Loxtercamp, & Kan, 2008). In their meta-analysis on nonverbal working memory, Vugs, Cuperus, Hendriks, and Verhoeven (2013) showed deficits on nonverbal working memory tasks in children with DLD relative to TD peers and an association between nonverbal working memory deficits and severity of language impairment (see also Vugs et al., 2017). Another study demonstrated poorer sustained selective attention and working memory on nonverbal tasks in children with DLD relative to age-matched peers overall, as well as correlations between performance on these tasks and narrative language

skills in the DLD group (Smolak et al., 2020). Furthermore, there is evidence of groups of children who have deficits specific to working memory (verbal and nonverbal) or to language, as well as groups of children who have deficits in both working memory and language, suggesting that working memory is not an independent causal pathway in language impairments (Archibald & Joanisse, 2009). Thus, it follows that researchers have proposed alternative theories of processing factors in DLD that account for performance in both the verbal and nonverbal domains.

One such theory is the Generalized Slowing Hypothesis (Kail, 1994; Miller et al., 2001). This hypothesis suggests that slowed processing speed on verbal and nonverbal tasks gives rise to language deficits in DLD (Kail, 1994; Miller et al., 2001). Empirical studies have shown that children with DLD have slower reaction times than TD peers on verbal (e.g., object naming) and nonverbal tasks (e.g., mental rotation; Kail, 1994; Miller et al., 2001), and other work shows links between processing speed and language skills in children with DLD (Leonard et al., 2007; Leonard et al., 2014; Montgomery et al., 2010; Park, Miller, & Mainela-Arnold, 2015; Park et al., 2020; Tallal et al., 1996). This hypothesis, however, is not sufficient on its own to explain the patterns of deficits seen in DLD. For instance, studies examining response time do not consistently find slowing for children with DLD relative to TD peers (Ebert & Kohnert, 2011; Ellis Weismer, Plante, Jones, & Tomblin, 2005; Finneran, Francis, & Leonard, 2009; Im-Bolter, Johnson, & Pasual-Leone, 2006; Marinis & Van Der Lely, 2007; Schul, Wulfeck, & Townsend, 2004).

In addition to working memory and processing speed, inhibition also appears to be an important factor in language processing (Archibald & Gathercole, 2007; Blum & Boerma, 2019; Dispaldro et al., 2013; Kapa & Erikson, 2020; Larson, Kaplan, Kaushanskaya, & Ellis Weismer,

2020; Marton et al., 2007; Montgomery et al., 2010). Inhibition is an executive function skill responsible for resisting interference from irrelevant stimuli (Diamond, 2013; Friedman & Miyake, 2004; Miyake et al., 2000). Children with DLD have deficits in inhibition relative to TD peers regardless of the relative verbal or nonverbal demands of the task (Blum & Boerma, 2020; Kapa, Plante, & Doubleday, 2017; Marton, 2008; Marton et al., 2007; Pauls & Archibald, 2016; Spaulding, 2010). Hence, the Inefficient Inhibition Hypothesis is another hypothesis of cross-domain processing factors in DLD (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). This hypothesis suggests that limitations in speed and accuracy of focusing on relevant information in the presence of irrelevant information leads to difficulty with language processing (Bjorklund & Harnishfeger, 1990; Marton, 2008; Marton et al., 2007; Marton & Schwartz, 2003; McMurray, Samelson, & Tomblin, 2010; Pauls & Archibald, 2016; Spaulding, 2010; Van Dyke & Johns, 2012; Vissers, Koolen, Hermans, Scheper, & Knoors, 2015). Studies have shown links between language and inhibition performance in children with DLD (Bishop & Norbury, 2005; Blum & Boerma, 2019; Kapa & Erikson, 2020; Leonard, Deevy, Fey, & Bredin-Oja, 2013; Marton et al., 2007; Marton, Campanelli, Eichorn, Scheuer, & Yoon, 2014; see also Marton et al., 2016 for a review), as well as concurrent differences in this relationship in children with DLD relative to TD peers (Dispaldro et al., 2013) and differences over time (Blum & Boerma, 2019; Larson, Kaplan, et al., 2020; see also Vissers et al., 2015 for further discussion). Similarly, Smolak et al. (2020) found concurrent correlations among nonverbal sustained selective attention, which may draw upon inhibitory control, nonverbal working memory and narrative language in a DLD group (i.e., with low-average NVIQ and potential comorbid ADHD), but found no evidence of correlations among these nonverbal skills and narrative language in a TD comparison group. This study did not examine reaction time on the nonverbal sustained selective attention or

nonverbal working memory tasks, nor did it statistically test whether groups differed in relationships among cognitive and language measures. Larson, Kaplan et al. (2020), however, demonstrated the importance of considering reaction time based on the finding that inhibition reaction time predicted later morphological comprehension skills in a DLD group (i.e., meeting traditional SLI criteria), but inhibition accuracy did not (see also Windsor et al., 2008 for evidence of a relationship between reaction time on a nonverbal working memory task and language in children with DLD). I also found that the relationship between inhibition reaction time and morphological comprehension significantly differed between the DLD and TD groups, underscoring the importance of statistically testing group differences in relationships among cognitive and language skills (see also Larson, Gangopadhyay, Kaushanskaya, & Ellis Weismer, 2019).

Collectively, prior research supports relationships among working memory, processing speed, and inhibition, as well as relationships among these skills and language, in children with DLD. However, no prior work examines interrelationships among these processing factors in order to determine how they work in concert to explain language deficits in DLD. In this dissertation, I explored the three processing-based hypotheses – working memory, processing speed, and inhibition – under an integrated theoretical framework. I aimed to examine how these factors are interrelated and how these interrelationships account for individual differences in language processing in school-aged children with DLD. The serial-order-in-a-box – complex span (SOB-CS) model posits a key role for interference in working memory capacity and a time-based mechanism for resisting this interference (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; Oberauer, Farrell, Jarrold, & Lewandowsky, 2016). The SOB-CS model is, therefore, able to account for the relationship between processing speed and inhibition of

irrelevant information as it pertains to working memory performance. This model further accounts for the relative effects of domain on the degree of interference between target and nontarget information, thereby capturing potential differences in performance depending on relative verbal versus nonverbal abilities.

Integrative Model of Working Memory, Processing Speed, and Inhibition

The Serial Order in a Box – Complex Span (SOB-CS; Oberauer et al., 2012) model is a highly specified interference-based computational model of working memory. This model has been shown to outperform decay-based (e.g., Baddeley, 2012; Baddeley & Hitch, 1974; Barrouillet, Portrat, & Camos, 2011) and resource-based (e.g., Cowan, 2014; Kane & Engle, 2002; Unsworth & Engle, 2006) models of working memory (Oberauer et al., 2016). Because the SOB-CS model is a computational model, its predictions are clear and have been tested along with a variety of assumptions. It accounts for processing speed demands and interference effects in order to capture working memory performance (Oberauer et al., 2012).

The SOB-CS model is a two-layer neural network with distributed representations of items and serial position markers. Distributed networks involve patterns of activation over many processing units in each layer of the network. Processing units within these distributed neural networks are analogous to neurons and weights between these neurons are analogous to synaptic connections. Encoding occurs via Hebbian learning, a type of associative learning where associations, or weights, between processing units become greater for units that frequently fire together relative to units that infrequently fire together (Oberauer et al., 2012).

An item or a serial position representation involves graded activation within each processing unit. These varied degrees of activation give rise to a pattern uniquely associated with

that item or serial position representation. Notably, different representations have different patterns of activation over the *same* set of units (see Appendix A, Figure A.1 continuous representation of features from Oberauer et al., 2012). The first layer of the neural network is devoted to item representations and the second is devoted to context position markers (i.e., serial position). Each item-position binding exists in the same weight matrix. Consequently, each representation in working memory is distorted relative to its veridical identity (Oberauer et al., 2012).

Capacity limitations are based on interference between similar representations or representations occurring in similar serial positions. The SOB-CS model does not require rehearsal to maintain representations in an active state, rather representations are maintained by default and displaced or distorted per interference with other representations. Under this framework, representations that enter working memory are bound to their serial position marker – a representation's position in the sequence by which it became active in working memory. Thus, the serial position of a representation is fundamental to the contents of working memory. Serial recall of information (i.e., in contrast to free recall) tests how well this information is maintained in working memory (Oberauer et al., 2012; Oberauer et al, 2016). For example, a serial recall task would ask a participant to reproduce the final word in a series of sentences *in order* of presentation whereas a free recall task would ask a participant to reproduce the final word in a series of sentences *regardless of order*.

Under the SOB-CS model, interference can be a function of feature similarity or serial position. Features may be similar due to their relative proximity in the distributed feature space, such as items from the same category (Oberauer et al., 2012). They share a large proportion of total features, such as words sharing phonologic, orthographic, and semantic features (e.g., *frog*

and *log*). Likewise, categorical similarity denotes whether items that share a large proportion of features are categorically similar or distinct (e.g., words and digits share phonemic features, but are from different categories; Oberauer et al., 2012). Alternatively, items within a category may share different degrees of features, such as words that are verbs versus nouns.

Feature-space overlap is another type of similarity and relates to domain-based interference between representations. While representations that are comprised of *only* verbal or *only* nonverbal features would have no feature-space overlap, this situation is not ecologically valid. Indeed, most representations will be domain impure, having some degree of features from a different domain (Fuster, Bodner, & Kroger, 2000; Oberauer et al., 2012). The SOB-CS model represents feature domain in a continuous fashion as the processing units of the item layer in the distributed network are responsible for either verbal or nonverbal information. Units that fire during verbal processing are assumed to draw on activation from nearby units that may or may not be associated with nonverbal processing. See Appendix A Figure A.1).

Under the SOB-CS model, working memory capacity is governed by an active removal mechanism whereby working memory is restored to a baseline state during *free time* between stimulus presentations or internal representations. This time-based active removal involves unbinding representations from their serial position markers, thus transferring a representation to long-term memory or forgetting a representation, depending on task goals. *Free time* refers to time intervals between, for instance, presenting new information, retrieving representations from long-term memory, or manipulating information (e.g., a truth value judgement in the Competing Language Processing Task, shifting focus from irrelevant to relevant information; Gaulin & Campbell, 1994). As a result, *free time* occurs when a) time passes, and b) there are no processing demands (i.e., unfilled intervals). For instance, the Competing Language Processing

Task presents a list of sentences for which a participant must indicate whether the sentence is true immediately after hearing the sentence, and then the participant must recall the final word in each sentence in the correct sequence after the full list is presented (note that some procedures may use free recall rather than serial recall, yet free recall does not require the recall item to be bound to a context position). There may be *free time* built into the task if there are time intervals between sentence presentations, or there may be no *free time* if sentences are presented in immediate succession after the truth value judgment. The SOB-CS model would predict better performance with *free time* between sentence presentations on this task because there would be a greater likelihood that working memory would be restored to a baseline state between sentence presentations which would result in less interference between words (see also Diamond, 2013). See Appendix A Figure A.2 for an interpretation of SOB-CS model with verbal stimuli.

Individual Differences

The mechanisms constraining working memory under the SOB-CS model may be further specified by considering individual differences in other cognitive skills. First, relative strengths in verbal versus nonverbal domains may relate to the degree of interference between items with overlapping features. Individuals with relative strengths in the verbal domain may represent verbal information with greater distinctiveness, whereby verbal items with overlapping features are confused to a lesser degree than in individuals with relative weakness in the verbal domain. Similarly, individuals with relative strengths in attention would be hypothesized to maintain temporal properties of information with greater distinctiveness as the SOB-CS model posits a close relationship between attention and serial positioning of representations (Oberauer et al., 2012). This relative strength in attention may lead to less confusion between items with closer serial positions compared to individuals with relative weakness in attention. In fact, the SOB-CS

model may contribute to differentiating between effects of individual differences in attention versus individual differences in processing speed. If *free time*, or processing speed, accounts for serial errors (e.g., a previously relevant item recalled instead of the currently relevant item), there is likely a lesser effect of individual differences in attention. However, if attention explains these errors, there is likely a lesser effect of individual differences in processing speed. Thus, individual differences in attention or individual differences in processing speed may relate to the degree of interference due to serial position overlap.

The SOB-CS Model and Processing-based Factors in DLD

There are calls for theoretically integrated frameworks across many fields of scientific research. With regard to the field of memory, researchers have indicated a need to account for interrelationships among working memory, attentional processes, and processing information from verbal and nonverbal domains (Archibald, 2018; Archibald, Levee, & Olino, 2015; Kane & Engle, 2002; Marton, 2008; Marton et al., 2016; Montgomery, Gillam, & Evans, 2016; Oberauer et al., 2012). In the developmental disabilities field, researchers advocate an interaction-based perspective which may contribute to increased understanding of comorbidity between deficits in different areas of development, as well as reciprocal relationships among cognitive processes throughout development (Vissers et al., 2015; see also Ellis Weismer, 2013). This is not a new phenomenon – Norman (1968) sought to unify theories of memory and attention under a comprehensive framework – and it is not a narrow issue – Thomas and Karmiloff-Smith (2005) posit a Neuroconstructivist approach to broadly account for all of development (see also Spencer et al., 2009 for information on the Developmental Systems framework).

The SOB-CS model may represent a unified framework of processing-based factors in DLD due to its ability to account for interrelationships among working memory, processing speed, and inhibition. These interrelationships, in turn, may be associated with important individual differences in language processing in children with DLD. The SOB-CS model suggests that working memory performance is governed by a time-based mechanism that is responsible for clearing representations from working memory and avoiding interference (Oberauer et al., 2012; Oberauer et al., 2016). Namely, it accounts for how individual differences in processing speed may relate to working memory performance through a relationship with interference effects. Thus, the SOB-CS model captures key processing-based factors in DLD. This framework also accounts for individual differences in performance based on interference between items which is affected not only by the similarity in features of items (e.g., verbal versus nonverbal features), but also by individual differences in the ability to represent features of items. Accordingly, the SOB-CS model has the potential to reveal important roles of relative abilities in verbal and nonverbal domains.

Processing Performance and Individual Differences in Children with DLD

The Hierarchical Competing Systems Model is a developmental model of executive function skills, including inhibition and working memory, and posits a key role for language (Marcovitch & Zelazo, 2009). It suggests that language in the form of verbal mediation underlies developmental advancement in executive function skills. That is, the ability to use self-regulating speech to guide goal-directed behavior is thought to facilitate performance on an executive function task. However, some studies have found differences in the relationship between language and performance on executive function tasks in children with DLD (Blum & Boerma, 2019; Dispaldro et al., 2013; Larson et al., 2019; Larson, Kaplan, et al., 2020) and in children

with Autism Spectrum Disorder with co-morbid structural language impairment (Ellis Weismer, Kaushanskaya, Larson, Mathee, & Bolt, 2018; Larson, Gangopadhyay, Prescott, Kaushanskaya, & Ellis Weismer, 2020). Based on this evidence, it is possible that children with DLD rely on alternative, nonverbal strategies to engage in executive function tasks (Blom & Boerma, 2019; Botting, Psarou, Caplin, & Nevin, 2013; Larson et al., 2019). Inasmuch as verbal or nonverbal skills predict processing performance, it is possible that verbal or nonverbal skills are drawn on to regulate behavior. Varying the domain of task demands may also reveal how relative abilities are drawn upon to engage in the task.

Hoffman and Gillam (2004) examined performance on working memory tasks with demands from one domain and tasks for which demands were divided between verbal and nonverbal domains. Specifically, their tasks had an interleaved processing task (e.g., verbal naming of colors) that, relative to recall items, was either from the same domain (i.e., verbal digit recall) or from the alternative domain (i.e., nonverbal location of X's). Findings revealed the poorest performance for both groups in the condition with nonverbal recall and nonverbal interleaved processing components. Findings also indicated better performance for both the DLD and TD groups in tasks that divided demands between domains, with greater performance benefit for the TD group (Hoffman & Gillam, 2004). Gillam, Cowan, and Marler (1998) also examined performance on working memory tasks with varied domain demands. Their tasks varied the domain of recall items (i.e., verbal or nonverbal) and response modality (i.e., verbal or pointing), and they included a condition for which demands were distributed across domains (i.e., verbal-nonverbal recall items). Gillam et al. (1998) showed that children with DLD performed disproportionately worse on tasks with only nonverbal demands relative to tasks that had only verbal demands and relative to tasks with demands in both the verbal and nonverbal domains.

Additionally, children with DLD performed more similarly to TD peers when distributing processing across domains (e.g., verbal-nonverbal recall items + verbal response) relative to the conditions with demands within one domain (i.e., verbal recall item + verbal response) and demands divided between domains (e.g., verbal recall item + nonverbal response; Gillam et al., 1998). Taken together, these studies suggest progressively better performance for children with DLD as the domain of task demands becomes more evenly dispersed across domains. These studies also point to a particular weakness on working memory tasks which primarily draw on nonverbal abilities rather than verbal abilities for children with DLD. These patterns may suggest that children with DLD rely on nonverbal abilities to engage in working memory tasks, resulting in the substantive difficulty when the processing load is largely nonverbal in nature (Botting et al., 2013; Larson et al., 2019). However, no prior studies have systematically examined conditions with task demands within one domain, divided between domains, or distributed across domains, nor related performance in these conditions to relative verbal and nonverbal ability in children with DLD.

Finally, children with DLD have more difficulty in attentional abilities than their TD peers (Mueller & Tomblin, 2012; Redmond & Ash, 2014; Smolak et al., 2020; but see Blom & Boerma for similar performance between children with TD and DLD on a selective attention task). Under some frameworks, like the Hierarchical Model of Inhibitory Control (Tiego, Testa, Bellgrove, Pantelis, & Whittle, 2018), attention is thought to be important to working memory due to its role in active maintenance of task goals (Friedman & Miyake, 2004; Kane & Engle, 2002; Tiego et al., 2018). Consequently, attention may be associated with inhibition and working memory, as goal maintenance is critical to deeming information relevant or irrelevant (Garon, Bryson, & Smith, 2008; Kapa & Erikson, 2020; Miyake et al., 2000; Miyake & Friedman, 2004;

Tiego et al., 2018). In contrast, the SOB-CS suggests that the role of attention relates to a bound item-position representation being in the focus of attention (i.e., similar to the role of attention in Cowan's (1988; 2010) Embedded Processes Model of working memory) and then displaced by subsequent item-position representations (Oberauer et al., 2012). Thus, the role of attention is important, particularly for maintaining serial properties of the input. However, this role of attention in the SOB-CS is important for more bottom-up reasons whereas the role of attention in the Hierarchical Model of Inhibitory Control is important for more top-down reasons (e.g., active goal maintenance; Oberauer et al., 2012; Tiego et al., 2018). Empirical evidence broadly supports these views, showing similar neural substrates for attention, inhibition, and working memory (Kane & Engle, 2002; Munakata et al., 2011). In children with DLD, studies have linked attention with inhibition and working memory (Kapa & Erikson, 2020; Kapa, et al., 2017; Marton, 2008; Schul et al., 2004; Smolak et al., 2020), yet many studies either examine performance on each task individually (e.g., Blom & Boerma, 2020, Kapa & Erikson, 2020, Kapa, et al., 2017) or examine a composite index which collapses performance across each task (e.g., Blom & Boerma, 2019). Only one study has examined interrelationships among attention, working memory, and language, yet their analytical approach was to examine correlations among performance on a nonverbal sustained selective attention task (i.e., may draw on inhibitory control), a nonverbal working memory task, and a standardized narrative language assessment (Smolak et al., 2020). Though the authors suggest that attention, as measured by the sustained selective attention task, may mediate the relationship between working memory and language, their study did not test this hypothesis. Beyond this correlational work, no prior studies have tested how individual differences in attention are related to interrelationships among working memory, processing speed, inhibition, and language.

Current Dissertation

Aims

The impetus of this dissertation was to address three major gaps in the literature. The first gap is the lack of integration of processing-based hypotheses of factors that may underlie DLD. Prior studies examine working memory, processing speed, and inhibition separately rather than considering how interrelationships among these cognitive processes relate to language in children with DLD. The second gap is a lack of fully-crossed experimental design when examining relationships between domain and working memory performance in children with DLD. Additional conditions which vary the domain of recall items and interleaved processing tasks are needed to account for potential DLD versus TD group differences in the relationship between task demand domain and performance. The third gap relates to individual differences. No prior work examines the relationship between working memory performance and verbal, nonverbal, and attentional ability while also considering potential DLD and TD group differences in these relationships. The primary goal of this dissertation was to better understand mechanisms of processing deficits in DLD by uniting three primary hypotheses of processing-based factors.

This goal was accomplished through three studies:

1. Study 1 was designed to systematically examine the effects of varying the domain of task demands on working memory performance in children with DLD relative to TD peers using the SOB-CS model as my theoretical framework. Children were asked to complete working memory tasks in five different conditions: a) verbal recall items with an interleaved verbal processing task; b) nonverbal recall items with an interleaved

nonverbal processing task; c) verbal recall items with an interleaved nonverbal processing task; d) nonverbal recall items with an interleaved verbal processing task; e) verbal-nonverbal recall items with an interleaved verbal-nonverbal processing task. Simply put, task demands were within a single domain (2 conditions), divided between two domains (2 conditions), or distributed across both verbal and nonverbal domains (1 condition), respectively, resulting in a fully crossed design (Table 2.1). Outcome measures were accuracy and reaction time, and predictors were group and condition – within versus divided conditions and divided versus distributed conditions. I compared overall group differences in performance, and the degree to which children with DLD and typical development benefitted from dispersing processing across domains.

2. Study 2 was designed to test how a key mechanism posited by the SOB-CS model, *free time*, relates to working memory accuracy in children with DLD relative to TD peers. I examined the relationship between *free time* within working memory task trials and performance accuracy in each of the same five conditions as Study 1. *Free time* represented the time between participant response on the interleaved processing task and the onset of recall test item presentation. Specifically, each interleaved processing task had a set time interval, thus *free time* varied depending on how quickly a participant responded to the processing task. This is a novel approach to examining the relationship between processing speed and working memory performance in DLD as I captured how processing speed affects working memory accuracy through its relationship with interference effects.
3. Study 3 was designed to examine how individual differences in verbal, nonverbal, and attentional abilities relate to working memory performance in children with DLD versus

TD peers using the SOB-CS model as my theoretical framework. The experimental design was the same as in Studies 1 and 2. I assessed verbal skills using a sentence comprehension task where participants listened to a sentence and selected the correct associated picture from a set of four pictures. I assessed nonverbal abilities using the Matrix Reasoning subtest from the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler, 2011). In order to account for potential relationships between attention and working memory accuracy, as well as group-based differences in sustained attention, I administered a visual Continuous Performance Task (CPT) adapted from Finneran et al. (2009). Outcome measures were accuracy and reaction time on the working memory tasks, accuracy on the sentence comprehension task, d-prime on the CPT, and t-scores on the WASI-II. This study elucidated the degree to which relative strengths are drawn upon, potentially reflecting the role of verbal versus nonverbal strategy use, during working memory tasks with varied domain-based demands in children with DLD versus TD peers. Study 3 also revealed the role of attention in working memory performance on these tasks in order to account for potential weakness in attention for the DLD group relative to the TD group, particularly as it relates to serial recall and the role of *free time* in working memory performance.

Population

A total of 55 participants, 34 typically developing children and 21 children with DLD, age 9-13 years were recruited to participate in the three studies for the present dissertation. Children with DLD had standard scores on the Core Language, Expressive Language, or Language Content composite indices 1.2 standard deviations below the mean (≤82) on the Clinical Evaluation of Language Fundamentals, Fifth Edition (CELF-5; Wiig, Semel, & Secord,

2013; see Blom & Boerma, 2020 and Smolak et al., 2020 for similar DLD criteria). The CELF-5 has a sensitivity of 1.0 and specificity of .91 at 1 standard deviation below the mean on the composite index scores and .97 sensitivity and .97 specificity at 1.33 standard deviations below the mean. A cutoff at 1.2 standard deviations below the mean, therefore, represents approximately .98 sensitivity and .95 specificity. The optimal cutoff in terms of balancing sensitivity and specificity is a standard score of 80 or below on either index. However, a score of 85 or below is more sensitive to the presence of language impairment, albeit slightly less specific to ruling out children who do not have a language impairment (Wiig et al., 2013). Recent work on DLD criteria in research suggests a minimum of .80 sensitivity and specificity (Nitido & Plante, 2020) and my cutoff exceeds this minimum for both sensitivity and specificity.

Children with DLD also had nonverbal t-scores on the WASI-II Matrix Reasoning subtest >30 (i.e., above the cutoff for intellectual disability). I did not limit my DLD group to having nonverbal abilities in the average range as my studies involved children with DLD rather children with SLI. Typically developing children had verbal scores on the CELF-5 (≥85) and nonverbal scores on the WASI-II within the normal range (≥40). All children were required to have no history of failed hearing screening, have normal or corrected to normal vision, be monolingual, and have no known history of biomedical conditions associated with their language disorder (Bishop et al., 2017). I also collected demographic information, including maternal education (i.e., a proxy for socioeconomic status), racial and ethnic background, t-scores from the Conners-3 abbreviated parent interview (i.e., a screening for Attention-Deficit/Hyperactivity Disorder; t-scores >64 reflect elevated symptoms), and baseline visual and auditory reaction time (i.e., separate reaction time tasks measuring simple response time to visually and auditorily presented stimuli; Willoughby, Blair, Kuhn, & Magnus, 2018).

Methodology

The methodological approach for the current dissertation offers four innovations in examining working memory in children with DLD. First, the task structure between conditions is consistent and closely aligns with current views of working memory as a construct. This working memory task structure involves: 1) maintenance and manipulation requirements during each trial; 2) items and serial information recall in concert; 3) consistent response modality (Alloway, Gathercole, & Pickering, 2006; Leonard et al., 2007; Oberauer et al., 2012; Oberauer et al., 2016; Smolak et al., 2020). Second, my experimental design allows for a systematic test of domain effects under a single framework. This approach provides a robust, fully-crossed paradigm for revealing how varying the domain of task demands relates to performance in children with DLD relative to TD peers (Table 2.2). Third, analyzing group differences in the relationship between working memory and verbal, nonverbal, and attentional abilities is another innovation of the current dissertation. This approach provides a comprehensive understanding of individual differences by group under a unified framework of working memory. Finally, all aspects of this work were conducted remotely using Zoom (i.e., a secure videoconferencing platform), E-Prime Go (Psychology Software Tools), and a dedicated laptop computer (Dell Inspiron, Intel® Core™ i5, Windows® 10) that I provided to participants. I adopted a remote-based approach due to the COVID-19 pandemic, yet this approach also offers a novel method of examining linguistic and cognitive profiles in children with DLD.

Overview

The current dissertation is organized into 5 additional chapters. Chapter 2, "Methods and Analysis," focuses on the participant sample, working memory task design, and working

memory performance analysis. Chapter 3, “The role of domain in working memory performance,” focuses on Study 1. Study 1 examines DLD and TD group differences in performance between conditions which vary the domain of task demands. Chapter 4, “The impact of *free time* on working memory accuracy,” focuses on Study 2. Study 2 tests a key mechanism posited by the SOB-CS by examining how *free time* affects working memory performance accuracy in children with DLD and typical development. Chapter 5, “Individual differences and working memory,” focuses on Study 3. Study 3 investigates relationships among working memory performance and verbal, nonverbal, and attentional abilities in children with DLD relative to TD peers. Chapter 6 is the General Discussion. This discussion synthesizes Studies 1-3 (Chapters 3-5) and draws broad preliminary conclusions about mechanisms of processing deficits in DLD using an integrative framework of working memory. Chapter 6 also includes a discussion of plausible future directions.

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Chapter 2: Methods and Analysis

Participants

This study was approved by the Education and Social Behavioral Institutional Review Board at the University of Wisconsin-Madison. Participants included 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. They were included as part of a larger remote-based project on language and working memory in children with DLD. I administered assessments and experimental tasks remotely over two visits that lasted approximately 2 hours each and were separated by one week or less. I used Zoom (i.e., a secure videoconferencing platform) and I provided a dedicated laptop computer (Dell Inspiron, Intel® Core™ i5, Windows® 10) to each participant. I 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 6 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 Developmental Language Disorder (DLD) group (4; e.g., history of speech-language services and all standardized language scores with the normal range). There were twenty-one 9-13 year old children with DLD (M = 10.46 years, SD = 1.09 years) and 34 age-matched peers with typical development (TD; M = 10.47 years, SD = 1.08 years; p = .95). A power analysis for the general linear model with four predictors indicated the need for 67 participants to detect a medium effect size (f2 = 0.15) and 23 participants to detect a large effect size (f2 = 0.35) at a significance level of .05 and power level of .80. Based on my participant sample, my study had adequate power to detect an effect size ≥ 0.17. Per Westfall, Kenny, and Judd's (2014) crossed random-effects

power analysis, my study design (i.e., stimuli-within-conditions) with a small effect size (d = 0.15) yields a power of 0.88 with a sample size of 55 and stimuli count of 300 (i.e., includes interference stimuli; see Appendix B Table B.1 for complete calculation information; Note that I did not include stimulus in my random effect structure).

In my participant sample, I included one participant in my DLD group who had a Core Language score of 85, but who also had a history of speech-language and reading difficulty and a scaled score of 6 (9^{th} percentile) on the Recalling Sentences subscale of the CELF-5. This subscale is thought to be particularly sensitive to core deficits of DLD (Christensen, 2019; Conti-Ramsden, Botting, & Faragher, 2001; and see Oetting, McDonald, Seidel, & Hegarty, 2016 for evidence of sentence recall diagnostic accuracy in nonmainstream dialects of English) and a Core Language composite score of 85 has a sensitivity of 1.0 and a specificity of .91. Further, I analyzed performance with and without this participant, and results were not meaningfully different. One exception was evidence of a significant interaction between group and sentence comprehension when removing this participant from analyses of reaction time on the verbal-within domain task (Chapter 5: Individual Differences). This interaction reflected a significant relationship between sentence comprehension and reaction time for the DLD group, but not the TD group in this condition. This pattern is noted and briefly interpreted in Chapter 5. I included one DLD participant whose nonverbal t-score was 27, which was within one standard error measurement of my cutoff score of 30, and I included one TD participant whose nonverbal t-score was 32. For the TD participant, a t-score of 32 is below the average range of 40-60, but this participant had no history of intellectual disability, speech-language services, or parent reported developmental concerns. Performance patterns for these participants were not meaningfully

different from performance of the DLD and TD group, respectively. Note that these participants are included in all group summary statistics.

Participants had no 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 which also included developmental and medical history of the participant. Eligibility for the TD group was: 1) no parental report of language delay or intervention; 2) 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); 3) 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, Semel, & Secord, 2013). The nonverbal ability criterion for the TD group reflects the lower cutoff for the normal range (i.e., 40-60) and is commonly observed for TD groups (e.g., Blom & Boerma, 2019; Smolak, McGregor, Arbisi-Kelm, & Eden, 2020). I did not, however, exclude the one TD participant with a somewhat lower t-score (i.e., 32) as they met other TD group criteria (e.g., no history of language delay or intervention) as noted above.

Eligibility for the DLD group was: 1) nonverbal t-scores >30 on the Matrix Reasoning subtest from the WASI-II (i.e., the intellectual disability cutoff); 2) standard scores on the Core Language, Expressive Language, or Language Content composite index 1.2 standard deviations below the mean (≤82) on the CELF-5. This CELF-5 criterion exceeds recommended sensitivity and specificity levels (Nitido & Plante, 2020; Wiig et al., 2013). I did not restrict nonverbal

ability to be within the normal range (i.e., t-scores ≥40) or exclude children with co-occurring disorders in cognitive, sensory-motor, or behavioral domains identified by Bishop et al. (2017) given that I were interested in examining a DLD group rather than a more restrictive Specific Language Impairment group. Children with language deficits who also have a differentiating condition, such as Autism Spectrum Disorder or intellectual disability, are viewed as having 'Language Disorder associated with X' (e.g., Language Disorder associated with intellectual disability) under the Bishop et al. (2017) classification system. Thus, I did not include children with differentiating conditions in the current study. Prior work indicates a higher prevalence for children with DLD than Specific Language Impairment (Norbury et al., 2016) and similar magnitude and direction of language growth, even on areas of greatest weakness (e.g., past-tense -*ed*), between DLD and SLI groups (Norbury et al., 2017; Rice, Tomblin, Richman, & Marquis, 2004). Furthermore, there is a movement in the field to conduct research on children with DLD rather than SLI in order to increase understanding of relationships among language and cognitive skills and to increase the ecological validity of research findings (Bishop et al., 2017; Leonard et al., 2007; Norbury et at., 2017; see Rice, Taylor, & Zubrick, 2008 for additional evidence and McGregor, Goffman, van Horne, Hogan, & Finestack, 2020 and Volkers, 2018 for further discussion). See Table 2.1 for demographic information and standardized test scores for participants. Note that all assessments were conducted using videoconferencing and digitized forms of the stimulus materials (i.e., Pearson Q-Global materials).

Table 2.1. 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			
Mean	10.47	10.46	p = .95
SD	1.08	1.09	(r^2 = -0.02)
Maternal education in years (SES)			
Mean	17.42	15.71	TD>DLD**
SD	2.53	1.45	(r^2 = 0.12)
WASI-II (Matrix Reasoning)			
Mean	58.00	46.05	TD>DLD***
SD	9.50	11.23	(r^2 = 0.24)
Conners t-score (Attention)			
Mean	67.21	72.40	p = .34
SD	17.01	22.09	(r^2 = -0.00)
Core Language (CELF-5)			
Mean	112.59	82.95	TD>DLD***
SD	12.14	10.39	(r^2 = 0.61)
Expressive Language (CELF-5)			
Mean	110.06	79.30	TD>DLD***
SD	11.70	10.03	(r^2 = 0.64)
Language Content (CELF-5)			
Mean	108.41	77.48	TD>DLD***
SD	14.20	9.22	(r^2 = 0.59)

Note: WASI-II = Wechsler Abbreviated Intelligence Scale, Second Edition, Matrix Reasoning subscale; Conners t-score = abbreviated parent interview for Attention-Deficit/Hyperactivity Disorder, 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. $^{**}p < .01$, $^{***}p < .001$.

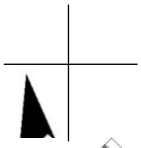
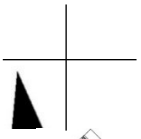
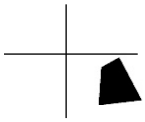
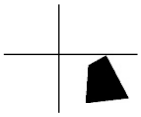
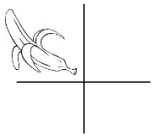
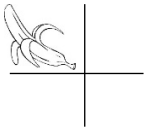
I also administered the Conners-3 abbreviated parent interview (i.e., a screening for Attention-Deficit/Hyperactivity Disorder; t-scores >64 reflect elevated symptoms), a sustained attention task adapted with permission from Finneran, Francis, and Leonard (2009), and a sentence comprehension task adapted with permission from Robertson and Gallant (2019). Participants did not differ significantly in Conners-3 t-scores ($p = .34$), however both groups had mean t-scores indicating elevated symptoms. See below for additional information. Participants also completed baseline visual and auditory reaction time tasks which measured simple response time to visual and auditory stimuli as prior work supports including these measures in analyses of cognitive skills (Willoughby, Blair, Kuhn, & Magnus, 2018). Groups did not differ significantly in visual or auditory baseline reaction time (p's > .05) when accounting for group differences in SES (DLD M = 15.71ms, SD = 1.45ms; TD M = 17.42ms, SD = 2.53ms; $p < .01$). All assessments and 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 my theoretical framework and other prior work (Alloway, Gathercole, & Pickering, 2006; Leonard et al., 2007; Oberauer, Lewnadowsky, Farrell, Jarrold, & Greaves, 2012; Oberauer, Farrel, Jarrold, & Lewandowsky, 2016). This structure involved presentation of potential recall items, an interference processing task, and recall of target items paired with serial information. My experimental paradigm was a fully-crossed design with 5 conditions (Table 2.2)

and my dependent variables were recall test accuracy and reaction time. This paradigm was drawn from the Brown-Peterson design which involves presenting a string of letters, then presenting an interference task involving counting backward by three, and finally testing recall of the string of letters in the correct sequence (see Siffredi et al., 2017 for an example).

Table 2.2. Description of experimental conditions.

Task	Recall Training Phase		Interference Processing Phase		Recall Test Phase	
	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 1 of 4 quadrants, indicated here via t-shaped lines (quadrant lines are not visible to participants for the experimental tasks).

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 2.2 for examples of stimuli). The same speaker (not the examiner) produced all auditory stimuli and had

a neutral Midwest accent. All auditory word/nonword stimuli were 1-2 syllables in length and were normalized to 65 dB and 650ms. I 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 (Fenson et al., 2007; i.e., criterion assessment of early language ability), rather than selecting infrequently occurring words, under the assumption that all participants had mastered these words by the time they enrolled in the study. Nonwords were acquired from the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002) and generated with frequency statistics information. All auditory question stimuli were 5 words in length and normalized to 65 dB and 1600ms. All visual stimuli were black-and-white and normalized to 4x4 and 600 pixels. The word-images were prototypical exemplars edited in Photoshop (2019), the abstract shapes were 4-sided shapes adapted with permission from Ceaser and Barch (2016; similar to the random shapes used by Vanderplas & 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 (p's > .31) and nonwords did not differ in length or frequency of phonological neighbors (p's > .07). See Appendix B Tables B.2 and B.3 for by-condition comparisons of stimuli features.

Task Design

Each trial had recall training, interference processing, and recall test phases for all conditions, and brief unfilled intervals between each phase based on task piloting (300-650ms). For the verbal within-domain condition, recall training involved three sequentially presented words and their associated images which appeared in the center of the screen. 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 3300ms after the word/nonword offset to respond and the recall test phase did not begin until after the 3300ms had elapsed (i.e., rather than after the participant responded), thus allowing for variance in *free time* available prior to the onset of the recall test phase. Importantly, this component of the task allows for variance between participants in *free time*, but also eliminates a possible dependency between *free time* and reaction time in the recall test phase of the task. The recall test phase onset is the same across participants and conditions, and across potential response times on the interference processing phase. For the recall test phase, two of the three recall training phase words were presented again with associated images pseudorandomized to appear on the right or left side of the screen. Participants were to select the item that appeared earlier in the recall training phase sequence of presentation, thereby assessing item plus serial position (i.e., their instructions were to "pick the winner, the one that came *before* the other"). Auditory words were sequentially presented due to necessity, but images appeared simultaneously in order to trigger the participant's recognition it was time to select the appropriate item. Participants had 5050ms after the offset of the second auditory word to respond prior to the onset of the subsequent trial.

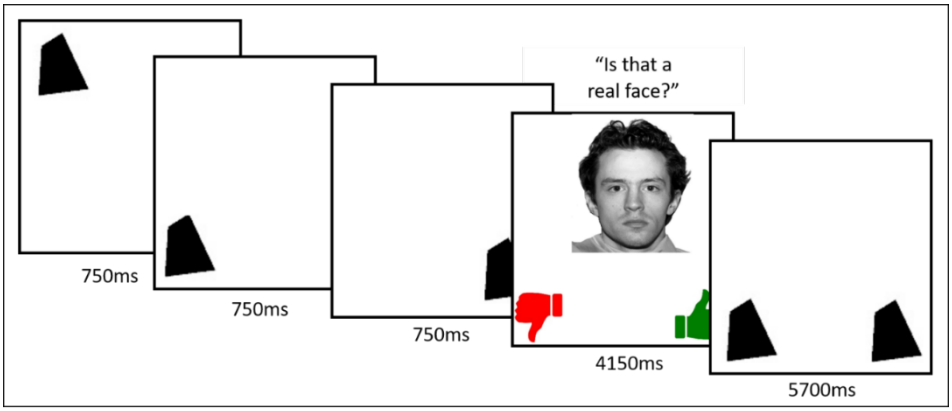


Figure 2.1. Nonverbal within-domain condition trial example.

For the nonverbal within-domain condition (Figure 1), recall training involved three presentations of a single abstract shape which appeared in one of four possible pseudorandomized locations (i.e., quadrants) on the screen, with no repeated locations during a given trial's recall training phase. The interference processing phase involved a face/nonface presented for the duration of the interference processing phase and a question prompt ("Is that a real face?"). Participants had 2550ms after the offset of the question prompt to respond prior to the onset of the test phase (i.e., allowing for variance in *free time*). This duration is 750ms shorter due to the verbal interference processing phase having a second presentation of the stimulus. Specifically, the visual stimulus – face/nonface – was present throughout the interference phase whereas the verbal stimulus – word/nonword – was inherently fleeting; thus, the verbal interference phase required additional time. This timing difference also accounts for potential processing-based differences between interference phase stimuli (e.g., processing verbal stimuli may be slower than nonverbal stimuli; Oberauer & Souza, 2020) and patterns observed in task piloting. For the recall test phase, the abstract shape reappeared in two of the three locations presented in recall training simultaneously and participants were to select the item location that occurred earlier in the recall training phase sequence. Participants had 5700ms (i.e., 5050ms as in the verbal within-domain condition plus the duration of a word stimulus – 650ms) after the onset of images to respond prior to the onset of the subsequent trial. For the divided-domain conditions, verbal recall was paired with nonverbal interference processing and nonverbal recall was paired with verbal interference processing (Table 2.2).

The distributed-domain condition adopted features of the verbal and nonverbal conditions. Recall training involved three presentations of a single word and associated image sequentially presented in one of four possible pseudorandomized locations on the screen; no

location was repeated within a given trial's recall training phase. The interference processing phase involved a word presented auditorily coming from either the left or right side of the laptop speakers, followed by a question prompt ("Where did you hear it?"), and then a second production of the word from the same side as the first production. Timing for the distributed-domain condition was the same as the verbal within-domain condition. Participants had 3300ms after the word offset to respond before advancing to the test phase, thus allowing for *free time* to vary by trial. For the recall test phase, the word and associated image simultaneously reappeared in two of the three locations presented in recall training and participants were to select the item location that occurred earlier in the recall training phase sequence (i.e., testing item location plus serial position). Participants had 5050ms after the offset of the auditorily presented word to respond prior to the onset of the subsequent trial. See Appendix B Figures B.1 and B.2 for additional examples.

Procedure

Tasks were administered using Zoom and E-Prime Go (Psychology Software Tools) – 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 so that the experimenter could monitor attention/participation. Note that the participant could view the experimenter's video only during instruction. E-Prime Go experiment files may be saved locally to the laptop computer in a neatly packaged form and run without needing E-Prime 3 installation. The experiment runs similarly to experiments run using E-Prime 3 and my laptops exceeded specifications required for accurate reaction time data (e.g., Windows® 10, Intel® Core™ i5; see Psychology Software Tools E-Prime 3 requirements for additional specifications). E-Prime Go also collects diagnostic information which provides

details about the software and hardware environment. Data files were stored locally to the laptop until they were uploaded using Qualtrics surveys and saved to a secure network drive. Laptops were scrubbed of all files after each participant completed the two study sessions.

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 2 complete instructional trials with experimenter verbal-visual instruction and feedback (e.g., “pick the winner,” “this one or this one?” paired with highlighting the selection with the mouse icon), 3 practice trials with automated visual feedback (e.g., smiley face), and 15 experimental trials. Instructions were broadly balanced in having verbally and visually presented information, and children were able to ask questions at any time during instruction. I instructed participants that the recall test phase was triggered by the simultaneous presentation of two images (across conditions) due to the absence of a question prompt during this phase. I further instructed participants that they were to “pick the winner” or the image occurring earlier in the sequence of images or image locations from the recall training phase of the two options (i.e., two of the three items presented during recall training), whereby they were required to recall the item and its serial position. Comprehension of this task demand was verified during instruction via three opportunities for the child to “pick the winner” with the examiner. Three practice trials with automatized visual feedback were presented after completing instructions. Participants who indicated that they received sad faces were offered 3 additional practice trials. No participants failed recall test for all three additional practice trials and all participants demonstrated comprehension during instructions. See below and Appendix B Table B.4 for information on chance level performance.

Analysis

Reaction Time

I analyzed reaction time (RT) using linear mixed-effects models with random by-subject intercepts and random by-condition slopes. I removed observations which exceeded acceptable levels of leverage and model influence (Judd, McClelland, & Ryan, 2009), specifically observations that were ≥ 3 standard deviations from each subject's mean (0.1% of the data) and observations that were < 150ms (0.3% of the data). I conducted follow-up within-group analyses based on descriptive performance patterns (Table 2.3, and Appendix B Tables B.6 and B.7) and significant group by condition interactions using mixed-effects linear models.

Accuracy

Accuracy was statistically analyzed using generalized linear mixed-effects models as accuracy was a dichotomous (0,1) variable and condition varied within participants (i.e., participants engaged in multiple conditions). I used the logit link function in the generalized models, a transformation of the logistic function, in order to yield log-odds coefficient estimates. Coefficient values were then converted to odds-ratios in order to more clearly quantify significant effects. Specifically, odds-ratios indicate the odds of a correct response on the working memory tasks at specific levels of the predictor (e.g., the odds of a correct response in the verbal divided condition versus the verbal within condition). Random effects included by-subject random intercepts and by-condition slopes. Follow-up within-group analyses were based on descriptive performance (Table 2.3, and Appendix B Tables B.6 and B.7) and significant group by condition interactions. I conducted these using mixed-effects generalized linear models. I removed performance from one TD participant in one condition (nonverbal-divided) due to it

being an extreme observation. See Appendix B Table B.4 for information on chance level performance on recall tasks and Appendix B Table B.5 on interference non-responses. All analyses were conducted in R (R Core Team, 2019; R Studio Team, 2020; version 1.2.5033).

Table 2.3. Descriptive statistics and by-group t-tests for working memory task conditions.

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 = 0.24
Reaction Time	M = 1963.12	M = 2176.00	p = .12
	SD = 461.78	SD = 509.12	r^2 = 0.03
Verbal Divided			
Accuracy	M = 0.91	M = 0.77	TD>DLD**
	SD = 0.12	SD = 0.20	r^2 = 0.15
Reaction Time	M = 1793.02	M = 1930.52	p = .30
	SD = 430.74	SD = 510.12	r^2 = 0.00
Nonverbal Within			
Accuracy	M = 0.87	M = 0.72	TD>DLD**
	SD = 0.14	SD = 0.21	r^2 = 0.14
Reaction Time	M = 1942.82	M = 2161.63	p = .16
	SD =516.19	SD = 599.74	r^2 = 0.02
Nonverbal Divided			
Accuracy	M = 0.90	M = 0.67	TD>DLD***
	SD = 0.12	SD = 0.26	r^2 = 0.25
Reaction Time	M = 2251.03	M = 2684.55	TD<DLD*
	SD = 684.68	SD = 879.77	r^2 = 0.05
Distributed			
Accuracy	M = 0.89	M = 0.76	TD>DLD**
	SD = 0.10	SD = 0.21	r^2 = 0.15
Reaction Time	M = 2089.22	M = 2528.06	TD<DLD*
	SD = 531.30	SD = 829.71	r^2 = 0.08

Note: M = mean; SD = standard deviation. *p < .05, **p < .01, ***p < .001.

Covariates

Maternal education, my proxy for socioeconomic status, was included in all mixed-effects models with a group contrast due to evidence of significant group differences in SES (p < .01). I did not include baseline RTs or age covariates because there was no significant group difference in visual or auditory RT performance (p's > .05) when accounting for SES and groups

were matched on age (p = .95). Nonverbal ability was not a covariate in statistical models due to the high overlap in working memory and fluid intelligence ability which may wash out important relationships between working memory and other factors (Leonard et al., 2007; Fry & Hale, 1996). Furthermore, nonverbal ability may be a key DLD-TD group differentiating characteristic given consistent evidence of group differences in nonverbal ability in the literature even when nonverbal ability is restricted to the average range (Kover & Atwood, 2013). Similarly, I did not include Conners t-scores in statistical models because groups did not differ significantly (p = .34). Conners t-scores were elevated in many of the TD participants (N =10), as well as the DLD participants (N = 14), and there was evidence that ranges of performance overlapped in children with and without elevated t-scores (see also Smolak et al., 2020). These elevated t-scores may also be related to the COVID-19 pandemic conditions, specifically by affecting parent report of ADHD symptoms in a way that was not accounted for in the norming of the rating scale. I included interference task accuracy or RT as a covariate where there was evidence of significant group differences in order to ensure that the condition manipulation, rather than group differences in performance on a particular interference task, was being tested (see Hoffman & Gillam, 2004 for a similar approach). See Table 2.3 for working memory performance descriptive statistics, and Appendix B Tables B.6 and B.7 for correlations among participant characteristics and performance on experimental tasks.

Missing Data

One participant had incomplete data due to completing only one of two study sessions. These data were not missing completely at random, therefore I used the gold standard approach to handling missing data – multiple imputation. Multiple imputation is a 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 (Akmam et al., 2021; Rubin, 1987; van Buuren, 2018). I used the mice package with predictive mean matching for continuous data (e.g., reaction time) 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) and used the imputed datasets for all statistical analyses. Data were imputed within subsets consistent with the substantive model (e.g., reflecting interaction terms; Bartlett et al., 2014). I then compared these analyses to raw data (outliers removed), and there were few substantive differences (see Appendix C Table C.1), yet these differences should be explored further in future work. Where there were differences between the imputed and raw data analyses on group interaction terms (e.g., the interaction between group and condition), I further analyzed within-group patterns. Additionally, I analyzed within group patterns based on descriptive performance patterns and correlations (Appendix B Tables B.6 and B.7). I reported all statistical results based on multiple imputation statistical analyses. See tables within Chapters 3-5 for complete statistical analysis output.

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Chapter 3: The Role of Domain in Working Memory Performance

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, Snowling, Thompson, Greenhalgh, & CATALISE Consortium, 2017; Leonard, 2014; 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 & Durkin, 2012; Johnson, Beitchman, & Brownlie, 2010; Le et al., 2020; Whitehouse, Watt, Line, & Bishop, 2009). Although DLD is primarily characterized by deficits in verbal processes, these children also present with deficits in nonverbal processes on tasks measuring working memory (Vugs, Hendriks, Cuperus, Knoors, & Verhoeven, 2017), processing speed (Kail, 1994; Miller, Kail, Leonard, & Tomblin, 2001; Leonard et al., 2007; Leonard, Ellis Weismer, Weber-Fox, & Miller, 2014; Tallal et al., 1996), and inhibition (Kapa, Plante, & Doubleday, 2017; Marton, Klemenson, & Pinhasova, 2007; Pauls & Archibald, 2016). It is possible that their performance on tasks with both verbal and nonverbal processing demands is more similar to TD peers than performance on tasks with only verbal demands (Gillam, Cowan, & Marler, 1998; Hoffman & Gillam). No prior studies, however, have systematically examined how dispersing processing across verbal and nonverbal domains affects performance in children with DLD relative to TD peers.

Three primary hypotheses of processing-based factors in DLD separately posit the following: 1) limited verbal working memory (Archibald & Gathercole, 2006, 2007; Ellis Weismer, Evans, & Hesketh, 1999); 2) slowed processing speed (Kail, 1994; Miller et al., 2001); 3) inefficient inhibition (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). The central issue

of these hypotheses, however, relates to how children with DLD are processing information. A theoretical framework which integrates each of these processing-based factors to explain processing performance may be best suited to reveal mechanisms underlying verbal and nonverbal deficits in DLD. One theoretical framework with the potential to unify these three disparate hypotheses is the serial-order-in-a-box – complex span (SOB-CS) computational model (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). This model captures these hypotheses because it posits a key role for time, or *processing speed*, in *inhibiting* interference in *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 provides a comprehensive theoretical framework for examining performance on tasks that tap verbal and nonverbal cognitive processes in children with DLD.

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, 2006, 2007; Ellis Weismer et al., 1999; Leonard et al., 2007; Leonard et al., 2014; Tallal et al., 1996; see also Alloway, Rajendran, & Archibald, 2009 for discussion of working memory difficulty being secondary to language deficits). This hypothesis is based on evidence of poorer performance on measures of verbal processing for children with DLD relative to TD peers. In fact, one such processing measure, nonword repetition, has been considered a potential clinical marker of DLD (Deevy, Wisman Weil, Leonard, & Goffman, 2010; Dollaghan & Campbell, 1998; Tager-Flusberg & Cooper, 1999). Nonword repetition involves asking children to verbally repeat word-like forms which are constructed to control for familiarity effects, articulatory difficulty, and predictability (Dollaghan & Campbell, 1998). It is thought to measure cognitive processes underlying language acquisition

(e.g., phonological working memory, speech perception; Dollaghan & Campbell, 1998; Ellis Weismer et al., 2000; see Coady & Evans, 2008 for further discussion). There is also empirical evidence linking nonword repetition with vocabulary (Bowey, 2001) and, perhaps to a greater degree, with morphosyntax (Adams & Gathercole, 2000; Botting & Conti-Ramsden, 2001; Thordardottir, 2008).

Besides difficulty on nonword repetition tasks, evidence suggests that children with DLD struggle on other verbal processing tasks, such as word recognition (McMurray, Samelson, & Tomblin, 2010; Mainela-Arnold, Evans, & Coady, 2008; Montgomery, 2005; Montgomery, Magimairaj, & Finney, 2010; Velez & Schwartz, 2010) and sentence comprehension (Leonard, Deevy, Fey, & Bredin-Oja, 2013; Montgomery, 2006; Pizzioli & Schelstraete, 2010). Additionally, children with DLD disproportionately struggle with verbal working memory relative to TD peers. One such verbal working memory measure is the Competing Language Processing Task (Gaulin & Campbell, 1994). This task involves presenting sets of sentences with each set varying from one to seven sentences in length, and after each sentence, the child is asked to decide whether the sentence was true or false (i.e., truth-value judgment). After each set of sentences, the child is then asked to verbally recall the final word from each of the sentences in the set in the correct sequence. The largest sentence set size for which the final words are recalled correctly is considered a measure of verbal span or verbal working memory capacity (Baddeley, Allen, & Hitch, 2011; Gaulin & Campbell, 1994). Children with DLD are generally slower and less accurate than TD peers on this sentence span task and other verbal working memory tasks (Archibald & Gathercole, 2006; Ellis Weismer et al., 1999; Ellis Weismer, Plante, Jones, & Tomblin, 2005; Mainela-Arnold, Evans, & Alibali, 2006; Montgomery & Evans, 2009).

There is also evidence of a developmental link between verbal working memory performance and language skills at a later timepoint in children with DLD (Vugs et al., 2017).

There is strong support for a relationship between verbal processing and language ability, yet many studies have also revealed deficits on processing tasks that are nonverbal in nature for children with DLD (Dispaldro et al., 2013; Marton, 2008; Smolak, McGregor, Arbisi-Kelm, & Eden, 2020; Vugs, Cuperus, Hendriks, & Verhoeven, 2013; Windsor, Kohnert, Loxtercamp, & Kan, 2008; but see Blom & Boerma, 2020). Vugs et al. (2013) conducted a meta-analysis on nonverbal working memory and found deficits for children with DLD relative to TD peers on both short-term storage and working memory with moderate and large effect sizes, respectively. Windsor et al. (2008), specifically, showed that school-age children with DLD had slower reaction times and poorer accuracy on mental rotation (i.e., indicating whether a shape is the same as an identical rotated shape or the same as a different shape) and nonverbal serial memory tasks (i.e., replicating a sequence of circles that illuminate in a series). Language, as measured by a standardized test, predicted performance on the mental rotation task, but not the serial memory task, for both groups after accounting for age and baseline visual reaction time (Windsor et al., 2008). Marton (2008) also showed poorer performance on several visuospatial working memory tasks for children with DLD relative to TD age-matched peers.

Only two studies have contrasted performance on processing tasks with varied verbal and nonverbal demands in children with DLD relative to TD peers (Gillam et al., 1998; Hoffman & Gillam, 2004). Gillam et al. (1998) examined performance accuracy on working memory tasks that varied the domain of recall items and response modality. Items were verbally presented digits, visually presented digits, or verbally and visually presented digits, and responses were either verbally produced words or nonverbal pointing. Thus, this study's task demands were

within the verbal or nonverbal domain (e.g., verbal item, verbal response), divided between verbal and nonverbal domains (e.g., verbal item, nonverbal response), or distributed between verbal and nonverbal domains (e.g., verbal-nonverbal item, verbal response). Compared to the other conditions, findings showed that children with DLD performed the most poorly in the condition with demands within the nonverbal domain. They also performed more poorly in the condition with demands within the verbal domain relative to the conditions with demands divided between verbal and nonverbal domains. Children with DLD performed most similarly to TD peers in the conditions with demands distributed across the verbal and nonverbal domains, suggesting a performance benefit when dispersing processing across domains for children with DLD (Gillam et al., 1998).

Nevertheless, Hoffman and Gillam (2004) showed that children with DLD benefitted to a lesser degree than TD peers when processing was divided between domains. In this study, the working memory task involved recall items that were either verbal or nonverbal and an interleaved processing task where participants had to verbally name a color (i.e., a verbal processing task) or point to a matching color (i.e., a nonverbal processing task). Both groups were less accurate in the condition with demands within the nonverbal domain than within the verbal domain. The DLD and TD groups were also less accurate in conditions with demands within one domain relative to conditions with demands divided between verbal and nonverbal domains. TD peers, however, benefitted to a greater degree than children with DLD when processing was divided between domains relative to when processing was limited to one domain (Hoffman & Gillam, 2004).

Both of these studies found that children with DLD were less accurate when processing was limited to the nonverbal domain (e.g., nonverbal item, nonverbal response) relative to

conditions in which processing was limited to the verbal domain (e.g., verbal item, verbal response) or conditions in which processing was dispersed across domains (e.g., verbal-nonverbal item, verbal response; Gillam et al., 1998; Hoffman & Gillam, 2004). Thus, these studies suggest that working memory tasks with demands within the nonverbal domain are particularly challenging for children with DLD even though their primary deficits are in the verbal domain.

Children with DLD are thought to draw on nonverbal abilities to facilitate processing performance (Botting, Psarou, Caplin, & Nevin, 2013; Blom & Boerma, 2019; Larson, Gangopadhyay, Kaushanskaya, & Ellis Weismer, 2019) which may also explain their disproportionate difficulty with processing demands being limited to the nonverbal domain (Gillam et al., 1998; Hoffman & Gillam, 2004). First, interference between representations is greater for representations of the same domain relative to representations from different domains – greater overlap in features (e.g., words and digits) leads to greater confusion of those features relative to lesser overlap in features (e.g., words and shapes; Oberauer et al., 2012). Second, children with DLD may recruit nonverbal skills, such as attentional refreshing, to a greater degree than verbal skills, such as verbal mediation, during performance on tasks that draw on processing (Arslan, Broc, & Mathy, 2020; Botting et al., 2013; Larson et al., 2019). For children with DLD, these patterns likely reflect strengths in nonverbal relative to verbal ability. When processing demands are limited to the nonverbal domain, interference between nonverbal representations may a) reduce their ability to draw on nonverbal strengths, or b) diminish the facilitative effect of drawing on nonverbal skills. Alternatively, when processing demands are in the verbal domain or dispersed across both domains, interference may have less of a detrimental effect on the relationship between drawing on nonverbal skills and processing performance.

Children with DLD appeared to benefit more from dispersing processing across domains in Gilliam et al. (1998) relative to Hoffman and Gillam (2004). This discrepancy may be due to differences in experimental task design. First, Gillam et al. (1998) varied the domain of recall items versus response modality (e.g., visually presented digit, verbal response) whereas Hoffman and Gillam (2004) yoked the domain of recall items and response modality (e.g., visual sequence-pointing response and digit label-verbal response) and varied the domain of an interleaved processing task. Under the current study's theoretical framework, the optimal working memory task structure would involve varying the domain of recall items versus the domain of an interleaved processing task and require serial recall of target items regardless of response modality (Oberauer et al., 2012; Oberauer, Farrell, Jarrold, & Lewandowsky, 2016; see also Alloway, Gathercole, & Pickering, 2006 and Leonard et al., 2007 for additional support and Blom & Boerma, 2019 for conflicting evidence when using a simpler task structure). Thus, Hoffman and Gillam's (2004) working memory task more closely aligned with the task structure that involves presenting recall items, followed by an interference processing task, and then recall test than Gillam et al.'s (1998) working memory task. Additionally, although both studies had conditions where processing was limited to the verbal or nonverbal domain, Hoffman and Gillam (2004) did not include the condition from Gillam et al. (1998) that involved processing demands distributed across both domains (i.e., verbal-nonverbal recall items). Instead, Hoffman and Gillam's (2004) conditions only involved task demands within one domain versus demands divided between both domains. Consequently, neither study examines working memory performance using an optimal working memory task structure in all conditions (i.e., a fully-crossed design) necessary to determine how dispersing processing across domains relates to working memory performance in children with DLD.

Integrative Theoretical Framework

Beyond the relationship between domain (verbal/nonverbal) and working memory performance, it is possible that two other key processing-based factors hypothesized to underlie DLD are also associated with working memory performance. The Generalized Slowing Hypothesis suggests that slowed response time on verbal or nonverbal tasks that draw on processing (e.g., grammaticality judgment, mental rotation) leads to downstream effects on language ability in DLD (Kail, 1994; Miller et al., 2001; Leonard et al., 2014; Tallal et al., 1996). There is evidence of links between processing speed and language ability (Montgomery et al., 2010; Leonard et al., 2007; Leonard et al., 2014; Park, Miller, & Mainela-Arnold, 2015; Park et al., 2020) and between processing speed and working memory (Kail, 1994; Leonard et al., 2007; Miller et al., 2001). Similarly, the Inefficient Inhibition Hypothesis suggests that slower and less accurate inhibition of interference affects processing and leads to downstream effects on language ability in DLD (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). Findings from other work also support these claims as they demonstrate a relationship between inhibition and language in children with DLD (Bishop & Norbury, 2005; Blom & Boerma, 2020; Kapa & Erikson, 2020; Leonard et al., 2013; Mainela-Arnold et al., 2008; Marton, 2008; Marton, Campanelli, Scheuer, & Yoon, 2014; McMurray et al., 2010; Van Dyke & Johns, 2012; see also Vissers, Koolen, Hermans, Scheper, & Knoors, 2015). Performance on inhibition tasks is linked to extant language abilities (Blom & Boerma, 2020; Dispaldro et al., 2013), later language outcomes (Blom & Boerma, 2019; Kapa & Erikson, 2020; Larson, Kaplan, Kaushanskaya, & Ellis Weismer, 2020), and to working memory (Marton et al., 2007). It is necessary, therefore, to examine the role of domain in working memory performance using a theoretical framework that

captures domain effects, as well as interrelationships among working memory, processing speed, and inhibition.

The serial-order-in-a-box – complex span model (SOB-CS) is an interference-based computational model of working memory (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) features depending on activation patterns (see Appendix A Figure B.1 adapted from Oberauer et al., 2012). Thus, this model does not represent working memory as dichotomous verbal or nonverbal (also referred to as visuospatial) working memory constructs, rather it accounts for the degree to which particular stimuli, and, in turn, representations in working memory, have verbal and nonverbal features. 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; Oberauer et al., 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). That is, activation for previous representations diminishes during *free time*, preventing

overlap in activation patterns between previous and current representations. *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 overlapping activation between representations. The SOB-CS model also captures the effects of domain on working memory performance by accounting for the degree to which representations may interfere regardless of *free time*.

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 (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 (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 explain working memory performance in children with DLD through interrelationships among processing speed, domain effects, and inhibition of interference.

The Current Study

The current study aimed to examine the role of domain in working memory performance using a fully- crossed design. I used a working memory task structure that is consistent across

conditions and consistent with the SOB-CS model and other views of working memory (Alloway et al., 2006; Leonard et al., 2007; Oberauer et al., 2012; Oberauer et al., 2016). My theoretical framework of working memory integrates key processing-based factors hypothesized to underlie DLD. This framework is also able to capture 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 affects working memory performance in school-age children with DLD relative to TD peers under a unified theoretical framework. My research questions were as follows:

1. How does working memory performance differ on tasks with demands within verbal or nonverbal domains compared to tasks that divide or distribute demands between verbal and nonverbal domains in school-age children with DLD relative to TD peers?
2. How does working memory performance differ on tasks with demands divided between verbal and nonverbal domains compared to tasks with demands distributed across both verbal and nonverbal domains in school-age children with DLD relative to TD peers?

I predicted poorer working memory performance for children with DLD and their TD peers on tasks with demands within the nonverbal than verbal domain (Gillam et al., 1998; Hoffman & Gillam, 2004). Based on Hoffman and Gillam's findings (2004), I predicted that children with DLD would perform better on tasks with demands divided between domains versus tasks with demands within one domain, but that TD peers would derive greater performance benefit than children with DLD. Based on Gillam et al.'s (1998) findings, I also predicted that children with DLD would perform better on tasks with demands distributed across domains versus tasks with demands divided between domains, and they would derive greater performance benefit than TD peers. These patterns may be attributable to a reliance on nonverbal skills in children with DLD

(Botting et al., 2013; Blom & Boerma, 2019; Larson et al., 2019; see also Arslan et al., 2020) which facilitates performance in the absence of marked interference between nonverbal representations. For instance, performance for children with DLD on working memory tasks may be particularly poor when demands are within the nonverbal domain relative to when demands are in the verbal domain or in both domains due to interference between nonverbal representations (Gillam et al., 1998; Hoffman & Gillam, 2004). See Chapter 2 for Methods.

Results

See Table 3.1 for multiple imputation mixed-effects model results.

Interference Processing Task

Verbal Interference Task

In the verbal-within condition, average 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 average RT was not significantly different between the groups (DLD M = 1210.13, SD = 476.10; TD M = 1027.46, SD = 323.14; $p = .21$), controlling for SES (p's > .25). In the nonverbal-divided condition, average accuracy was not significantly different between the groups (DLD M = 0.78, SD = 0.15; TD M = 0.84, SD = 0.11; $p = .14$) and average 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; $p < .05$; note that descriptive values differ from the statistical test b estimate), controlling for SES (p's > .50).

Nonverbal Interference Task

In the nonverbal-within condition, average accuracy was not significantly different between the DLD and TD groups (DLD M = 0.91, SD = 0.09; TD M = 0.95, SD = 0.10; p = .25) and average RT was not significantly different between the groups (DLD M = 1942.71, SD = 394.95; TD M = 2007.81, SD = 422.10; p = .36), controlling for SES (p's > .25). In the verbal-divided condition, average accuracy was not significantly different between the groups (DLD M = 0.91, SD = 0.10; TD M = 0.94, SD = 0.09; p = .17) and average RT was not significantly different between the groups (DLD M = 1992.16, SD = 450.40; TD M = 2089.71, SD = 445.28; p = .36), controlling for SES (p's > .24).

Distributed Interference Task

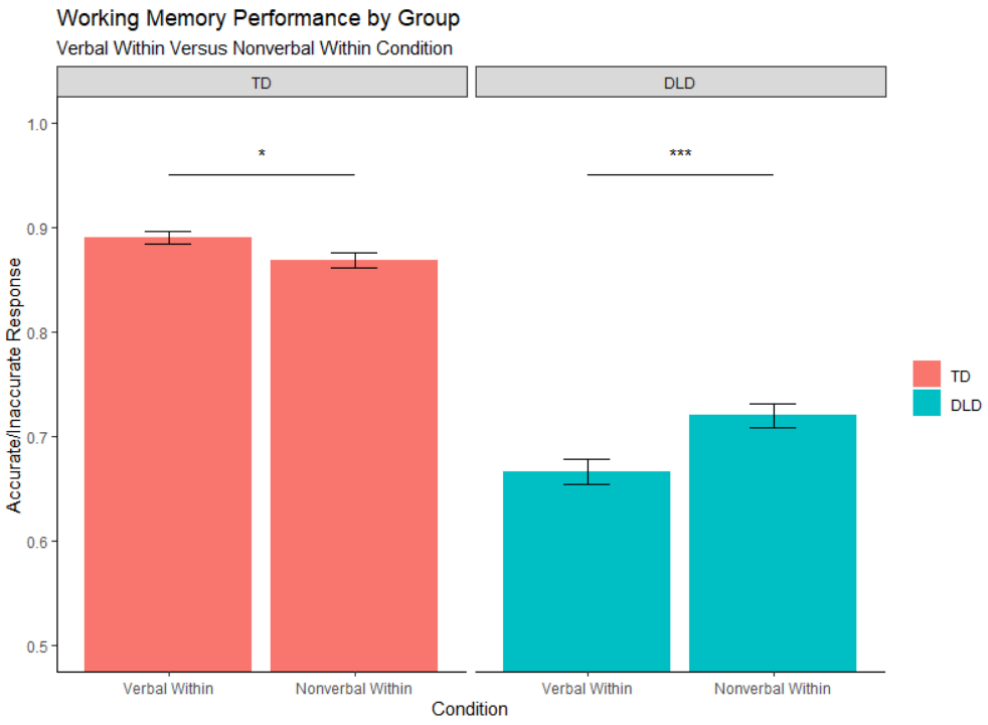
In the distributed condition, average accuracy was significantly poorer for the DLD (M = 0.85, SD = 0.18) group than the TD group (M = 0.94, SD = ; b = 0.08; t-value = 2.12; p < .05) and average RT was not significantly different between the groups (DLD M = 1141.36, SD = 371.6; TD M = 1139.68, SD = 282.71; p = .92), controlling for SES (p's > .71).

Recall Accuracy

Verbal-within vs. Nonverbal-within

There was no significant effect of condition (p = .32). 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 no significant effect of the group by condition interaction, SES, or verbal-within condition interference accuracy (p's > .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). After removing chance-level performance, all results remained the same. See Figure 3.1.



Note. Y-axis range is 0.50-1.0; *p < .05, ***p < .001.

Figure 3.1. Group differences in verbal-within versus nonverbal-within condition accuracy.

Verbal-within vs. Verbal-divided

There was no significant effect of condition (p = .68). 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 significant effect of the group by condition interaction, SES, or verbal-within condition interference accuracy (p's > .30). After removing chance-level performance, all results remained the same.

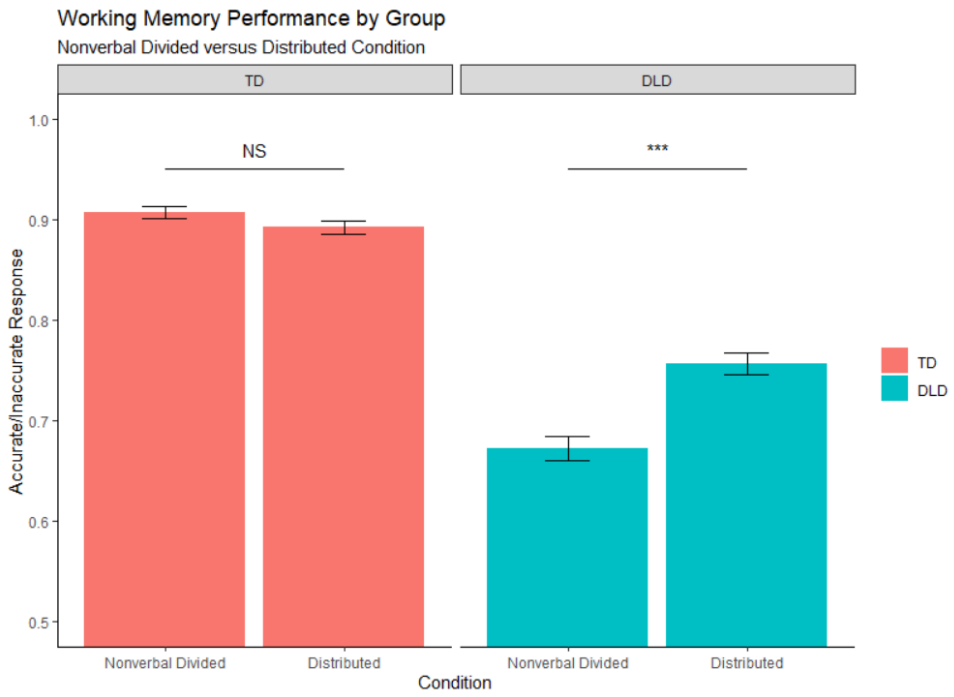
Nonverbal-within vs. Nonverbal-divided

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 worse odds of a correct response by a factor of 3.3 for the DLD group than the TD group. There was no significant group by condition interaction or significant effect of SES (p's > .12). I conducted follow up analyses based on descriptive performance patterns. These analyses 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). After removing chance-level performance, the effect of condition was no longer significant (p = .06).

Verbal-divided vs. Distributed

There was no significant effect of condition (p = .13). 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 significant effect of the group by condition interaction, SES, or distributed-condition interference accuracy (p's > .06). I conducted follow up analyses based on descriptive performance patterns. These analyses showed that there was no significant effect of condition for the DLD group (p = .36) and 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). After removing chance-level performance,

the effect of distributed-condition interference accuracy became significant (b = 1.15; stat = 2.23; p < .05).



Note. Y-axis range is 0.50-1.0; NS = not significant, ***$p < .001$.

Figure 3.2. Group differences in nonverbal-divided versus distributed condition accuracy.

Nonverbal-divided vs. Distributed

There was no significant effect of condition (p = .06). There was a significant effect of group (b = -1.81; stat = -3.23; p < .01), indicating that the DLD group had 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 by condition interaction (b = 0.94; stat = 2.33; p < .05). There was no significant effect of SES (p = .79). 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 there was no significant effect of condition for the TD group (p = .10). After removing chance-level performance, all results remained the same. See Figure 3.2.

Recall Reaction Time

Verbal-within vs. Nonverbal-within

There was no significant effect of condition, group, the group by condition interaction, or SES (p's > .12). After removing chance-level performance, all results remained the same.

Verbal-within vs. 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 significant effect of group, the group by condition interaction, or SES (p's > .09). After removing chance-level performance, all results remained the same.

Nonverbal-within vs. 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 no significant group by condition interaction or significant effect of SES (p's > .44). There was a significant effect of nonverbal interference RT (b = 0.47; stat = 2.27; p < .05). After removing chance-level performance, the effect of group was no longer significant (p = .08).

Verbal-divided vs. 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 significant effect of group, the group by condition interaction, SES, or nonverbal-divided condition interference RT (p's > .08). After removing chance-level performance, all results remained the same.

Nonverbal-divided vs. 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 no significant effect of group, the group by condition interaction, or SES (p's > 05). There was a significant effect of nonverbal-divided condition interference RT (b = 0.49; stat = 2.02; p < .05). After removing chance-level performance, the effect of group became significant (b = 533.94; stat = 2.59; p < .05), indicating that the DLD group had slower RT than the TD group.

Table 3.1. Multiple imputation mixed-effects model results.

Condition	**Predictor**	***b estimate***	**test-statistic**	***p-value***
Verbal-within vs Nonverbal-within				
Accuracy				
	Condition	-0.39	-0.99	*p* = .32
	Group	-1.87	-3.51	*p* < .001***
	SES	0.01	0.12	*p* = .91
	Verbal-within interference accuracy	0.57	0.99	*p* = .33
	Group*Condition	0.64	1.07	*p* = .29
Reaction Time				
	Condition	-28.90	0.30	*p* = .76
	Group	208.06	1.54	*p* = .12
	SES	-10.70	-0.43	*p* = .67
	Group*Condition	7.61	0.05	*p* = .96

Verbal-within vs. Verbal-divided				
Accuracy				
	Condition	0.24	0.80	$p = .42$
	Group	-2.03	-3.77	$p < .001$***
	SES	-0.10	-1.02	$p = .31$
	Verbal-within interference accuracy	0.37	0.65	$p = .52$
	Group*Condition	0.42	0.97	$p = .33$
Reaction Time				
	Condition	-180.54	-2.38	$p < .05$*
	Group	224.96	1.66	$p = .10$
	SES	-1.01	-0.04	$p = .97$
	Group*Condition	-26.94	-0.21	$p = .83$
Nonverbal-within vs. Nonverbal-divided				
Accuracy				
	Condition	0.68	2.02	$p < .05$*
	Group	-1.19	-2.48	$p < .05$*
	SES	0.05	0.49	$p = .62$
	Group*Condition	-0.74	-1.52	$p = .13$
Reaction Time				
	Condition	442.57	4.51	$p < .001$***
	Group	355.45	2.27	$p < .05$*
	SES	24.46	0.77	$p = .44$
	Nonverbal-divided interference RT	0.47	2.27	$p < .05$*
	Group*Condition	5.86	0.04	$p = .97$
Verbal-divided vs. Distributed				
Accuracy				
	Condition	-0.53	-1.50	$p = .13$
	Group	-1.44	-3.05	$p < .01$**
	SES	-0.01	-0.09	$p = .93$
	Distributed interference accuracy	1.39	1.94	$p = .06$
	Group*Condition	0.46	0.86	$p = .39$
Reaction Time				
	Condition	314.81	3.36	$p < .001$***
	Group	212.00	1.72	$p = .09$
	SES	14.29	0.57	$p = .57$

	Group*Condition	215.09	1.40	$p = .16$
Nonverbal-divided vs. Distributed				
Accuracy				
	Condition	-0.54	-1.89	$p = .06$
	Group	-1.81	-3.23	$p < .01$**
	SES	0.03	0.27	$p = .79$
	Distributed interference accuracy	2.26	3.18	$p < .01$**
	Group*Condition	0.94	2.33	$p < .05$*
DLD Group	Condition	0.57	6.22	$p <$ .001***
TD Group	Condition			$p = .10$
Reaction Time				
	Condition	-247.34	-2.27	$p < .05$*
	Group	414.25	1.88	$p = .06$
	SES	22.48	0.60	$p = .55$
	Nonverbal-divided interference RT	0.49	2.02	$p < .05$*
	Group*Condition	87.34	0.51	$p = .61$

Note. Test-statistic = chi-sq for accuracy and t-value for reaction time; Group = Typically Developing vs. Developmental Language Disorder group comparison; Sentence Comprehension = Accuracy on the sentence comprehension task; NS = not significant; Matrix Reasoning = t-score on the Matrix Reasoning subscale from the Wechsler Abbreviated Intelligence Scale, Second Edition (WASI-II); *significant difference at $p < .05$; **significant difference at $p < .01$; *** significant difference at $p < .001$

Discussion

The current 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. This design allowed us to test how representations interfere in working memory under different types of interference (e.g., within versus cross domain). I examined how performance differs when working memory task demands are within the verbal (i.e., word) or nonverbal domain (i.e., shape location), divided between the verbal (i.e., nonword judgment) and nonverbal domain (i.e., face/nonface judgment + shape location), and distributed across both domains (i.e., auditory-word location judgment + word-image location). Findings indicated a greater effect of within

domain interference with nonverbal recall than verbal recall for the DLD group, contrary to my hypothesis of poorer performance for the nonverbal-within domain condition. Conversely, results revealed a greater effect of within domain interference with verbal recall than nonverbal recall for the TD group.

I predicted that working memory performance would be better on tasks with demands divided between domains 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. Although this prediction was borne out with verbal reaction time, nonverbal recall reaction time was slower for both groups in the nonverbal-within than nonverbal-divided condition and these effects did not differ between groups. However, there was modest evidence that recall accuracy was better in the nonverbal-within than nonverbal-divided condition for the DLD group, and better in the nonverbal-divided than nonverbal-within condition for the TD group. I also predicted that working memory performance would be better on tasks with demands distributed across domains 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. 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 relative to the nonverbal-divided condition for the DLD group, but not the TD group, and that both groups had faster reaction time in the distributed condition than nonverbal-divided condition. In contrast, both groups had faster reaction time in the verbal-divided condition relative to the distributed condition. Collectively, findings underscore a role for interference in in working memory performance that differs depending on the domain of task demands, as well as DLD versus TD group status. See Table 3.2 to for a breakdown of hypotheses and whether each hypothesis was confirmed.

Table 3.2. Hypothesis Confirmation.

Hypothesis	Result	Confirmed Acc	Confirmed RT
DLD: Verbal-within > nonverbal-within	*DLD*: Verbal-within > nonverbal-within	-	-
TD: Verbal-within < nonverbal-within	*TD*: Verbal-within < nonverbal-within	+	-
DLD: Verbal-within ~ verbal-divided	*DLD*: Verbal-within ~ verbal-divided	-	+/-
TD: Verbal-within < verbal-divided	*TD*: Verbal-within < verbal-divided	-	-
DLD: Nonverbal-within ~ nonverbal-divided	*DLD*: Nonverbal-within ~ nonverbal-divided	-	-
TD: Nonverbal-within < nonverbal-divided	*TD*: Nonverbal-within < nonverbal-divided	-	-
DLD: Verbal-divided < distributed	*DLD*: Verbal-divided < distributed	-	-
TD: Verbal-divided ~ distributed	*TD*: Verbal-divided ~ distributed	+/-	-
DLD: Nonverbal-divided < distributed	*DLD*: Nonverbal-divided < distributed	+	+
TD: Nonverbal-divided ~ distributed	*TD*: Nonverbal-divided ~ distributed	+/-	+/-

Note. ~ indicates less of a difference between conditions relative to the other group (e.g., the difference between nonverbal-divided and distributed condition performance was hypothesized to be greater for the DLD than TD group); - indicates that the hypothesis was not confirmed; + indicates that the hypothesis was confirmed; +/- indicates that the hypothesis was partially confirmed; Acc = Recall accuracy; RT = Recall reaction time.

The Role of Domain

The only prior study that has examined the role of domain in working memory performance using a fully-crossed design varied response modality (i.e., pointing or speaking) and recall items (e.g., auditorily or visually presented digits; Gillam et al., 1998) whereas the current study varied the domain of an interference task (e.g., nonword judgment) and recall items (e.g., shape location). A later study from the same research group varied the domain of an interference task (i.e., naming versus matching colors) and the domain of recall items (i.e., digits versus "X" location; Hoffman & Gillam, 2004), but only examined within-domain (e.g., naming colors + digit recall) versus divided-domain (e.g., naming colors + "X" location recall) conditions. The current findings broadly align with these prior studies with key differences related to verbal versus nonverbal interference.

Consistent with these prior studies, children with DLD and TD peers had faster reaction time 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. Yet for nonverbal recall (i.e., shape location) in the current study, both groups had faster reaction time when processing was limited to the nonverbal domain than when processing was divided between verbal interference and nonverbal recall. There was also a modest indication of 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 when interference and recall are divided between domains regardless of recall domain (Gillam et al., 1998; Hoffman & Gillam, 2004). One obvious explanation for this discrepancy is methodological differences, such as Gillam et al. (1998) varying response modality rather than interference task domain, and lack of reaction time measures in prior work. Another explanation for this discrepancy is that my verbal interference (i.e., nonword judgment) task may have been more difficult than my nonverbal interference (i.e., face/nonface judgment) task, particularly for my 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. However, performance on interference tasks was not reported in this study, an approach that is in conflict with other related work (Ellis Wesmer et al., 1999; Gaulin & Campbell, 1994; Mainela-Arnold & Evans, 2005; Montgomery & Evans, 2009; see also Siffredi et al., 2017 for a similar approach in TD children, but see Archibald & Gathercole, 2006 and Montgomery et al., 2009). The explanation that my

verbal interference task was more challenging than my nonverbal interference task is consistent with my finding that when processing was distributed across both domains (i.e., auditory-word location judgment + word-image location) both groups had faster reaction time and only the DLD group had better accuracy than when processing was divided between verbal interference and nonverbal recall. Interestingly, this finding is also consistent with Gillam et al.'s (1998) finding of better performance in a distributed domain than divided domain condition, particularly for their DLD group.

If verbal interference drove results across conditions in my study, I would expect that the verbal-within condition would be substantially more difficult than the verbal-divided condition. I would also hypothesize a group difference in this effect given the DLD group's difficulty with the verbal interference task, and nonwords more generally, relative to TD peers (Deevy, Wisman Weil, Leonard, & Goffman, 2010; Dollaghan & Campbell, 1998; Tager-Flusberg & Cooper, 1999). My findings showed that reaction time 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, I may expect this effect to also be present for reaction time, but it was only evident for accuracy. Moreover, I controlled for group differences in interference task performance (e.g., in the verbal-within condition) in order to remove this potential confound from my analysis of condition effects. This approach is broadly consistent with prior work that allows interference task performance to vary when groups do not differ (Ellis Wesmer et al., 1999; Gaulin & Campbell, 1994; Mainela-Arnold & Evans, 2005; Montgomery & Evans, 2009). Nevertheless, I 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).

Turning to nonverbal interference, my nonverbal interference task (i.e., face/nonface judgment) appears to have been easier than Hoffman and Gillam's (2004) nonverbal interference task (i.e., pointing to matching colors). If so, my study may have involved diminished nonverbal interference relative to this prior study. My DLD group did not differ from the TD group in nonverbal interference task accuracy or reaction time and had poorer recall performance across conditions for *verbal* than nonverbal interference. In contrast, Hoffman and Gillam's (2004) DLD group had poorer recall performance across conditions for *nonverbal* than verbal interference. This difference may further explain why I did not find that children with DLD had disproportionate difficulty with nonverbal recall when paired with nonverbal interference as was found previously (Gillam et al., 1998; Hoffman & Gillam, 2004; but see Botting et al., 2013). Children with DLD may have been more able to draw on nonverbal strategies (e.g., attentional refreshing) to engage my tasks than in Hoffman and Gillam (2004) due to my nonverbal interference task being relatively easy (Botting et al., 2013; Blom & Boerma, 2019; Larson, et al., 2019). In contrast, verbal interference appears to have caused greater interference than nonverbal interference for nonverbal recall, which may suggest that verbal interference elicited verbal strategies that are difficult to disengage once activated and not particularly facilitative for children with DLD (Larson et al., 2019; Marton, 2008; see Marcovitch & Zelazo, 2009 for an association between secondary task performance and perseverative behavior). The within domain interference effect on verbal recall, but not nonverbal recall, for the DLD group may also reflect their general weakness in verbal abilities. This interpretation aligns with prior work showing poorer verbal than nonverbal working memory skills in DLD (Vugs et al., 2013) and that verbal

working memory performance is linked to language ability (Archibald & Gathercole, 2006; Ellis Weismer et al., 1999; Gaulin & Campbell, 1994; Vugs et al., 2017).

Taken together, the role of interference differed depending on the domain of interference and recall. Children with DLD presented with different patterns than TD peers in these relationships. For the DLD group, there as not a clear benefit in dividing processing between verbal and nonverbal domains or distributing processing across verbal and nonverbal domains. 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. These group differences underscore the importance of inhibiting verbal interference during verbal and nonverbal processing for the DLD group. Alternatively, the effect of nonverbal interference appears to be less important, and there appear to be fewer group differences in the role of interference domain for processing speed than accuracy.

Theoretical and Clinical Implications

The three primary processing-based hypotheses of DLD separately suggest that deficit patterns observed in DLD are related to limitations in verbal working memory (Archibald & Gathercole, 2006, 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). The serial-order-in-a-box – complex span (SOB-CS) computational model (Oberauer et al., 2012) 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 explain working memory performance.

My findings have shown that children with DLD perform 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, 2006; Ellis Weismer et al., 1999; Vugs et al., 2017), as well as other work suggesting that these limitations extend to working memory with nonverbal information (Dispaldro et al., 2013; Marton, 2008; Smolak et al., 2020; Vugs et al., 2013). Given that nonverbal working memory performance was also poorer in my DLD than TD group, it is unlikely that a verbal working memory account of DLD provides a comprehensive explanation of the deficits observed in DLD (see also Archibald & Joanisse, 2009).

I also found that working memory deficits were present for reaction time (i.e., a measure of processing speed) with nonverbal item and verbal-nonverbal item (i.e., word-image location) recall for the DLD group, but not with verbal item recall. These patterns were present in the absence of significant group differences in baseline reaction time. Other prior work shows deficits in reaction time for nonverbal tasks that draw on processing (Kail, 1994; Miller et al., 2001) and some work casts doubts on processing speed as a sufficient explanation of DLD (Ebert & Kohnert, 2011; Ellis Weismer et al., 2005; Finneran, Francis, & Leonard, 2009; Marinis & Van Der Lely, 2007; Schul, Wulfeck, & Townsend, 2004). My findings allow for the possibility of a role for processing speed, but align more closely with the latter view that a processing speed account of DLD is insufficient.

It is clear that my DLD group had greater difficulty inhibiting interference from the verbal (i.e., nonword judgment) than nonverbal (i.e., face/nonface judgment) domain, even after controlling for group differences in performance on interference tasks. While the TD group broadly demonstrated the anticipated interference effects – within domain interference had a larger effect on recall than cross domain interference (Gillam et al., 1998; Hoffman & Gillam, 2004; Oberauer et al., 2012; Siffredi et al., 2017) – the DLD group demonstrated a larger effect of verbal interference than nonverbal interference regardless of recall item domain. Moreover, the effect of nonverbal interference on nonverbal recall appeared to be minimal. This finding is consistent with work showing substantial difficulty inhibiting verbal interference in DLD (Hoffman & Gillam, 2004; Leonard et al., 2013; Marton et al., 2018), but is potentially inconsistent with work showing difficulty inhibiting nonverbal interference in DLD (Gillam et al., 1998; Hoffman & Gillam, 2004; Dispaldro et al., 2013).

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). Whether a given unit represents verbal versus nonverbal features depends on activation patterns (e.g., proximal versus dispersed co-activated units), and whether there is overlapping activation between recall items, giving rise to interference, depends on the amount of *free time* available. Additionally, relative strengths within a given domain (e.g., verbal) are associated with heightened distinctiveness in feature representation (e.g., the sound pattern of a word) which would, in turn, be associated with a diminished likelihood of interference between similar items within that domain (e.g., words that rhyme).

Based on prior work showing differences in how verbal versus nonverbal strategies are used to engage in performance (Botting et al., 2013; Blom & Boerma, 2019; Larson et al., 2019), children with DLD appear to have different activation patterns than TD peers during the same processing task (Ellis Weismer et al., 2005; Herbert et al., 2005; Njiokiktjien et al., 2001). These differences in activation patterns are likely a function of their weakness in language. Children with DLD may recruit nonverbal abilities with greater activation strength or with more widespread activation on language tasks in particular (e.g., Ellis Weismer et al., 2005) and on processing tasks in general (e.g., Botting et al., 2013) to compensate for their language deficits.

Given that children with DLD often have slower processing speed than TD peers on 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. Reduced *free time* is associated with greater overlapping activation patterns between items – greater interference. The interplay of heightened nonverbal unit activation, relative weakness in representing verbal item features, and increased overlap in activation patterns (i.e., due to diminished *free time*) could yield working memory performance patterns similar to those observed in my DLD group.

Specifically, there was a lesser effect of within domain interference for nonverbal than verbal recall for my DLD group, but not for the TD group, suggesting greater distinctiveness or diminished overlapping activation (i.e., 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-task to a greater degree than at each phase of the divided-domain condition. Nevertheless, the only group difference in reaction time was found across nonverbal- within and divided domain conditions, so there is little evidence in the current 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.

Summary

Children with DLD had verbal and nonverbal working memory deficits relative to TD peers in accuracy, but only in reaction time with nonverbal recall. Additionally, children with DLD had worse performance with verbal than nonverbal interference regardless of recall domain. Collectively, this study demonstrated a role for each of the three primary processing-based hypotheses of DLD, thereby implicating aspects of each hypothesis in processing performance in DLD. Yet, none of these hypotheses are fully consistent with the current findings. According to the SOB-CS framework, children with DLD are likely to have worse performance on working memory tasks with verbal items and on working memory tasks with greater levels of interference. These patterns were borne out in my findings. Patterns of performance may be further elucidated under this framework by examining *free time*, a time-based active-removal mechanism that diminishes interference between similar items (Oberauer et al., 2012). This time-based mechanism may be particularly relevant to children with DLD given their difficulty with processing speed (Kail, 1994; Miller et al., 2001), efficient inhibition (Bjorklund & Harnishfeger, 1990; Marton et al., 2007), and verbal information, which is particularly dependent on millisecond timescales (Archibald & Gathercole, 2006, 2007; Ellis Weismer, et al., 1999; Hsu & Bishop, 2011; Gillam, Cowan, & Day, 1995; Montgomery et al., 2010; Tallal et al., 1996; Van Dyke & Johns, 2012). Thus, the next step in understanding processing in DLD is to examine the role of *free time* in working memory performance.

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. Children with DLD appear to struggle with maintaining and manipulating successive presentations of verbal information in working memory, likely hindering their language processing. Of course, verbal information is inherently dependent on timescales, so it may be beneficial to supplement verbal information with nonverbal information. This implication is supported by evidence of better performance relative to the verbal-within condition for my DLD group when: a) there was verbal and nonverbal information present at each phase of the working memory task, and b) when nonverbal information was interleaved between phases of verbal information. Likewise, children with DLD appear to manage nonverbal interference better than verbal interference. Thus, it may be beneficial to present nonverbal information at high rates and quantities to support language processing in the classroom and in therapy sessions. For instance, when targeting tense morphology, pieces of paper with the verb (e.g., walk) and the potential morphological markers (e.g., -*ed*, -*ing*) coupled with visual depictions (e.g., a person walking on a sidewalk and the same person 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 based on the image) are used together with verbal information to target a morphological tense marker.

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; Lidstone et al., 2012) and other work with children (e.g., Gangopadhyay, McDonald, Ellis Weismer, & Kaushanskaya, 2018; Larson, Gangopadhyay, Prescott, Kaushanskaya, & Ellis Weismer, 2020; 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 possible that similarities or differences between conditions are affected by this inequality or that relationships between conditions differ between groups due to this difficulty difference. However, I statistically controlled for group differences in interference task performance and my findings do not align with the conclusion that verbal interference difficulty drove results (e.g., performance in the verbal-within versus verbal-divided condition). Additionally, my approach to interference task performance is broadly consistent with prior work (Ellis Wesmer et al., 1999; Gaulin & Campbell, 1994; Mainela-Arnold & Evans, 2005; Montgomery & Evans, 2009). Future work would benefit from developing interference tasks that vary the domain of interference while equating difficulty to a greater degree.

It is also important to note that my remote-based procedures may explain some differences between the current findings and prior research. For instance, methodological differences, such as a button box versus mouse press response, environmental differences, such as a relatively distraction-free lab versus home environment, or other factors, such as the in-person versus remote-based feedback, could explain some of the variance in my findings. Within the context of the current work, however, I was able to account for many of these variables. Specifically, I provided the same laptop system to each participant, my experimental tasks did not require internet use (i.e., reaction time measurement, in particular, can be challenging when using web-based tasks), and I compared groups on level of background noise (i.e., a coarse

measure of background distractions). Nonetheless, future work should examine potential differences between lab-based and remote-based administration of working memory tasks in children with DLD.

Another limitation of the current study is my examination of domain as a category rather than continuum of features. One advantage of the SOB-CS model relative to other models of working memory (e.g., Baddeley & Hitch 1994) is that stimulus features are represented via a continuum where a processing unit may represent verbal or nonverbal features depending on activation patterns (Oberauer et al., 2012; see Appendix A Figure A.1). The current study builds on prior work examining the role of domain in the processing performance of children with DLD (e.g., Gillam et al., 1998; Hoffman & Gillam, 2004) by using a fully crossed design (i.e., similar to the Brown-Peterson paradigm; see Siffredi et al., 2017 for an example) and a more well-validated working memory task structure (Alloway et al., 2006; Leonard et al., 2007; Oberauer et al., 2012; Oberauer et al., 2016). The current study did not, however, take the additional step of obtaining adult ratings of stimuli, for instance, and determining the degree to which a given item has verbal and nonverbal features. This approach would add further nuance to the role of domain and interference in working memory performance.

There are a couple of limitations related to my participant sample: sample size and sample characteristics relative to prior work on similar populations. First, my power analysis indicated that I had an adequate sample size to detect a medium effect. Moreover, I had even greater power to analyze within-group patterns, giving us a reasonable level of confidence in the current findings. However, there are important limitations to my statistical approach. Specifically, a frequentist approach does not account for uncertainty in statistical models and does not clarify the degree to which my data support a given finding. Rather, I can only make

claims as to the presence or absence of a relationship with relative confidence. A solution to these statistical issues for future work would be to use a Bayesian approach to statistical analysis – this approach quantifies uncertainty and provides information about both the presence and absence of relationships. Additionally, prior work has focused on a more narrowly defined population, children with Specific Language Impairment, relative to my DLD group which may limit my ability to predict effect sizes accurately. My choice to examine a DLD group was motivated in part by a movement in the field to conduct research on children who are representative of clinical populations (Bishop et al., 2017; McGregor, Goffman, van Horne, Hogan, & Finestack, 2020; Volkers, 2018). There is work suggesting similar patterns in language development regardless of the nonverbal ability criterion (Norbury et al., 2017), but additional work must be done to clarify the role of nonverbal ability criteria in phenomena related to language impairments in children (e.g., Smolak et al., 2020).

Conclusions

The current study examined the role of domain in working memory performance using a design that varied the domain of interference and recall. My theoretical framework was the SOB-CS model, which posits a time-based active removal mechanism, *free time*, that governs how interference affects working memory performance. My aim in using the SOB-CS was to merge three key processing-based hypotheses of DLD under one integrated framework: limited verbal working memory (Archibald & Gathercole, 2006, 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). I found that children with DLD demonstrated deficits in verbal and nonverbal working memory accuracy and deficits in nonverbal working memory reaction time (i.e., a measure of processing speed) relative to age-matched TD peers. I also found

that children with DLD had poorer working memory performance regardless of the domain of recall when presented with a verbal interference processing task prior to recall. Taken together, findings support a role for each processing-based hypothesis, but incomplete roles. The SOB-CS model can account for overall findings from the current study, although further examination of the key mechanism, *free time*, is needed to clarify the relationship between processing speed and inhibition of interference, particularly for verbal items.

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Chapter 4: The Impact of *Free Time* on Working Memory Performance

A recent epidemiologic investigation by Norbury et al. (2016) found a prevalence at school entry of approximately 7% for language impairment of unknown origin, also referred to as Developmental Language Disorder (DLD; Bishop, Snowling, Thompson, Greenhalgh, & CATALISE Consortium, 2017). This disorder is characterized by significant deficits in verbal processing as compared to typically developing (TD) peers that are not attributable to a biomedical condition (e.g., Autism Spectrum Disorder; Bishop et al., 2017; Leonard, 2014; Norbury et al., 2016). There are long-term negative effects of this disorder on academic, vocational, social-emotional, and health-related outcomes (Conti-Ramsden & Durkin, 2012; Johnson, Beitchman, & Brownlie, 2010; Le et al., 2020; Whitehouse, Watt, Line, & Bishop, 2009). Beyond deficits in verbal processing, children with DLD have difficulty processing nonverbal information, such as on working memory tasks (Gillam, Cowan, & Marler,1998; Hoffman & Gillam, 2004; Vugs, Cuperus, Hendriks, Verhoeven, & 2013; Vugs, Hendriks, Cuperus, Knoors, & Verhoeven, 2017; but see Blom & Boerma, 2020). Findings of weakness in verbal and nonverbal processing have led researchers to hypothesize that processing-based factors may underlie the language deficits seen in DLD.

Three primary processing-based factors hypothesized to underlie DLD include: a) deficits in verbal working memory (Archibald & Gathercole, 2006, 2007; Ellis Weismer, Evans, & Hesketh, 1999); b) slowed processing speed of verbal and nonverbal information (Kail, 1994; Miller, Kail, Leonard, & Tomblin, 2001); c) slow and inaccurate inhibition of interference (Bjorklund & Harnishfeger, 1990; Marton, Kelmenson, & Pinkhasova, 2007). Each of these hypotheses focuses on a single factor, yet it is possible to integrate these factors under a single framework. The serial-order-in-a-box – complex span (SOB-CS) computational model

(Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012) may be the ideal integrative framework. This model suggests that processing performance is limited by interference and a time-based mechanism governs the degree to which interference affects processing performance, *free time*. Thus, this model captures the three primary processing-based factors as it accounts for working memory performance based on the relationship between processing speed and interference effects. In Chapter 3, I showed important roles of verbal information, processing speed, and inhibition of interference in working memory performance, although these roles were incomplete when considered separately. Children with DLD performed more poorly on tasks with relatively greater interference, particularly with verbal interference, than TD peers. This finding is consistent with the role of interference under the SOB-CS. It is possible that these performance patterns are additionally explained by the relationship between *free time* and performance, but there was little evidence based on my Chapter 3 study that there were substantial group differences in reaction time on tasks with verbal task demands (e.g., verbal interference). However, it is not clear the degree to which reaction time is a valid proxy measure of *free time*, and no prior studies on children with DLD have directly tested the role of *free time* in working memory performance under the SOB-CS model (Oberauer et al., 2012).

Theoretical Framework

The SOB-CS model is an interference-based computational model of working memory which has been shown to capture key behavioral phenomena to a greater degree than decay-based (e.g., Baddeley & Hitch, 1974; Barrouillet, Portrat, & Camos, 2011) and resource-based (e.g., Cowan, 2014; Kane & Engle, 2002) working memory models (Oberauer, Farrell, Jarrold, & Lewandowsky, 2016). This model is a two-layer neural network with distinct layers for items and serial positions. Items and position markers are represented via distributed activation

patterns and bound in a single weight matrix. Interference between these bound representations may emerge due to similarity between item features (e.g., “animal” category) or proximal serial positions (e.g., early position in a list). The SOB-CS model posits a time-based active restoration mechanism whereby working memory is restored to a baseline state and interference between representations is reduced during *free time* between processing demands. Thus, the SOB-CS model has the potential to capture processing-based hypotheses of DLD as it accounts for working memory performance through the effect of *free time*, which reflects processing speed, on the degree of interference between representations.

Free time is an active-removal mechanism that restores working memory to a baseline state during unfilled pauses. Removal of nontarget information is critical to working memory since: a) accumulating information would quickly overwhelm the system (e.g., proactive interference) and b) items are maintained by default per the SOB-CS model (Oberauer et al., 2012). Because time is required to encode items into working memory (~500ms asymptote) and to remove items from working memory (~1000-2000ms asymptote), *free time* between stimulus presentations is necessary for these processes to fully transpire (i.e., both processes are graded; Oberauer et al., 2012). During *free time*, items are unbound from their context positions and either transferred to long-term memory or forgotten (see Oberauer et al., 2012 regarding Hebbian antilearning operations underlying this mechanism). That is, activation for prior representations diminishes and overlapping activation with subsequent representations is minimized. In the absence of *free time*, a representation may remain active in working memory as another representation enters working memory. Current items and serial position markers would then occupy the same processing units as previous items and serial position markers, resulting in

overlapping activation patterns. Overlap in activation patterns gives rise to interference by confusion or distortion, thus limiting working memory performance.

Free time may arise as a function of experimental design (e.g., unfilled intervals) or processing speed (e.g., rapid encoding). Although other cognitive operations (e.g., verbal rehearsal of item labels) may occur during time between stimulus presentations, the assumption is that working memory has been restored to a baseline state (e.g., nontarget item removed from working memory) if prior internal representations (e.g., target item labels) become re-activated and these internal representations do not cause interference. Alternatively, if a nontarget item has been only partially removed from working memory and a prior internal representation is re-activated, these representations will interfere. The SOB-CS model does not make differential claims regarding interference between novel input and re-activated representations of prior input. The SOB-CS model also does not make claims against the existence of rehearsal processes, rather this model is able to capture complex-span phenomena without rehearsal; *free time* fills the role that rehearsal plays in decay-based and resource-based complex-span frameworks (Oberauer et al., 2012). In brief, rehearsal is necessary to maintain activation for target items in the presence of decay in decay-based models (e.g., Baddeley & Hitch, 1974; Barrouillet et al., 2011), and rehearsal is necessary to strengthen target items in the presence of limited available resources in resource-based models (e.g., Cowan, 2014; Kane & Engle, 2002). However, *free time* is necessary to reduce the effects of interference between items in the SOB-CS interference-based model. It should also be noted that *free time* reflects a more bottom-up approach to working memory processes whereas rehearsal reflects a more top-down approach. Consequently, *free time* is likely to be more robust to individual differences while rehearsal is likely to be subject to individual differences, such as in age (e.g., developmental differences in verbal

rehearsal; Alderson-Day & Fernyhough, 2015; Fatzer & Roebers, 2012) and relative verbal and nonverbal abilities (e.g., children with DLD may use nonverbal rather than verbal strategies during performance; Botting, Psarou, Caplin, & Nevin, 2013; Blom & Boerma, 2019; Larson, Gangopadhyay, Kaushanskaya, & Ellis Weismer, 2019).

For example, the Competing Language Processing task (Gaulin & Campbell, 1994) involves sequential presentation of a set of sentences. After each sentence, the participant is asked to decide whether the sentence was true or false. After each set of sentences, the participant is asked to recall the final word of each sentence in the correct sequence. There are no unfilled intervals during this task, therefore, no *free time* inherent to the task by which working memory may be restored to a baseline state. Interference may arise due to overlap in features of the words (e.g., words may share phonemic characteristics) or due to serial position proximity (e.g., words occurring at the beginning of the set; Oberauer et al., 2012). Specifically, overlapping activation patterns of the first word (e.g., "book") with the second word (e.g., "bear") in a set may result in confusion between these two words, such as by only recalling the first phoneme (i.e., "b-") or by recalling the second word (i.e., "bear") in place of the first word (i.e., "book") during serial recall. If the experimental design of the Competing Language Processing Task were altered to include filled pauses between sentence presentations, such as repeating instructions or nontarget verbal information (e.g., an unrelated word), interference effects would be more likely than the current task design which includes brief unfilled pauses between sentence presentations. This interference would be the result of overlapping activation.

Likewise, it is possible that children who process information more slowly, such as children with DLD, would have less *free time* available, even with unfilled pauses, relative to children who process information more quickly. They may have less *free time* due to slowed

cognitive operations, such as encoding or removing items from working memory, or due to longer pauses between cognitive operations (Oberauer et al., 2012). This latter possibility would result in similar *free time* regardless of pause intervals if the input is matched to pause intervals (e.g., a speech stream controlled by the listener), but less *free time* if the input continues to require encoding during the pause intervals (e.g., an ongoing speech stream). Regardless, pauses that are unfilled for fast processors may be filled with residual (e.g., nontarget) activation for slow processors. Residual activation may lead to overlap in activation patterns that gives rise to interference due to feature (e.g., words that share phonemic representations) or context position similarity (e.g., items at the end of a list). Indeed, the distinctiveness of representations would be reduced when the activation of separate representations is superimposed.

Language, being particularly dependent on milisecond timescales (Hsu & Bishop, 2011; Gillam, Cowan, & Day, 1995; Montgomery, Magimairaj, & Finney, 2010; Tallal et al., 1996; Van Dyke & Johns, 2012), may represent a highly challenging processing task for children with slower processing speed. As verbal information incrementally enters working memory and aspects of prior verbal representations remain active, interference will compound and lead to diminished distinctiveness of verbal representations. Thus, verbal representations will be confused or distorted relative to the veridical input. This confusion or distortion could surface as weakness in a variety of language skills, such as producing word-final bound morphemes (e.g., "walk-*ed*") or understanding passive sentences (e.g., "The girl was waved at by the boy"; Blom & Boerma, 2019; Durrleman & Delage, 2016; Leonard et al., 2007; Miller et al., 2001; Montgomery et al., 2010). For instance, comprehending this passive sentence requires maintenance of words and syntactic frames for subject, verb, and actor, as well as the preposition, in the correct order. If any one of these components is confused or distorted, such as

the “was” and “waved” being superimposed, the meaning of the sentence will be incomprehensible or incorrect (e.g., due to syntactic error), such as the meaning becoming “The girl wa-aved at (by) the boy.” These effects may be more pronounced for individuals with poor language knowledge, such as children with DLD, as their representations for linguistic information are likely less distinctive than individuals with superior language knowledge prior to the effects of interference on verbal processing. The SOB-CS model may be able to explain how these kinds of verbal processing difficulties arise based on interference and *free time* during processing being fundamental to working memory. Thus, this model may be the ideal framework by which processing-based factors in DLD are integrated.

Processing in DLD

Children with DLD present with deficits on verbal (Archibald & Gathercole, 2006, 2007; Ellis Weismer et al., 1999; Gillam et al., 1998; Hoffman & Gillam, 2004; Leonard et al., 2007; Leonard et al., 2014; Mainela-Arnold, Evans, & Alibali, 2006; Montgomery & Evans, 2009; Tallal et al., 1996) and nonverbal processing tasks (Dispaldro et al., 2013; Marton, 2008; Vugs et al., 2013; Vugs et al., 2017; Tallal et al., 1996; Smolak, McGregor, Arbisi-Kelm, & Eden, 2020; Windsor, Kohnert, Loxtercamp, & Kan, 2008; but see Blom & Boerma, 2020). These deficits are hypothesized to be related to underlying difficulty with three separate processing factors – working memory (Archibald & Gathercole, 2006, 2007; Ellis Weismer et al., 1999), processing speed (Kail, 1994; Miller et al., 2001), and inhibition (Blom & Boerma, 2020; Dispaldro et al., 2013; Kapa & Erikson, 2020; Larson, Kaplan, Kaushanskaya, & Ellis Weismer, 2020; Marton et al., 2007) – which give rise to downstream difficulty with language. However, there is substantive evidence suggesting that these underlying factors may be interrelated.

Children with DLD respond more slowly on verbal and nonverbal processing tasks than TD peers, and this slowed processing speed may lead to difficulty with language processing per the generalized slowing hypothesis (Kail, 1994; Miller et al., 2001). There is evidence of processing speed performance discriminating school-age children with and without DLD (Park, Miller, & Mainela-Arnold, 2015), as well as evidence of improvements on language assessments for children with DLD after receiving an intervention targeting temporal processing (Tallal et al., 1996). However, processing speed does not independently account for all patterns of deficits seen in DLD (Ellis Weismer, Plante, Jones, & Tomblin, 2005; Finneran, Francis, & Leonard, 2009; Im-Bolter, Johnson, & Pasual-Leone, 2006; Schul, Wulfeck, & Townsend, 2004; see limited evidence of group differences in reaction time on working memory tasks in Chapter 3), rather the relationship between processing speed and language may be better understood by also considering the role of working memory.

Working memory difficulty has been hypothesized to underlie language deficits in DLD based on evidence of deficits relative to TD peers on verbal (Archibald & Gathercole, 2006, 2007; Ellis Weismer et al., 1999; Kapa & Erikson, 2020; Leonard et al., 2007; Leonard et al., 2014; Montgomery et al., 2010; see also Alloway, Rajendran, & Archibald, 2009 for discussion of language deficits giving rise to working memory difficulty) and nonverbal tasks (Marton, 2008; Smolak et al., 2020; Vugs et al., 2013; Tallal et al., 1996; Vugs et al., 2017). For instance, children with DLD perform more poorly than TD peers on Competing Language Processing (Ellis Weismer et al., 1999; Gaulin & Campbell, 1994; Thordardottir, 2008) and mental rotation tasks (Vugs et al., 2013; Windsor et al., 2008). Leonard et al. (2007) examined the structure of working memory in children with DLD via confirmatory factor analysis and found separable, yet related factors for general speed, verbal and nonverbal speed, and verbal and nonverbal working

memory. The overall working memory model accounted for substantial variance in composite language scores, and composite language was uniquely associated with verbal working memory and general speed (i.e., processing speed; Leonard et al., 2007).

It is notable, however, that some of the tasks in this study aligned with the SOB-CS model working memory task structure (e.g., Competing Language Processing, mental rotation), whereas others did not (e.g., Nonword Repetition, odd-one-out) due to the lack of serial recall or an interleaved processing task (Oberauer et al., 2016). Thus, it is possible that at least some of the latter tasks captured simple storage rather than working memory (Alloway, Gathercole, & Pickering, 2006; Blum & Boerma, 2020; Kapa & Erikson, 2020; Smolak et al., 2020; Vugs et al., 2013). Relationships between simple storage and verbal or nonverbal abilities often reflect the verbal or nonverbal properties of stimuli used in the task, yet relationships between working memory and verbal or nonverbal abilities are more likely to be present regardless of the domain of stimuli. In fact, the odd-one-out task was the only measure purported to capture nonverbal working memory used in Leonard et al. (2007) whereas there were three measures purported to capture verbal working memory. It is possible that had this study included more and more optimal nonverbal working memory tasks, they would have found unique associations between language and nonverbal working memory, as a meta-analysis on nonverbal working memory has shown (Vugs et al., 2013). Additionally, for a working memory task involving nonverbal recall, I showed a greater effect of verbal than nonverbal interference in children with DLD and TD peers (see Chapter 3).

Beyond interrelationships among working memory, processing speed, and language, inhibition appears to be an important additional factor. The inefficient inhibition hypothesis posits that slow and inaccurate inhibition of interference leads to less effective encoding of

information into working memory, particularly for language (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). In Chapter 3, for instance, I showed poorer performance when verbal recall was paired with verbal interference than when nonverbal recall was paired with nonverbal interference for the DLD group, but not the TD group. Children with DLD have deficits in inhibition regardless of the domain of task demands (Bishop & Norbury, 2005; Blom & Boerma, 2020; Dispaldro et al., 2013; Marton, 2008; Marton et al., 2007; Pauls & Archibald, 2016; Spaulding, 2010; Van Dyke & Johns, 2012; see also Vissers, Koolen, Hermans, Scheper, & Knoors, 2015), and these deficits are related to language ability (Bishop & Norbury, 2005; Blom & Boerma, 2020; Kapa & Erikson, 2020; Leonard, Deevy, Fey, & Bredin-Oja, 2013; Marton et al., 2007; Marton, Campanelli, Eichorn, Scheuer, & Yoon, 2014; see also Marton, Eichorn, Campanelli, & Zakarias, 2016 for a review). In fact, there is evidence of concurrent differences in the relationship between language and inhibition in children with DLD relative to TD peers (Dispaldro et al., 2013), as well as differences over time (Larson, Kaplan, et al., 2020; see also Blom & Boerma, 2019 for evidence of group differences over time in the relationship between language and a composite executive function index which included inhibition and working memory performance).

Accurate inhibition of interference may share an important relationship with processing speed and working memory (Bjorklund & Harnishfeger, 1990; Leonard et al., 2013; Mainela-Arnold, Evans, & Coady, 2008; Marton et al., 2007; Marton et al., 2014; Marton & Schwartz, 2003; Van Dyke & Johns, 2012). In order to prevent irrelevant items from entering working memory, rapid filtering of irrelevant information must occur, yet children with DLD struggle with this process. They produce more errors related to recently presented items compared to TD peers and compared to errors related to more distally presented items (Marton et al., 2007) and

they show a slower rate of overcoming interference effects than TD peers on tasks that draw on working memory (Marton et al., 2014). Likewise, Dispaldro et al. (2013) revealed that children with DLD had greater difficulty than TD peers inhibiting items presented with shorter versus longer intervals on a nonverbal processing task (i.e., visual attentional engagement). Mainela-Arnold et al. (2008) found that children with DLD take longer to suppress competitors in word recognition tasks relative to TD peers (see McMurray, Samelson, & Tomblin, 2010 for similar evidence in children with low-average language ability). Taken together, these patterns reflect sluggish inhibition in children with DLD which, in turn, affects how they perform on processing tasks (Dispaldro et al., 2013; Marton et al., 2014).

However, prior work that examines processing speed, working memory, and inhibition do not directly test interrelationships among these factors, nor how potential interrelationships predict individual differences in language. For instance, Kapa and Erikson (2020) found significant correlations between verbal working memory capacity and verbal inhibition accuracy in preschoolers without DLD, but not in preschoolers with DLD. They did not examine group differences in the relationships among working memory, inhibition, and language, nor did they measure processing speed. Correspondingly, Smolak et al. (2020) found correlations among nonverbal sustained attention accuracy (i.e., may also draw on inhibitory control), nonverbal working memory accuracy, and narrative language in a DLD group, but not in TD peers. They did not examine group differences in these relationships, nor reaction time on the attention or working memory tasks. Thus, processing-based factors in DLD have not yet been integrated under a unified theoretical framework and interrelationships remain underspecified. Moreover, prior studies examine accuracy and reaction time separately (e.g., Marton, 2008 and Windsor et al., 2008; see also Chapter 3) or examine how accuracy changes depending on intervals between

item presentation (e.g., Dispaldro et al., 2013 and Marton et al., 2007). Thus, no prior work captures how the time-based active removal mechanism (i.e., *free time*) posited by the SOB-CS model relates to working memory through its relationship with interference.

The Current Study

I aimed to test the role of *free time* in working memory performance through its effect on interference between representations in children with DLD relative to TD peers. My theoretical framework integrated three key processing-based factors hypothesized to underlie language deficits in DLD. The current study used a working memory task structure that aligns with the SOB-CS model and other current views of working memory as a construct, whereby I presented recall items and an interference processing task, and then asked participants to recall items and their serial positions (Alloway et al., 2006; Oberauer et al., 2012; Oberauer et al., 2016). In order to test interference effects, I varied the domain of recall and interference processing task demands according to the following conditions: 1) verbal recall items and verbal interference processing; 2) nonverbal recall items and nonverbal interference processing; 3) verbal recall items and nonverbal interference processing; 4) nonverbal recall items and verbal interference processing; 5) verbal-nonverbal recall items and verbal-nonverbal interference processing. In sum, my conditions involved task demands within one domain, divided between two domains, and distributed across both domains. *Free time* was measured as the time between the participant's response on the interference processing task and the onset of the recall test phase; thus, it varied according to a participant's processing speed. I used this experimental design to answer the following research questions:

1) Do children with DLD and children with typical development differ in the amount of *free time* available during working memory tasks? Do potential group differences in *free time* differ depending on the domain of task demands?
2) What is the relationship between *free time* and interference effects on working memory accuracy in children with DLD relative to TD peers?

I predicted that children with DLD would have less *free time* between their response on interference processing tasks and the onset of recall test phases based on evidence of slowed processing speed relative to TD peers (Kail, 1994; Miller et al., 2001). I also predicted that this group difference would be more pronounced on within-domain tasks relative to divided- and distributed- domain tasks as task demands being limited to one domain is typically more challenging than task demands being distributed across multiple domains (Gillam et al., 1998; Hoffman & Gillam, 2004). Furthermore, I predicted that children with DLD would have the least *free time* on the nonverbal within-domain task based on evidence of poor performance under similar conditions in prior work (Gillam et al., 1998; Hoffman & Gillam, 2004) and evidence of nonverbal strategy use on processing tasks in DLD (Botting et al., 2013; Larson et al., 2019; see also Arslan, Broc, & Mathy, 2020). Finally, I predicted that individual differences in *free time* on working memory tasks will be related to interference effects on working memory performance for both groups. Thus, I would expect that under similar levels of potential interference (e.g., in divided-domain conditions), more *free time* will be associated with better working memory accuracy relative to less *free time* given that *free time* allows for interference effects to be minimized. I do not anticipate DLD and TD group differences in this relationship given that I expect differences in the amount of *free time* available rather than differences in the relationship

between *free time* and working memory accuracy. See Chapter 2 for Methods, including participant sample, experimental design, and analysis.

Results

See Table 4.1 for *free time* descriptive performance across conditions and Table 4.2 multiple imputation mixed-effects model results.

Table 4.1. Descriptive statistics and by-group t-tests for *free time*.

Condition	TD (n = 34)	SLI (n = 21)	p-value
Verbal Within			
free time	M = 4114	M = 4031	p = .49
	SD =327	SD = 516	(r^2 = -0.01)
Verbal Divided			
free time	M = 3262	M = 3319	p = .66
	SD = 440	SD = 428	(r^2 = -0.02)
Nonverbal Within			
free time	M = 3311	M = 3369	p = .63
	SD = 407	SD = 375	(r^2 = -0.02)
Nonverbal Divided			
free time	M = 3880	M = 3972	p = .37
	SD = 343	SD = 369	(r^2 = -0.00)
Distributed			
free time	M = 3981	M = 3992	p = .92
	SD = 301	SD = 439	(r^2 = -0.02)

Note. free time = milliseconds; M = mean; SD = standard deviation. *p < .05, **p < .01, ***p < .001.

Free Time and Recall Reaction Time Exploratory Analyses

For recall RT in the verbal-within condition, there was a significant effect of free time (b = -0.10; stat = -3.33; p < .001), indicating that relatively less free time was associated with longer recall RT, and there was no significant effect of group, the group by free time interaction, or SES (p's > .10). I conducted follow up analyses based on descriptive performance patterns. These analyses showed no significant effect of free time for the DLD group (p = .52), and a significant effect of free time for the TD group (b = -0.10; stat = -3.42; p < .001), indicating that relatively

less free time was associated with longer recall RT. After removing chance-level performance, all results remained the same. For recall RT in the verbal-divided condition, there was a significant effect of free time ($b = -0.08$; stat = -2.42; $p < .05$), indicating that relatively less free time was associated with longer recall RT, and there was a significant effect of group ($b = 447.07$; stat = 2.03; $p < .05$), indicating that the DLD group had slower RT than the TD group. There was no significant group by free time interaction or significant effect of SES (p's $> .15$). After removing chance-level performance, the effect of group was no longer significant ($p = .08$).

For recall RT in the nonverbal-within condition, there was a significant effect of free time ($b = -0.25$; stat = -7.57; $p < .001$), indicating that relatively less free time was associated with longer recall RT. There was no significant effect of group, the group by free time interaction, or SES (p's $> .22$). After removing chance-level performance, all results remained the same. For recall RT in the nonverbal-divided condition, there was no significant effect of free time, group, the group by free time interaction, or SES (p's $> .08$). After removing chance-level performance, all results remained the same. For recall RT in the distributed condition, there was a significant effect of free time ($b = -0.11$; stat = -3.26; $p < .01$), indicating that relatively less free time was associated with longer recall RT, and there was no significant effect of group, the group by free time interaction, or SES (p's $> .15$). After removing chance-level performance, all results remained the same.

Note. Data points are jittered.

Figure 4.1. The significant group by *free time* interaction in the verbal-within condition.

Accuracy

Verbal-within Condition Accuracy

There was a significant effect of free time (b = 0.00; stat = 3.11; p < .01), indicating better odds of a correct response by a factor of 1.0 with relatively more free time, and no significant effect of group (p = .86). There was a significant group by free time interaction (b = -0.00; stat = -3.66; p < .001), and no significant effect of SES (p = .16). Follow-up analyses showed that the DLD group had significantly worse odds of a correct response by a factor of 1.0 with relatively more free time (b = -0.00; stat = -2.03; p < .05) and the TD group had significantly better odds of a correct response by a factor of 1.0 with relatively more free time (b

= 0.00; stat = 3.15; p < .01). After removing chance-level performance, all results remained the same. See Figure 4.1.

Note. The group by *free time* interaction was significant when chance-level performance was removed; Data points are jittered.

Figure 4.2. The significant relationship between accuracy and *free time* for the DLD group relative to the lack of significant relationship between accuracy and *free time* for the TD group in the nonverbal divided-domain condition.

Verbal-divided Condition Accuracy

There was no significant effect of free time (p = .99). There was a significant effect of group (b = -3.25; stat = -3.92; p < .001), indicating that DLD group had significantly worse odds of a correct response by a factor of 25.8 than the TD group, and a significant group by free time interaction (b = 0.00; stat = 2.97; p < .01). There was no significant effect of SES (p = .70). Follow-up analyses showed that the DLD group had significantly better odds of a correct response by a factor of 1.0 with relatively more free time (b = 0.00; stat = 4.57; p < .001) and

there was no effect of free time for the TD group (p = .98). After removing chance-level performance, all results remained the same. See Figure 4.2.

Nonverbal-within Condition Accuracy

There was no significant effect of free time, group, the group by free time interaction, or SES (p's > .19). After removing chance-level performance, all results remained the same.

Nonverbal-divided Condition Accuracy

There was no significant effect of free time (p = .10). There was a significant effect of group (b = -3.55; stat = -3.74; p < .001), indicating that DLD group had significantly worse odds of a correct response by a factor of 34.9 than the TD group. There was no significant group by free time interaction or significant effect of SES (p's > .22). After removing chance-level performance, all results remained the same.

Distributed Condition Accuracy

There was a significant effect of free time (b = 0.00; stat = 3.05; p < .01), indicating better odds of a correct response by a factor of 1.0 with relatively more free time. There was no significant effect of group, the group by free time interaction, or SES (p's > .39). After removing chance-level performance, all results remained the same.

Table 4.2. Multiple imputation mixed-effects model results.

Condition	**Predictor**	***b estimate***	**test-statistic**	***p-value***
Verbal Within				
Accuracy				
	Free Time	0.00	3.11	$p < .01$**
	Group	-0.14	-0.17	$p = .86$
	SES	-0.18	-1.42	$p = .16$
	Group*Free Time	-0.00	-3.66	$p < .001$***
DLD Group	Free Time	-0.00	-2.03	$p < .05$*

TD Group	Free Time	0.00	3.15	$p < .01$**
Reaction Time				
	Free Time	-0.10	-3.33	$p < .001$***
	Group	-180.30	-0.77	$p = .44$
	SES	-23.80	-0.78	$p = .43$
	Group*Free Time	0.08	1.64	$p = .10$
Verbal Divided				
Accuracy				
	Free Time	-0.00	-0.01	$p = .99$
	Group	-3.25	-3.92	$p < .001$***
	SES	-0.05	-0.39	$p = .70$
	Group*Free Time	0.00	2.97	$p < .01$**
DLD Group	Free Time	0.00	4.57	$p < .001$***
TD Group	Free Time	-0.00	-0.02	$p = .98$
Reaction Time				
	Free Time	-0.08	-2.42;	$p < .05$*
	Group	447.07	2.03	$p < .05$*
	SES	16.89	0.70	$p = .49$
	Group*Free Time	-0.08	-1.44	$p = .15$
Nonverbal Within				
Accuracy				
	Free Time	0.00	1.29	$p = .20$
	Group	-0.85	-1.10	$p = .27$
	SES	0.07	0.57	$p = .57$
	Group*Free Time	-0.00	-0.95	$p = .34$
Reaction Time				
	Free Time	-0.25	= -7.57	$p < .001$***
	Group	53.43	0.23	$p = .82$
	SES	17.31	0.55	$p = .59$
	Group*Free Time	0.07	1.23	$p = .22$
Nonverbal Divided				
Accuracy				
	Free Time	0.00	1.64	$p = .10$
	Group	-3.55	-3.74;	$p < .001$***
	SES	-0.19	-1.21	$p = .23$
	Group*Free Time	0.00	1.22	$p = .22$
Reaction Time				
	Free Time	-0.05	-1.75	$p = .08$
	Group	411.98	1.27	$p = .21$
	SES	13.35	0.27	$p = .79$
	Group*Free Time	-0.01	-0.21	$p = .83$

Distributed				
Accuracy				
	Free Time	0.00	3.05	$p < .01$**
	Group	-0.50	-0.70	$p = .48$
	SES	0.01	0.14	$p = .89$
	Group*Free Time	-0.00	-0.84	$p = .40$
Reaction Time				
	Free Time	-0.11	-3.26	$p < .01$**
	Group	0.04	1.42	$p = .15$
	SES	9.94	0.26	$p = .80$
	Group*Free Time	0.01	0.15	$p = .88$

Note. Test-statistic = chi-sq for accuracy and t-value for reaction time; Group = Typically Developing vs. Developmental Language Disorder group comparison; Sentence Comprehension = Accuracy on the sentence comprehension task; NS = not significant; Matrix Reasoning = t-score on the Matrix Reasoning subscale from the Wechsler Abbreviated Intelligence Scale, Second Edition (WASI-II); *significant difference at $p < .05$; **significant difference at $p < .01$; *** significant difference at $p < .001$

Discussion

This study examined working memory performance by varying the domain of interference and recall items using a fully-crossed design. My theoretical framework was the serial-order-in-a-box – complex span computational model which posits a time-based active removal mechanism, *free time*, that governs the degree to which representations interfere in working memory (Oberauer et al., 2012). More *free time* relative to less *free time* is associated with less interference between items in working memory according to the SOB-CS model. *Free time* between cognitive operations allows items to be unbound from context positions, avoiding overlap in activation patterns that may distort item representations. Based on evidence of slowed reaction time in DLD (e.g., Kail, 1994 and Miller et al., 2001), I predicted that children with DLD would have less *free time* than the TD group. This finding was not borne out in my data – groups did not differ in *free time* in any condition. This finding could suggest that *free time* is not proportionate to behavioral reaction time in children with DLD, but this finding more closely

aligns with my finding of inconsistent group differences in reaction time across my working memory tasks (see Chapter 3).

I also predicted that individual differences in *free time* would be associated with working memory performance across conditions and I did not anticipate group differences in this effect. Findings indicated that relatively more *free time* was associated with better accuracy in the distributed domain condition (i.e., auditory-word location judgment + word-image location recall), and with faster reaction time in the verbal-within, verbal-divided, nonverbal-within and distributed domain conditions. This latter finding suggests that *free time* is related to reaction time, a measure of processing speed, even in the absence of predicted group differences in *free time*. I also demonstrated a group difference in the relationship between *free time* and accuracy in the verbal-within (i.e., nonword judgment + word recall) and verbal-divided (i.e., face/nonface judgment + word recall) conditions. In the verbal-within domain condition, relatively more *free time* was associated with worse accuracy for the DLD group, but with better accuracy for the TD group. In the verbal-divided domain condition, relatively more *free time* was associated with better accuracy for the DLD group, but there was no relationship between *free time* and accuracy for the TD group. The current work provides preliminary evidence that *free time* facilitates working memory performance with verbal and nonverbal items for children with DLD and TD peers, particularly for verbal items and particularly in the presence of heighted interference (e.g., nonverbal-within domain condition). Accuracy in the verbal-within condition for the DLD group is the exception to this finding and may be better explained by considering attention and encoding than solely considering the role of *free time*. See Table 4.3 for information on hypotheses confirmation.

Table 4.3. Hypothesis Confirmation.

Hypothesis	Result	Confirmed Acc	Confirmed RT
Verbal-within + *free time*	Verbal-within + *free time*	+	+
Group difference in *free time* effect	Group difference in *free time* effect	+	+/-
Verbal-divided + *free time*	Verbal-divided ≠/+ *free time*	-	+
Group difference in *free time* effect	Group difference in *free time* effect	+	-
Nonverbal-within + *free time*	Nonverbal-within ≠/+ *free time*	-	+
Group difference in *free time* effect	No group difference in *free time* effect	-	-
Nonverbal-divided + *free time*	Nonverbal-divided ≠/+ *free time*	-	-
Group difference in *free time* effect	No group difference in *free time* effect	-	-
Distributed + *free time*	Distributed + *free time*	+	+
Group difference in *free time* effect	No group difference in *free time* effect	-	-

Note. ~ indicates less of a difference between conditions relative to the other group (e.g., the difference between nonverbal-divided and distributed condition performance was hypothesized to be greater for the DLD than TD group); - indicates that the hypothesis was not confirmed; + indicates that the hypothesis was confirmed; -/+ indicates that the hypothesis was partially confirmed; Acc = Recall accuracy; RT = Recall reaction time.

Working Memory and Free Time in DLD

Generalized Slowing Hypothesis

The Generalized Slowing Hypothesis, one processing-based hypothesis of DLD, suggests that slowed processing speed relative to TD peers on verbal and nonverbal tasks explains language deficits associated with this disorder (Kail, 1994; Miller et al., 2001). In the presence of slowed processing speed, it is likely that there is diminished *free time* available to restore working memory to a baseline state and therefore heightened interference between representations (Oberauer et al., 2012). For instance, if processing speed is slower on my interference task, there will be less *free time* available between a participant's response and the onset of the recall trial. Nevertheless, it is impossible to determine whether behaviorally slow responses indicate slowed activation of a representation during encoding, maintenance, or

retrieval. Therefore, I cannot make strong claims as to whether the lack of group difference in the amount of *free time* available within each condition corresponds to a lack of group difference in the amount of *free time* available at the neural level. This finding does align with prior evidence suggesting inconsistent DLD versus TD group differences in processing speed, and increasing agreement that a slowed processing speed account of DLD does not fully explain their patterns of deficits (Ebert & Kohnert, 2011; Ellis Weismer et al., 2005; Finneran et al., 2009; Marinis & Van Der Lely, 2007; Schul et al., 2004; see also Chapter 3). Even in the absence of overall group differences in *free time*, it is possible that a child could continue to engage in processing related to the interference task after responding, rather than immediately beginning to restore working memory to a baseline state (e.g., errored responses are associated with a slower reaction time on subsequent trials; Kirschner et al., 2020). In this scenario, there is less *free time* available at the neural level than what was measured behaviorally. One alternative to measuring *free time* based on behavioral responses is increasing the pace of processing operations within a task, such as increasing the speed at which training items are presented (Barrouillet et al., 2009; Oberauer et al., 2012). For the current study, I turn to examining the relationship between *free time* and performance measures on the working memory tasks under assumptions associated with *free time* measured at the level of the behavioral response rather than at each level of processing and assumptions associated with an absence of overall group differences in my measure of *free time*.

Limited Verbal Working Memory Hypothesis

Interestingly, the current findings do provide preliminary support for an association between *free time* and recall reaction time regardless of recall item domain. In the nonverbal-divided condition, however, there was no significant relationship between *free time* and reaction time. It is notable that there was a relationship between *free time* and accuracy in each condition

where recall involved verbal features (e.g., verbal-within and distributed conditions). There was also a relationship between *free time* and reaction time in the nonverbal-within condition, but not the nonverbal-divided condition. Taken together, these patterns provide support for a closer link between *free time* and verbal working memory performance. This interpretation is consistent with prior work that links processing speed and language in DLD (Leonard et al., 2007; Montgomery, 2005; Park et al., 2020) and prior work showing that verbal processing is particularly dependent on timescales (Hsu & Bishop, 2011 Gillam, Cowan, & Day, 1995; Tallal et al., 1996), as well as with my finding of a greater effect of verbal than nonverbal interference in Chapter 3. Furthermore, this interpretation is consistent with the processing-based hypothesis of DLD suggesting that limited verbal working memory skills lead to language difficulty (Archibald & Gathercole, 2006, 2007; Ellis Weismer et al., 1999). There is evidence, however, that verbal *and* nonverbal processing performance is worse for children with DLD relative to TD peers, although their deficits appear to be greater for verbal than nonverbal tasks (e.g., Pauls & Archibald, 2016; Vugs et al., 2013; but see Gillam et al., 1998 and Hoffman & Gillam, 2004).

Even so, I also found a relationship between *free time* and reaction time for the nonverbal-within condition which does not have a verbal component, but no relationship between *free time* and reaction in the nonverbal-divided condition which does have a verbal component. Theoretically, the nonverbal-divided condition should be associated with less interference than the nonverbal-within condition due to greater similarity between interference and recall items of the same domain versus different domains (Oberauer et al., 2012). I would expect *free time* to be more important for within domain interference than cross domain interference because items from different domains are less likely to have overlapping activation patterns than items from the same domain regardless of *free time* between cognitive operations

on those items. In fact, the association of *free time* with accuracy and reaction time in the verbal-divided condition may be considered more surprising than association between *free time* and reaction time in the nonverbal-within condition from this perspective. The relationship between *free time* and performance on the verbal-divided condition may be driven by the verbal component of the verbal-divided task given that I am testing recall of verbal items. Again, the relationship between *free time* and recall appears to be greater for verbal than nonverbal items. Under the constraint of within-domain interference, however, I also found a relationship between *free time* and nonverbal recall.

Inefficient Inhibition Hypothesis

These patterns, therefore, may be further clarified by integrating another processing-based hypothesis of DLD, the inefficient inhibition hypothesis (Bjorklund & Harnishfeger, 1990; Marton et al., 2007). Children with DLD have poorer inhibition of interference than TD peers on verbal tasks and to a lesser degree on nonverbal tasks (Kapa, Plante, & Doubleday, 2017; Marton et al., 2007; Pauls & Archibald, 2016; Spaulding, 2010; see also evidence of poorer performance for verbal than nonverbal within domain interference for the DLD group in Chapter 3; but see Gillam et al., 1998 and Hoffman & Gillam, 2004). Importantly, there is work showing group differences in the relationship between language and inhibition concurrently (Blum & Boerma, 2019; Dispaldro et al., 2013; Smolak et al., 2020) and over time (Larson, Kaplan, et al., 2020). *Free time* is the key mechanism that modulates the level of interference between similar items in working memory, according to the SOB-CS model (Oberauer et al., 2012). I found that *free time* was related to reaction time for verbal items regardless of the level of interference (e.g., within versus cross domain) and for nonverbal items in the presence of within-domain interference, suggesting an association between *free time* processing efficiency for verbal items and for

nonverbal items when inhibitory demands are high. I also found that *free time* was related to accuracy for verbal items and verbal-nonverbal items (i.e., word-image locations), suggesting an association with verbal processing accuracy. Specifically, *free time* was associated with better accuracy across groups in the distributed condition and better accuracy in the DLD group in the verbal-divided condition. In Chapter 3, I showed that reaction time was faster across groups in the verbal-divided than distributed condition, suggesting that the distributed condition was more challenging than the verbal-divided condition. Theoretically, it's possible that *free time* was related to accuracy in the verbal-divided condition for the DLD group, but only for both groups in the distributed condition, because distributed condition taxed inhibition skills to a greater degree. There was within-domain verbal *and* nonverbal interference at each stage of the distributed condition (i.e., verbal-nonverbal interference and verbal-nonverbal recall), but nonverbal interference and verbal recall in the verbal-divided condition. With greater inhibition demands, the role of *free time* is more important than when inhibition demands are minimal because minimal inhibition demands suggest little baseline overlap in activation patterns (Oberauer et al., 2012). Although interference and recall are divided between domains in the verbal-divided condition, there remains the possibility for interference among the three potential verbal recall targets presented during the training phase of the task. Accordingly, *free time* may be more important to performance in this condition for the DLD than TD group due to their disproportionate weakness in inhibiting verbal interference (Pauls & Archibald, 2016; see Chapter 3) and the important relationship between inhibition and language in this group (Dispaldro et al., 2013; Larson, Kaplan, et al., 2020). These interpretations are consistent with the relationship between *free time* and performance in the TD group as well.

Encoding and Attention Under the SOB-CS Framework

Contrary to predictions, I found that more *free time* was associated with poorer accuracy in the verbal-within domain condition – the condition expected to have the greatest inhibition demands for the DLD group. For instance, in Chapter 3, I showed that children with DLD performed more poorly in the verbal-within domain condition than the nonverbal-within and verbal-divided conditions. The finding that more *free time* was associated with poorer accuracy in the verbal-within condition is inconsistent with other patterns showing a relationship between *free time* and recall with verbal items and inconsistent with predictions of the SOB-CS model. The negative relationship between *free time* and accuracy found in the DLD group in the verbal-within condition may have been a function of poor performance on the verbal interference task. I found that the DLD group had the highest rate of nonresponse on the interference task in the verbal-within condition (12%) relative to other conditions (Appendix B Table B.5). They also had significantly worse accuracy for the verbal-within condition than TD peers. It is possible that this task difficulty had downstream effects on *free time* or the relationship between *free time* and performance in this condition (e.g., slowed subsequent reaction time in the presence of error processing; Kirschner et al., 2020). However, I only examined *free time* for accurate responses on the interference task and this explanation does not clarify the negative relationship I observed.

Another explanation for this finding is that children with DLD had difficulty attending to and encoding verbal items. *Free time* is relevant to inhibiting interference after an item has been attended to and encoded (Oberauer et al., 2012). Items are unbound from context positions during *free time* in order to diminish the degree to which activation patterns overlap and give rise to interference. However, if recall targets are not encoded (i.e., they are not bound to a context position), the roles of overlapping activation patterns and *free time* are likely to be less

important. Similar to *free time*, encoding is a time-based process where the robustness of an encoded representation (e.g., the strength of activation patterns) increases as time passes asymptotically (Oberauer et al., 2012). Attention plays a role in encoding because an item becomes available for cognitive operations like encoding when the item is attended to. Additionally, an attended item has greater temporal distinctiveness (i.e., binding to a serial position). For instance, the last item encoded into working memory has a heightened level of availability for further processing (i.e., consistent with Cowan's focus of attention in the Embedded Processes Model of working memory; Cowan, 1988; 2010). Poor attention or encoding may be signaled behaviorally by faster reaction time coupled with poor accuracy or by high nonresponse rates. Children with DLD have deficits in both encoding (Leonard et al., 2019; McGergor et al., 2017) and attention (Ebert & Kohnert, 2011; Marton & Schwartz, 2003; Redmond & Ash, 2014). In fact, the inefficient inhibition hypothesis suggests that deficits in inhibition may be associated with poor encoding, particularly with verbal items (Bjorklund & Harnishfeger, 1990; Marton et al., 2007).

Consistent with this hypothesis, I showed greater difficulty inhibiting verbal than nonverbal interference for the DLD group whereas the TD group had greater difficulty inhibiting nonverbal than verbal interference in Chapter 3. Children with DLD had significantly worse reaction time on the verbal interference task than TD peers for the nonverbal-divided condition, but not the verbal-within condition. Children with DLD did, however, have significantly worse accuracy on the verbal interference task than TD peers for the verbal-within condition, as well as a high nonresponse rate. These patterns may reflect poor attention and encoding on the verbal interference task for the verbal-within domain condition, as they appear to have more *free time* in the verbal-within condition than the nonverbal-divided condition coupled with poor accuracy and

a high nonresponse rate. This interpretation is consistent with Smolak et al. (2020) demonstrating a mediation effect of selective attention (i.e., on a task that also draws on inhibition) on the relationship between working memory and language in children with DLD (Smolak et al., 2020). Thus, working memory performance in children with DLD may be susceptible to poor encoding, potentially as a function of poor attention skills and particularly for verbal relative to nonverbal items. An attention and encoding account of performance in the verbal-within condition may, therefore, explain performance to a greater degree than a *free time* account. Specifically, the negative relationship between *free time* and accuracy on this task might signal diminished attention and poor encoding during the verbal interference task.

Summary

Findings from the current study demonstrate a relationship between *free time* and reaction time on working memory tasks regardless of recall domain for children with DLD and TD peers. However, *free time* may be related to reaction time for nonverbal recall only in the presence of heightened within-domain interference. The relationship between *free time* and reaction time on working memory tasks requires further examination, such as determining the degree to which *free time* at the neural level relates to various measures of processing speed at the behavioral level. Findings also demonstrate an important relationship between *free time* and accuracy for verbal recall. This relationship was evident for children with DLD across conditions requiring a degree of verbal recall, but it was only evident for TD peers in conditions with a degree of verbal-within domain interference. *Free time* appeared to have a facilitative effect, except in the case of verbal-within domain interference for children with DLD. Under the constraints of verbal-within domain interference, considering attention and encoding may account for this finding that appears contradictory. It's possible children with DLD attended to and encoded

interference items to a lesser degree, signaled by a lack of group difference in reaction time coupled with poor accuracy in the verbal-within relative to the nonverbal-divided condition. Diminished attention to verbal interference, as reflected in fast responses paired with poor accuracy (e.g., a speed-accuracy tradeoff, impulsivity), may be associated with more *free time*, but also with diminished attention to verbal recall. In this scenario, having more *free time* rather than less *free time* is not necessarily associated with better recall performance due to a breakdown in at an earlier stage of processing – encoding. This hypothesis, however, requires further exploration. Together, these findings provide partial support for each of the three processing-based hypotheses of DLD – limited verbal working memory, slowed processing speed, and inefficient inhibition of interference. Alternatively, the SOB-CS is able to provide a more integrated explanation of working memory performance in DLD with the potential to further clarify verbal processing in DLD based on the roles of attention and encoding.

Clinical Implications

This work demonstrates relationships among *free time*, reaction time and accuracy on working memory tasks, and inhibition of interference, particularly for verbal items. These findings reinforce clinical implications for Chapter 2, while further highlighting the importance of providing time between successive presentations of verbal information. The current work suggests that children with DLD rely on time intervals between presentations of items to be attended to and encoded, and maintained or manipulated in working memory. This unfilled interval of time allows them to inhibit interference between similar items. In practice, children with DLD may benefit from greater verbal versus nonverbal feature contrast between items that are presented successively. For example, *-ed* production trial may be followed by selecting a visual depiction of a completed action from a set of images depicting ongoing and completed

actions. They may also benefit from longer pauses between verbal items that are presented successively (e.g., -*ed* produced in walk-*ed* and play-*ed*). However, there may also be important roles for encoding and attention that affect how feature contrasts and unfilled pauses relate to verbal and nonverbal processing in classroom or therapeutic settings.

Limitations and Future Directions

There are different methods for measuring the *free time* mechanism, including varying the pace of recall item presentation and measuring neural activation patterns, and my method of measuring *free time* may capture different aspects of this construct than other prior work (e.g., Barrouillet et al., 2011). It is possible that my study did not capture TD versus DLD group differences in *free time* that may be observed with other methods and that might be expected based on evidence that children with DLD have slower processing speed than TD peers (Kail, 1994; Miller et al., 2001). Although my power analysis indicated that I had adequate power to detect a medium effect size, it's possible that I was unable to detect group differences due to the modest sample size of my DLD group. Additionally, I allowed nonverbal ability to vary to a greater extent than prior work that examines Specific Language Impairment groups. Nonverbal ability may extend to the intellectual impairment cutoff for DLD, but must be within the normal range (no more than 1 SD below the mean) for a Specific Language Impairment group. Consequently, there may be more variance in my DLD group relative to prior work on Specific Language Impairment that diminishes my power to detect true effects. Furthermore, my frequentist statistical approach does not quantify uncertainty or the degree to which the data support the null versus alternative hypothesis as in Bayesian statistics, for instance. My approach is able to reveal the presence of a relationship versus there not being enough evidence to indicate the presence of a relationship, rather than also providing information about the absence of a

relationship. Thus, the absence of a significant effect does not reveal whether the relationship does not exist. However, I found that my measure of *free time* was significantly related to reaction time in a majority of my working memory conditions, and I found minimal group differences in working memory reaction time. Taken together, these patterns suggest that my measure of *free time* is associated with another processing speed measure in the current study and my goal of examining time-based processes in DLD was largely achieved. Future work may benefit from examining *free time* using other methods in order to further characterize the relationship between *free time* and working memory performance in DLD.

It would also be useful for future work to examine stimulus domain via a continuous approach to domain features. I examined domain from a categorical perspective in order to build on prior work using similar methods (e.g., Gillam et al., 1998; Hoffman & Gillam, 2004) and extend prior work by including additional condition comparisons. I also built on prior work by using a task structure that aligns with current views of working memory in general (Alloway et al., 2006; Leonard et al., 2007) and under the SOB-CS model specifically (Oberauer et al., 2012; Oberauer et al., 2016). The SOB-CS model is able to account for stimulus domain as a continuum via distributed feature activation patterns and processing units that may represent verbal or nonverbal information. This component represents an advantage relative to other working memory models (e.g., Baddeley & Hitch 1994) and examining the degree to which a stimulus has verbal versus nonverbal features may add novel nuance to the current findings. See Chapter 3 for additional limitations related to my remote-based administration procedures.

Conclusions

The current study examined the key mechanism of the serial-order-in-a-box – complex span model, *free time* (Oberauer et al., 2012). *Free time* is an active-removal mechanism that governs the degree of interference in working memory and restores working memory to a baseline state during unfilled intervals between cognitive operations. *Free time* in the current study was the time between a correct response on the interference task and the onset of the recall trial. I aimed to determine whether *free time* differed between age-matched DLD and TD groups, and to characterize relationship between *free time* and interference on working memory tasks involving varied verbal versus on verbal task demands. There were no DLD versus TD group differences in *free time* regardless of working memory task domain (i.e., verbal versus nonverbal). I demonstrated a positive relationship between *free time* and reaction time regardless of domain, suggesting that *free time* is related to processing speed, even in the absence of overall group differences in *free time*. Groups differed in the relationship between *free time* and working memory accuracy for verbal recall. When interference was nonverbal and recall was verbal, *free time* was positively associated with accuracy for the DLD group, but not the TD group. However, when interference and recall were verbal, *free time* was negatively associated with accuracy for the DLD group, but positively associated with accuracy for the TD group. These reaction time and accuracy patterns suggest that *free time* between cognitive operations is facilitative of performance in working memory for both verbal and nonverbal recall, particularly in the presence of high interference (e.g., nonverbal interference paired with nonverbal recall). The exception to these patterns is the negative relationship between *free time* and accuracy in the presence of high verbal interference for the DLD group (i.e., verbal interference paired with verbal recall). This finding may reflect poor encoding and attention under particularly

challenging verbal processing demands for the DLD group. Thus, I have shown that processing speed interacts with interference during processing, but further work is needed to examine potential downstream effects of attention and encoding on verbal working memory.

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Chapter 5: Individual differences and Working Memory

Language impairment of unknown origin, also referred to as Developmental Language Disorder (DLD), has been shown to have a prevalence of 7% at school entry by a recent epidemiologic study (Norbury et al., 2016). DLD is associated with significant weakness in verbal abilities relative to typically developing (TD) peers (Bishop, Snowling, Thompson, Greenhalgh, & CATALISE Consortium, 2017; Norbury et at., 2017). These wesaknesses in verbal ability include deficits in language knowledge, such as on morphosyntax production tasks (Leonard, 2014; Rice & Wexler, 1996; Rice, Tomblin, Hoffman, Richman, & Marquis, 2004), and in language processing, such as on verbal working memory tasks (Archibald & Gathercole, 2006, 2007; Ellis Weismer, Evans, & Hesketh, 1999; Gaulin & Campbell, 1994; Leonard, Deevy, Fey, & Bredin-Oja, 2013). In addition to verbal weakness, children with DLD have poorer nonverbal abilities than TD peers, such as in working memory (Vugs, Cuperus, Hendriks, & Verhoeven, 2013; Windsor, Kohnert, Loxtercamp, & Kan, 2008), resistance to interference (i.e., inhibition; Dispaldro et al., 2013; Pauls & Archibald, 2016), attention (Ebert & Kohnert, 2011; Marton & Schwartz, 2003; Redmond & Ash, 2014), and processing speed (Kail, 1994; Miller, Kail, Leonard, & Tomblin, 2001).

Although verbal deficits are primary in DLD, studies have shown poorer performance with nonverbal stimuli (e.g., shapes) than with verbal stimuli (e.g., words) on working memory tasks (Gillam, Cowan, & Marler, 1998; Hoffman & Gillam, 2004). It is possible that children with DLD draw on relative strengths in nonverbal abilities to engage in performance on tasks that draw on processing whereas TD peers draw on verbal abilities (Botting, Psarou, Caplin, & Nevin, 2013; Blom & Boerma, 2019; Larson, Gangopadhyay, Kaushanskaya, & Ellis Weismer, 2019). Drawing on nonverbal abilities may lead to poorer performance on working memory tasks

with nonverbal than verbal stimuli due to greater interference between similar representations (e.g., shapes and locations) than dissimilar representations (e.g., shapes and words; Oberauer, Farrell, Jarrold, & Lewandowsky, 2016; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). Gillam et al. (1998) and Hoffman and Gillam (2004) found that children with DLD benefitted from distributing processing across both verbal and nonverbal domains relative to processing being limited to a single domain on working memory tasks. These findings further point to a role for interference in processing performance.

In Chapter 3, I showed that children with DLD had worse performance on tasks with verbal than nonverbal interference, and I showed modest benefits of distributing processing across verbal and nonverbal domains relative to processing being limited to one domain (i.e., tasks with less relative to more interference). These patterns were further clarified in Chapter 4 where I demonstrated that time-based processes were related to performance on working memory tasks with verbal and nonverbal task demands. I also demonstrated DLD versus TD group differences in the role of time-based processes and working memory performance on tasks with verbal interference paired with verbal recall. These patterns may reflect individual differences in verbal and nonverbal abilities, as well as attention. However, no prior work has examined how working memory performance relates to individual differences in these abilities using a fully-crossed experimental paradigm. Thus, the current study examined relationships between performance on working memory tasks with varied domain of task demands and individual differences in verbal and nonverbal abilities. It will also examine the role of attention in working memory performance given the importance of attention in processing (Friedman & Miyake, 2004; Kane & Engle, 2002; Tiego, Testa, Bellgrove, Pantelis, & Whittle, 2018), evidence of attention deficits in DLD (Ebert & Kohnert, 2011; Redmond & Ash, 2014; Smolak,

McGregor, Arbisi-Kelm, & Eden, 2020), and the high comorbidity rate of DLD and Attention Deficit-Hyperactivity Disorder (Mueller & Tomblin, 2012; Redmond, 2020).

Working Memory in DLD

Working memory is thought to be critical to language processing and storage as working memory allows information to be maintained in an active state and manipulated for further use (e.g., when answering a question; Archibald & Gathercole, 2006; Ellis Weismer et al., 1999; Durrleman & Delage, 2016; Montgomery, Magimairaj, & Finney, 2010). In fact, working memory is thought to constrain language processing due in part to the incremental nature of language and nonadjacent dependencies inherent to language (Leonard et al., 2007; Montgomery et al., 2010; Van Dyke & Johns, 2012). For instance, the English singular present-progressive syntactic frame *is* verb-*ing* requires maintaining the subject property of number while producing the auxiliary *be* (i.e., *is* instead of *are*), and then producing the verb plus the verb aspect marker -*ing* (i.e., ongoing action; e.g., *she is running*). This example shows that language unfolds over time and that there may be intervening information between syntactic contingencies (i.e., nonadjacent dependencies). Many studies show that children with DLD struggle on working memory tasks that involve verbal stimuli (Ellis Weismer, Plante, Jones, & Tomblin, 2005; Mainela-Arnold, Evans, & Alibali, 2006; Montgomery & Evans, 2009; Vugs, Hendriks, Cuperus, Knoors, & Verhoeven, 2017), but there is mounting evidence of deficits on working memory tasks with nonverbal stimuli as well (Kapa, Plante, & Doubleday, 2017; Marton, 2008; Smolak et al., 2020; Vugs et al., 2013; Vugs et al., 2017; Windsor et al., 2008; but see Blom & Boerma, 2020).

In their longitudinal study, Vugs et al. (2017) showed that verbal and nonverbal working memory performance differed between DLD and TD groups at 4-5 years of age, but performance only differed for verbal working memory at 7-8 years of age when accounting for age and nonverbal IQ. However, meaningful variance in results may have been washed out due to the close relationship between fluid intelligence and working memory (Kane et al., 2004). Indeed, nonverbal intelligence was significantly related to nonverbal working memory in this study (Vugs et al., 2017). Vugs et al. (2017) also found that verbal working memory and verbal simple storage predicted composite language scores (vocabulary and concepts and following directions) one year later. Interestingly, nonverbal simple storage, but not nonverbal working memory, predicted composite language scores one year later and the DLD and TD groups presented with similar developmental patterns. Whereas Blom and Boerma (2020) showed no evidence of deficits in nonverbal working memory in children with DLD relative to TD peers, Smolak et al. (2020) did show deficits. This discrepancy may be related to between-study differences in language ability within the DLD groups as both studies found a concurrent relationship between nonverbal working memory performance and language in children with DLD. In fact, Vugs et al.'s (2013) meta-analysis showed nonverbal working memory deficits in children with DLD relative to TD peers, as well as an association between nonverbal working memory and language impairment severity in children with DLD. There is also converging evidence of DLD and TD group differences in relationships between executive function skills, like working memory, and language concurrently (Dispaldro et al., 2013; Larson et al., 2019; Smolak et al., 2020) and over time (Blom & Boerma, 2019; Larson, Kaplan, Kaushanskaya, & Ellis Weismer, 2020). Taken together, working memory appears to be important to language, likely with a closer relationship between verbal working memory and language than nonverbal working memory and language.

None of these studies, however, has compared performance on verbal versus nonverbal working memory tasks, nor how differences in performance on these tasks may vary in children with DLD relative to TD peers. It may be useful to vary the domain of task demands in order to tease apart potential confounds between skills and stimuli of the same domain and how these relationships may differ between DLD and TD groups.

Few studies have directly compared performance on verbal and nonverbal working memory tasks in children with DLD relative to TD peers. One study varied the domain of task demands to be within one domain (e.g., verbal stimuli, verbal response) or distributed between two domains (e.g., verbal-nonverbal stimuli, verbal response; Gillam et al., 1998) and a follow up study from the same lab varied the domain of task demands to be within one domain (e.g., nonverbal stimuli, nonverbal interference processing task) or divided between two domains (e.g., nonverbal stimuli, verbal interference processing task) using a slightly different experimental paradigm (Hoffman & Gillam, 2004). Findings from these studies showed that children with DLD performed the most poorly on nonverbal within-domain tasks and their performance improved when dispersing processing across both domains. In fact, Gillam et al. (1998) showed that performance was more similar between DLD and TD groups when processing was distributed across domains. My findings from Chapter 3 indicated only modest benefits of dividing processing between domains or distributing processing across domains relative to processing being limited to one domain for children with DLD and their TD peers. Rather, verbal interference appeared to have a greater effect on verbal and nonverbal recall performance in DLD than in TD peers. There was also a group difference in the relationship between time-based processes and performance on tasks with verbal interference and verbal recall, which may be further clarified by examining how relative verbal, nonverbal, and attentional abilities relate to

working memory performance (Chapter 4). No prior work, however, has examined how individual differences in verbal and nonverbal skills relate to working memory performance in children with DLD compared to TD peers, even though a there is evidence of close relationships between working memory and these skills (Alloway, Gathercole, & Pickering, 2006; Blom & Boerma, 2020; Archibald & Gathercole, 2006; Ellis Weismer et al., 1999; Kane et al., 2004; Kapa & Erikson, 2020; Leonard et al., 2007; Montgomery et al., 2010).

Theoretical Framework

There are three primary hypotheses of processing-based factors that may underlie DLD: 1) limited verbal working memory (Archibald & Gathercole, 2006, 2007; Ellis Weismer et al., 1999); 2) slowed processing speed (Kail, 1994; Miller et al., 2001); 3) inefficient inhibition (i.e., resistance to interference; Bjorklund & Harnishfeger, 1990; Marton, Kelmenson, & Pinkhasova, 2007). The serial-order-in-a-box-complex span (SOB-CS) computational model (Oberauer et al., 2012) may be ideally suited to integrate these three hypotheses. The SOB-CS model is an interference-based model of complex span. It proposes a time-based active removal mechanism, *free time*, responsible for diminishing the interference that constrains working memory performance. Items are decoupled from their context (i.e., serial) positions during *free time* between stimulus presentations or cognitive operations, for example, which removes them from working memory and restores working memory to a baseline state. The SOB-CS model, therefore, captures limitations in working memory based on the relationship between processing speed and interference effects. I have shown group differences in effects of interference on working memory performance (Chapter 3) and group differences in associations between *free time* and working memory performance (Chapter 4). It is possible that examining the roles of relative abilities in verbal, nonverbal, and attentional skills may further clarify these findings.

Individual Differences Under the SOB-CS Model

According to the SOB-CS model, individual differences in verbal or nonverbal abilities may be associated with the relative distinctiveness of verbal and nonverbal representations. In children with DLD, working memory may be more susceptible to interference between verbal items given their relative weakness in language. As children with DLD encode incoming verbal information, encoding strength is likely to be less than that of TD peers and less than for nonverbal information. Diminished encoding strength results in less-robust representations (e.g., features are less precise, fewer features encoded), and features are therefore more likely to overlap, particularly for similar items (e.g., items from the same category; Oberauer et al., 2012). For instance, on a Competing Language Processing task (Gaulin & Campbell, 1994), children are administered sets of sentences for which they must provide a truth value judgment and then recall the final word in each sentence in the correct sequence. Children with DLD are likely to confuse sentence-final words with similar features, such as phonology (e.g., same initial phoneme), category (e.g., animals), or other word properties (e.g., frequency of co-occurrence), assuming these features are encoded less robustly than TD peers. Indeed, prior work suggests that children with DLD have poorer encoding than TD peers, which may lead to language processing difficulty (Alt & Plante, 2006; Ellis Weismer, Plante, Jones, & Tomblin, 2005; Evans, Selinger, & Pollack, 2011; Leonard et al., 2019). Moreover, children with DLD are thought to process information more slowly than TD peers (Kail, 1994; Miller et al., 2001). This slowed processing may involve slowed encoding or slowed removal of items from working memory, both of which result in greater interference between items than rapid encoding or removal. This interference may be further exacerbated if *free time* is also reduced.

Although the SOB-CS model does not make claims as to the relationship between verbal or nonverbal strategies (e.g., rehearsal) and working memory performance, it also does not rule out the potential utility of such strategies, particularly on the level of individual differences. The SOB-CS model is able to outperform decay-based (e.g., Baddeley & Hitch, 1974; Barrouillet, Portrat, & Camos, 2011) and resource-based (e.g., Cowan, 2014; Kane & Engle, 2002) models of working memory in capturing key working memory phenomena without verbal or nonverbal strategies (Oberauer et al., 2012; Oberauer et al., 2016). However, a prominent theory of executive function, the Hierarchical Competing Systems Model, suggests that language in the form of verbal mediation underlies developmental advancement in executive function (Marcovitch & Zelazo, 2009). Executive function refers to goal-directed behavior and is an umbrella term that includes subcomponents, such as working memory and inhibition (Marcovitch & Zelazo, 2009; Friedman & Miyake, 2004). Empirical work on executive function skills provides support for facilitative effects of verbal strategies in typical development (Alderson-Day & Fernyhough, 2015; Arslan, Broc, & Mathy, 2020; Fatzer & Roebers, 2012), but perhaps for facilitative effects of nonverbal strategies in children with DLD (Botting et al., 2013; Larson et al., 2019) and Autism Spectrum Disorder with co-morbid structural language impairment (Ellis Weismer, Kaushanskaya, Larson, Mathee, & Bolt, 2018; Larson, Gangopadhyay, Prescott, Kaushanskaya, & Ellis Weismer, 2020).

It is possible that the SOB-CS model does not need verbal or nonverbal strategies in its account of working memory performance given that it is a computational model tested primarily on data from adults with typical development. Thus, it may be important to consider how children with and without language impairment draw on verbal and nonverbal abilities to engage in working memory tasks in order to capture developmental patterns. Indeed, the poorer

performance of children with DLD on working memory tasks with task demands within the nonverbal domain relative to task demands within the verbal domain (e.g., Gillam et al., 1998; Hoffman & Gillam, 2004) may be explained by their reliance on nonverbal abilities (e.g., visual scene tracing) to supplement performance on working memory tasks (Botting et al., 2013; Larson et al., 2019). There may be interference between recently active nonverbal items and incoming nonverbal items, as well as between incoming nonverbal items and re-activated internal representations. For instance, a nontarget item's location may interfere with a re-activated representation associated with a visuospatial tracing strategy (e.g., using eye-gaze to 'placehold' a location) of where a prior target item was located. Alternatively, on tasks with demands within the verbal domain, drawing on nonverbal abilities to supplement performance would result in less interference than when drawing on nonverbal abilities to supplement performance on nonverbal tasks.

In contrast to children with DLD, typically developing children often draw on verbal skills to facilitate performance (Alderson-Day & Fernyhough, 2015; Arslan et al., 2020; Fatzer & Roebers, 2012; Marcovitch & Zelazo, 2009), thus their poor performance in the nonverbal conditions in Gillam et al. (1998) and Hoffman and Gillam (2004) may have been related to verbal strategies being ineffective. For instance, the nonverbal interleaved processing task involved recalling a sequence of locations via pointing. Using a verbal strategy, such as attaching labels to the visual sequence, may have led to poorer performance rather than better performance for the TD group. This strategy likely requires more time than a nonverbal strategy, such as visual tracing, and may overgeneralize key location features, such as using the label "center" for center-left and center-right positions. Indeed, findings from Larson et al. (2019) suggest that the TD group who appeared to draw on verbal skills to plan behavior took longer to plan moves in a

nonverbal planning task than the DLD group who appeared to draw on nonverbal skills to plan behavior (see Arslan et al., 2020, Botting et al., 2013, and Blom & Boerma, 2019 for additional evidence of DLD and TD differences in strategy use). Interestingly, performance of the TD and DLD groups in Larson et al. (2019) did not differ in overall accuracy. Taken together, strategy use may reveal another source of interference in younger and clinical populations. However, it is unclear how the relative effects of interference on performance relate to individual differences in verbal and nonverbal abilities. Accordingly, further examination of the relationship between verbal and nonverbal abilities and performance on working memory tasks with varied domain of task demands is needed, as is examination of how these relationships may differ in children with DLD relative to TD peers.

Attention is also viewed as a key underlying factor in working memory, potentially due to its role in active maintenance of task goals (e.g., the Hierarchical Model of Inhibitory Control; Tiego et al., 2018). In order to discern relevant from irrelevant information, the goals of the task must remain active and must be drawn upon to govern the assignment of relevancy (Kane & Engle, 2004; Miyake et al., 2000; Friedman & Miyake, 2004; Tiego et al., 2018). Classic selective sustained attention tasks, such as the continuous processing task, are thought to also involve response inhibition, specifically during presentation of the distractor stimulus (Finneran, Francis, & Leonard, 2009; Smolak et al, 2020). As a result, attention is thought to share an important relationship with inhibitory control, and, in turn, with working memory (Garon, Bryson, & Smith, 2008; Kapa & Erikson, 2020; Miyake et al., 2000; Miyake & Friedman, 2004; Tiego et al., 2018). In contrast, the role of attention under the SOB-CS model is more similar Cowan's (2010; 1988) Embedded Processes Model, whereby an activated representation is the focus of attention. A currently active representation – the most recently presented item plus its

serial position – is the focus of attention and is therefore available for further processing (e.g., encoding or removal; Oberauer et al., 2012). Subsequent to encoding, the bound item-position representation is removed from working memory and replaced with the next item-position representation. Due to encoding involving associating an item with a context position and due to sequential displacement of representations in working memory, the SOB-CS framework hypothesizes that attention is associated with the temporal distinctiveness of representations in working memory (Oberauer et al., 2012). Recall errors related to serial properties, such as recency effects or poorer performance on early than late trials, are suggestive of problems with attention, when holding *free time* and other sources of interference constant. Under the SOB-CS model, these types of errors may be particularly evident in individuals with temporal processing or attention difficulties, such as children with DLD (Bishop, Carlyon, Deeks, & Bishop, 1999; Mueller & Tomblin, 2012; Oram Cardy, Flagg, Roberts, Brian, & Robers, 2005; Redmond & Ash, 2014). Whereas the SOB-CS model adopts this more bottom-up view of attention, the Hierarchical Model of Inhibitory Control adopts a more top-down view of attention (Oberauer et al., 2012; Tiego et al., 2018). Nevertheless, both views hold attention as a key factor in working memory.

Neuroimaging evidence supports associations among attention, inhibition, and working memory as these functions been shown to share neural substrates (Kane & Engle, 2002; Munakata et al., 2011). Associations among these cognitive processes are also supported in children with DLD (Kapa et al., 2017; Marton, 2008; Schul, Wulfeck, & Townsend, 2004). It is therefore not surprising that children with DLD present with attentional difficulties (Ebert & Kohnert, 2011; Redmond & Ash, 2014; Smolak et al., 2020; but see Blom & Boerma 2020 for evidence of similar levels of performance between DLD and TD groups on a selective attention

task), as well as a high comorbidity rate with Attention Deficit-Hyperactivity Disorder (Mueller & Tomblin, 2012). Indeed, it is possible that attention mediates the relationship between working memory and language in individuals with DLD (Smolak et al., 2020). Yet, no prior studies have examined the role of attention in the relationship between language and working memory performance on tasks with varied domain of task demands in children with DLD relative to TD peers under an integrated theoretical framework like the SOB-CS model.

The Current Study

I examined the role of individual differences in verbal, nonverbal, and attentional abilities in working memory performance in children with DLD relative to TD peers. I measured verbal abilities with a language processing task, nonverbal abilities using a standardized matrix reasoning scale, and attentional abilities using a continuous processing task. The theoretical framework for the study was an interference-based model of working memory, the SOB-CS model, which has been shown to capture working memory performance in these groups and account for processing-based factors hypothesized to underlie DLD (see Chapters 3 and 4). The working memory task structure involved: 1) presentation of target and nontarget items, 2) an interference processing task, and 3) recall of target items in serial order. The conditions were designed to manipulate the domain of task demands so that processing was either within a single domain (verbal or nonverbal), divided between verbal and nonverbal domains (verbal and nonverbal), or distributed across verbal and nonverbal domains (verbal-nonverbal). This design allowed us to tease apart relationships among interference effects on working memory performance and verbal, nonverbal, and attentional skills depending on the domain of task demands. It also allowed us to determine whether these relationships differed in children with DLD relative to TD peers. Accordingly, my research questions were as follows:

1) What is the relationship between language processing and performance on working memory tasks with demands within the verbal or nonverbal domain, divided between verbal and nonverbal domains, and distributed across verbal and nonverbal domains in school-age children with DLD relative to TD peers?
2) What is the relationship between nonverbal cognition and performance on working memory tasks with demands within the verbal or nonverbal domain, divided between verbal and nonverbal domains, and distributed across verbal and nonverbal domains in school-age children with DLD relative to TD peers?
3) What is the relationship between attention and performance on working memory tasks with demands within the verbal or nonverbal domain, divided between verbal and nonverbal domains, and distributed across verbal and nonverbal domains in school-age children with DLD relative to TD peers?

I predicted that language processing would be more strongly related to working memory tasks with demands within the verbal domain and that nonverbal cognition would be more strongly related to working memory tasks with demands within the nonverbal domain, but groups would differ in the magnitude of these relationships. That is, children with DLD would show a stronger relationship between nonverbal cognition and performance on working memory tasks with demands within the verbal domain than TD peers, and TD peers would show a stronger relationship between language processing and performance on working memory tasks with demands within the nonverbal domain than children with DLD. These predictions are based on findings of relationships between language skills and nonverbal cognition and working memory (Adams & Gathercole, 2000; Blom & Boerma, 2020; Botting & Conti-Ramsden, 2001; Marton, 2008; Thordardottir, 2008; Vugs et al., 2013; Vugs et al., 2017), and evidence

suggesting differences in how children with DLD draw on language and nonverbal skills relative to TD peers (Arslan et al., 2020; Botting et al., 2013; Blom & Boerma, 2019; Larson et al., 2019). I predicted that attentional abilities would be related to working memory performance (Kapa et al., 2017; Marton, 2008; Munakata et al., 2011; Schul et al., 2004; Smolak et al., 2020), and this relationship would reflect temporal strengths or weaknesses during the task (Oberauer et al., 2012). I did not predict group differences in this relationship, although the DLD group is likely to have greater overall weakness in attention and therefore maintaining serial properties of recall items (Ebert & Kohnert, 2011; Kapa et al., 2017; Redmond & Ash, 2014; but see Smolak et al., 2020 for evidence of correlations between selective sustained attention and working memory in a DLD group, but not in a TD group).

Methods

See Chapter 2 for participant information and working memory task design and analysis.

Sentence Comprehension Task

My sentence comprehension task included auditory and visual stimuli adapted with permission from Robertson and Joanisse (2010; see also Robertson & Gallant, 2019). I asked participants to match one of four visually presented pictures with the auditorily presented sentence. There were 3 practice trials with feedback followed by 15 experimental trials. Of the stimuli provided, I randomly assigned 15 sentences to experimental trials. Five of these sentences were created by Robertson and Gallant (2010) to act as fillers so that participants did not learn the pattern of the relationship between active and passive sentences (e.g., *"This is the orange circle that is to the left of the green rectangle."*). For the active and passive sentences (N = 10), each sentence was paired with four images: 1) the target image; 2) a subject-object

reversal image (i.e., syntactic distractor); 3) an incorrect adjective image (i.e., adjective distractor); and 4) a subject-object reversal and incorrect adjective image. For instance, *"The boy in the dark blue pants waves at the man in the light grey shirt."* is an active sentence which may be paired with the syntax distractor image of a man waving at a boy, the adjective distractor image of a man with a blue shirt, and both the syntax and adjective distractors in an image. See Robertson and Joanisse (2010) for additional information and example images. The active and passive experimental sentences were 4152ms and filler sentences were 3274ms in duration. The experimental sentences disambiguated upon verb or adjective presentation at 3050ms, thus reaction time values at 3200ms or greater were retained for further analysis. Participants had 12,000ms to respond prior to the onset of the subsequent trial. I used each participant's average accuracy on sentence comprehension trials as my linguistic predictor of working memory performance.

Continuous Processing Task

This sustained attention task was adapted with permission from Finneran et al. (2009). I modified the task to be run using the current version of E-Prime (E-Prime 3; Psychology Software Tools) which allowed us to convert it to an E-Prime Go file format. There are no meaningful differences between my procedures and those of Finneran et al. (2009). Participants were instructed to click on the orange circles (target) and to *not* click on the orange squares (distractor). Circles and squares were similar in size on the laptop screen and were presented for 400ms in a pseudorandomized order. Consistent with Finneran et al. (2009), I presented two event rates: 10 tokens per minute (slow) and 40 tokens per minute (fast). Participants completed the slow event rate followed by the fast event rate and both conditions involved presentation of 40% targets and 60% distractors. Thus, there was a total of 20 targets and 30 distractors in the

slow condition and 80 targets and 120 distractors in the fast condition over the two 5-minute testing periods. Unlike Finneran et al. (2009), I did not repeat the slow condition on consecutive days given that I were not examining how performance varied over 1-minute intervals between the slow and fast rate conditions. Therefore, I did not need the number of tokens to be matched between event rate conditions at each 1-minute epoch. Data were analyzed for accuracy using signal detection theory (see Finneran et al., 2009 and Spaulding, Plante, & Vance, 2008). According to this approach, correct responses to targets (circles) are considered *hits* and incorrect responses to distractors (squares) are considered *false alarms*. Accuracy is the z-score of the hit rate minus the z-score of the false alarm rate (i.e., *d'* or d-prime).

Relative Importance of Each Individual Differences Predictor

My final analytic step was to examine the relative importance of the individual differences predictors: sentence comprehension, matrix reasoning, and attention. For example, it is possible that matrix reasoning would predict working memory performance across conditions, given the close relationship between working memory and fluid intelligence (Kane et al., 2004; Vugs et al., 2017), and sentence comprehension would not explain substantive additional variance. In this scenario, I would expect to identify a model of working memory that included matrix reasoning and did not include sentence comprehension.

I used the Bayesian information criterion (BIC) and leave-one-out-cross-validation information criterion (LOOIC) to compare combinations of these predictors with the goal of selecting the model with the best performance. The BIC is a derivation of the Bayesian posterior probability of a given model, and the model with the smallest BIC corresponds to the model that is most probable based on the data (Neath & Cavanaugh, 2012). Leave-one-out-cross-validation

involves leaving a single observation out of the dataset, using the remaining observations to predict the eliminated observation, and completing this process, in turn, for all observations in the dataset. The LOOIC is a derivation of the predictive accuracy of the leave-one-out-cross-validation, and the model with the smallest LOOIC corresponds to the model with the greatest predictive accuracy (Kass & Raftery, 1995). See Table 5.2 for complete BIC and LOOIC results. Note that I also included age and SES as predictors in these models under the assumption I have adopted across analyses that these factors are important.

Results

Performance on Individual Differences Tasks

The DLD group performed significantly more poorly than the TD group on the sentence comprehension ($b = 0.19$; t-value = 4.64; $p < .001$; $r^2 = 0.28$), matrix reasoning ($b = 11.95$; t-value = 4.17; $p < .001$; $r^2 = 0.24$), and attention task ($b = 0.55$; t-value = 3.87; $p < .001$; $r^2 = 0.21$). See Table 5.1.

Table 5.1 Descriptive statistics and by-group t-tests for language processing, nonverbal cognition, and attention.

Condition	TD ($n = 34$)	DLD ($n = 21$)	p-value
Sentence Comprehension	M = 0.84 SD = 0.11	M = 0.65 SD = 0.19	TD>DLD*** ($r^2 = 0.28$)
Matrix Reasoning (WASI-II)	M = 58.00 SD = 9.50	M = 46.05 SD = 11.23	TD>DLD*** ($r^2 = 0.24$)
Attention (CPT)	M = 1.24 SD = 0.55	M = 0.68 SD = 0.43	TD>DLD*** ($r^2 = 0.21$)

Note. CPT = Continuous Processing Task, ds'; M = mean; SD = standard deviation; *$p < .05$, **$p < .01$, ***$p < .001$.

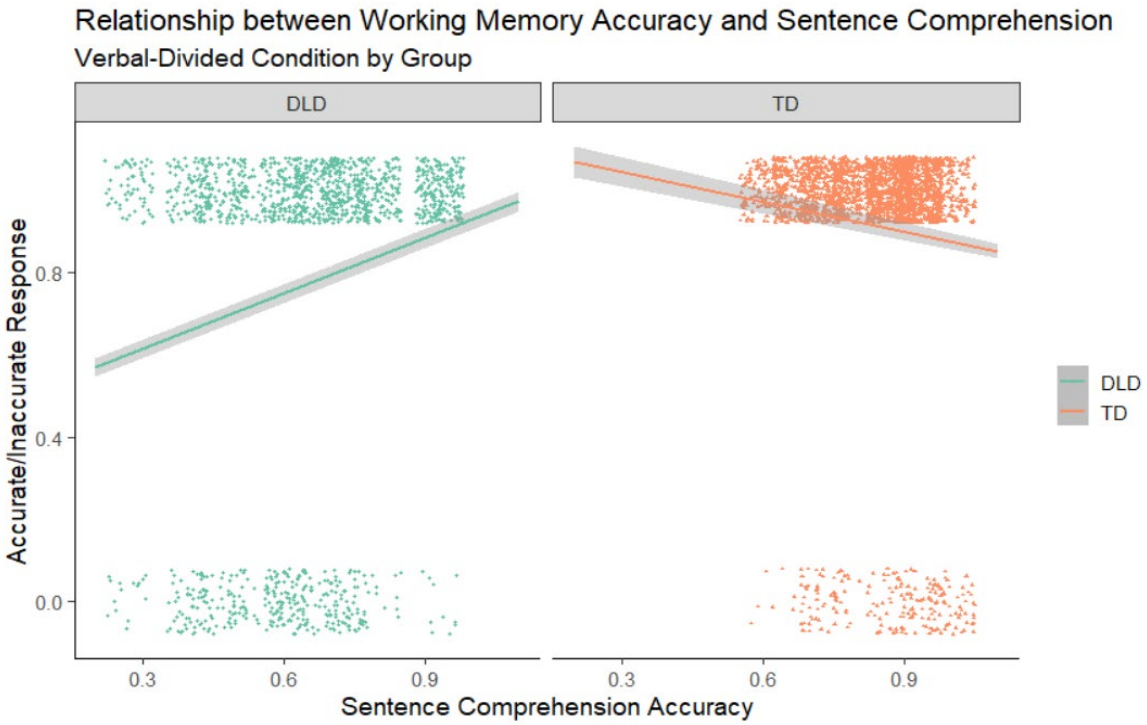
See Appendix D Table D.1 for complete multiple imputation mixed-effects model results for individual differences predictors and working memory task conditions.

Language Processing

Accuracy

For the verbal-within condition, there were no significant effects of sentence comprehension, group, the group by sentence comprehension interaction, or SES (p's > .17). After removing chance-level performance, all results remained the same. For the verbal-divided condition, there was no significant effect of sentence comprehension (p = .12). There was a significant effect of group (b = -7.61; stat = -2.96; p < .01), indicating worse odds of a correct response by a factor of 2022.84 for the DLD group than the TD group, and a significant group by sentence comprehension interaction (b = 8.10; chi-sq = 2.54; p < .05). There was no significant effect of SES (p = .43). Follow-up analyses showed a significant effect of sentence comprehension for the DLD group (b = 4.01; stat = 2.50; p < .05), indicating relatively better sentence comprehension was associated with better odds of a correct response by a factor of 55.3, and a significant effect of sentence comprehension for the TD group (b = -3.95; stat = -4104.44; p < .001), indicating relatively better sentence comprehension was associated with worse odds of a correct response by a factor of 51.7. After removing chance-level performance, all results remained the same. See Figure 5.1. For the nonverbal-within condition, there were no significant effects of sentence comprehension, group, the group by sentence comprehension interaction, or SES (p's > .13). For the nonverbal-divided condition, there were no significant effects sentence comprehension, group, the group by sentence comprehension interaction, or SES (p's > .14). I conducted follow up analyses based on descriptive performance patterns. These

analyses showed a significant effect of sentence comprehension in the DLD group (b = 3.99; stat = 2.06; p < .05), indicating relatively better sentence comprehension was associated with better odds of a correct response by a factor of 54.1, and no significant effect of sentence comprehension in the TD group (p = .78). After removing chance-level performance, all results remained the same. For the distributed condition, there was a significant effect of sentence comprehension (b = 4.53; stat = 2.22; p < .05), indicating that relatively better sentence comprehension was associated with better odds of a correct response by a factor of 92.7, and no significant effect of group, the group by sentence comprehension interaction, or SES (p's > .62). After removing chance-level performance, all results remained the same.



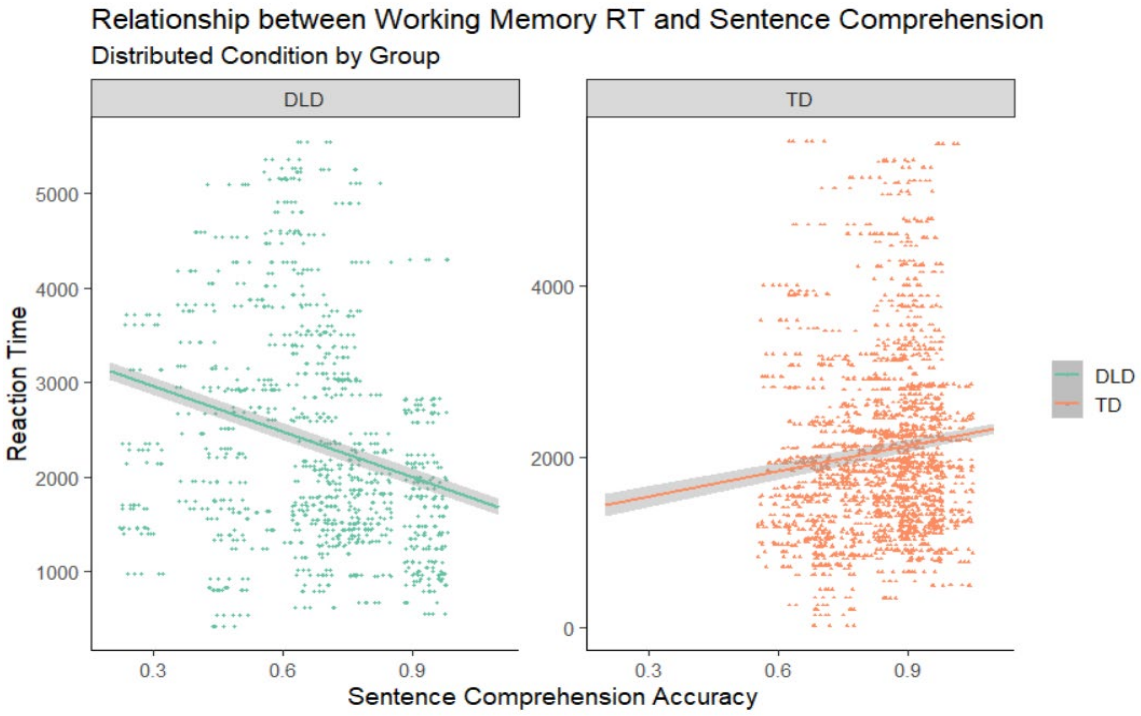
Note. Data points are jittered.

Figure 5.1. The significant relationship between sentence comprehension and accuracy for the DLD group relative to the lack of significant relationship between sentence comprehension and accuracy for the TD group in the verbal divided-domain condition.

Reaction Time

For the verbal-within condition, there was no significant effect of sentence comprehension, group, the group by sentence comprehension interaction, or SES (p's > .07). After removing chance-level performance, all results remained the same. For the verbal-divided condition, there was no significant effect of sentence comprehension, group, the group by sentence comprehension interaction, or SES (p's > .06). I conducted follow up analyses based on descriptive performance patterns. These analyses showed a significant effect of sentence comprehension in the DLD group (b = -1133.93; stat = -2.06; p < .05), indicating relatively better sentence comprehension was associated with faster RT, and no significant effect of sentence comprehension in the TD group (p = .62). After removing chance-level performance, all results remained the same, but the group by sentence comprehension interaction was significant when excluding the DLD participant with slightly higher standardized language scores (see Chapter 2). For the nonverbal-within condition, there was no significant effect of sentence comprehension, group, the group by sentence comprehension interaction, or SES (p's > .15). After removing chance-level performance, all results remained the same. For the nonverbal-divided condition, there was no significant effect of sentence comprehension, group, the group by sentence comprehension interaction, or SES (p's > .19). I conducted follow up analyses based on descriptive performance patterns. These analyses showed a significant effect of sentence comprehension in the DLD group (b = -1936.63; stat = -2.43; p < .05), indicating relatively better sentence comprehension was associated with faster RT, and no significant effect of sentence comprehension in the TD group (p = .87). After removing chance-level performance, all results remained the same. For the distributed condition, there was no significant effect of sentence comprehension (p = .28). There was a significant effect of group (b = 2682.90; stat =

2.90; $p < .01$), indicating slower RT for the DLD group than the TD group, and a significant group by sentence comprehension interaction (b = -3185.35; stat = -2.71; $p < .01$). There was no significant of SES ($p = .59$). Follow-up analyses showed a significant effect of sentence comprehension in the DLD group (b = -2294.18; stat = -2.59; $p < .05$), indicating relatively better sentence comprehension was associated with faster RT, and no significant effect of sentence comprehension in the TD group ($p = .25$). After removing chance-level performance, all results remained the same. See Figure 5.2 and Appendix D Table D.1 for complete output.



Note. Data points are jittered.

Figure 5.2. The significant group by sentence comprehension interaction for RT in the distributed condition.

Nonverbal Cognition

Accuracy

For the verbal-within condition, there was no significant effect of matrix reasoning ($p = .92$). There was a significant effect of group ($b = -5.76$; stat = -2.22; $p < .05$), indicating worse odds of a correct response by a factor of 317.5 for the DLD group, and no significant group by matrix reasoning interaction or significant effect of SES (p's $> .11$). I conducted follow up analyses based on descriptive performance patterns. These analyses showed a significant effect of matrix reasoning in the DLD group ($b = 0.08$; stat = 3.15; $p < .01$), indicating relatively better matrix reasoning was associated with better odds of a correct response by a factor of 1.1, and no significant effect of matrix reasoning in the TD group ($p = .94$). After removing chance-level performance, all results remained the same. For the verbal-divided condition, there was no significant effect of matrix reasoning ($p = .76$). There was a significant effect of group ($b = -6.41$; stat = -2.73; $p < .001$), indicating worse odds of a correct response by a factor of 604.9 for the DLD group than the TD group, and a significant group by matrix reasoning interaction ($b = 0.10$; stat = 2.34; $p < .05$). There was no significant effect of SES ($p = .41$). Follow-up analyses showed a significant effect of matrix reasoning for the DLD group ($b = 0.09$; stat = 3.31; $p < .01$), indicating that relatively better matrix reasoning was associated with better odds of a correct response by a factor of 1.1, and no significant effect of matrix reasoning for the TD group ($p = .69$). After removing chance-level performance, all results remained the same. For the nonverbal-within condition, there was a significant effect of matrix reasoning ($b = 0.11$; stat = 3.91; $p < .001$), indicating that relatively better matrix reasoning was associated with better odds of a correct response by a factor of 1.1, and no significant effect of group, the group by matrix reasoning interaction, or SES (p's $> .07$). After removing chance-level performance, all results

remained the same. For the nonverbal-divided condition, there was no significant effect of matrix reasoning, group, the group by matrix reasoning interaction, or SES (p's > .09). I conducted follow up analyses based on descriptive performance patterns. These analyses showed a significant effect of matrix reasoning in the DLD group (b = 0.09; stat = 3.16; p < .01), indicating relatively better matrix reasoning was associated with better odds of a correct response by a factor of 1.1, and no significant effect of matrix reasoning in the TD group (p = .58). After removing chance-level performance, all results remained the same. For the distributed condition, there was no significant effect of matrix reasoning, group, the group by matrix reasoning interaction, or SES (p's > .12). I conducted follow up analyses based on descriptive performance patterns. These analyses showed a significant effect of matrix reasoning in the DLD group (b = 0.09; stat = 3.50; p < .001), indicating relatively better matrix reasoning was associated with better odds of a correct response, and no significant effect of matrix reasoning in the TD group (p = .18). After removing chance-level performance, all results remained the same.

Reaction Time

For the verbal-within condition, there was no significant effect of matrix reasoning, group, the group by matrix reasoning interaction, or SES (p's > .34). After removing chance-level performance, all results remained the same. For the verbal-divided condition, there was no significant effect of matrix reasoning, group, the group by matrix reasoning interaction, or SES (p's > .16). After removing chance-level performance, all results remained the same. For the nonverbal-within condition, there was no significant effect of matrix reasoning, group, the group by matrix reasoning interaction, or SES (p's > .15). After removing chance-level performance, all results remained the same. For the nonverbal-divided condition, there was a significant effect of matrix reasoning, indicating that relatively better matrix reasoning was associated with faster

RT (b = -29.61; stat = -2.25; p < .05), and there was no significant effect of group, the group by matrix reasoning interaction, or SES (p's > .38). I conducted follow up analyses based on descriptive performance patterns. These analyses showed no significant effect of matrix reasoning in the DLD group (p = .23), and a significant effect of matrix reasoning in the TD group (b = -27.61; stat = -2.26; p < .05), indicating relatively better matrix reasoning was associated with faster RT. After removing chance-level performance, all results remained the same. For the distributed condition, there was no significant effect of matrix reasoning (p = .08). There was a significant effect of group, indicating slower RT for the DLD group than the TD group (b = 1643.60; stat = 2.21; p < .05), and a significant group by matrix reasoning interaction (b = -30.04; stat = -2.15; p < .05; see Figure 4). There was no significant effect of SES (p = .23). Follow-up analyses showed a significant effect of matrix reasoning for the DLD group (b = -45.72; stat = -4.32; p < .001), indicating that relatively better matrix reasoning was associated with faster RT, and no significant effect of matrix reasoning for the TD group (p = .11). After removing chance-level performance, all results remained the same. See Appendix D Table D.1 for complete output.

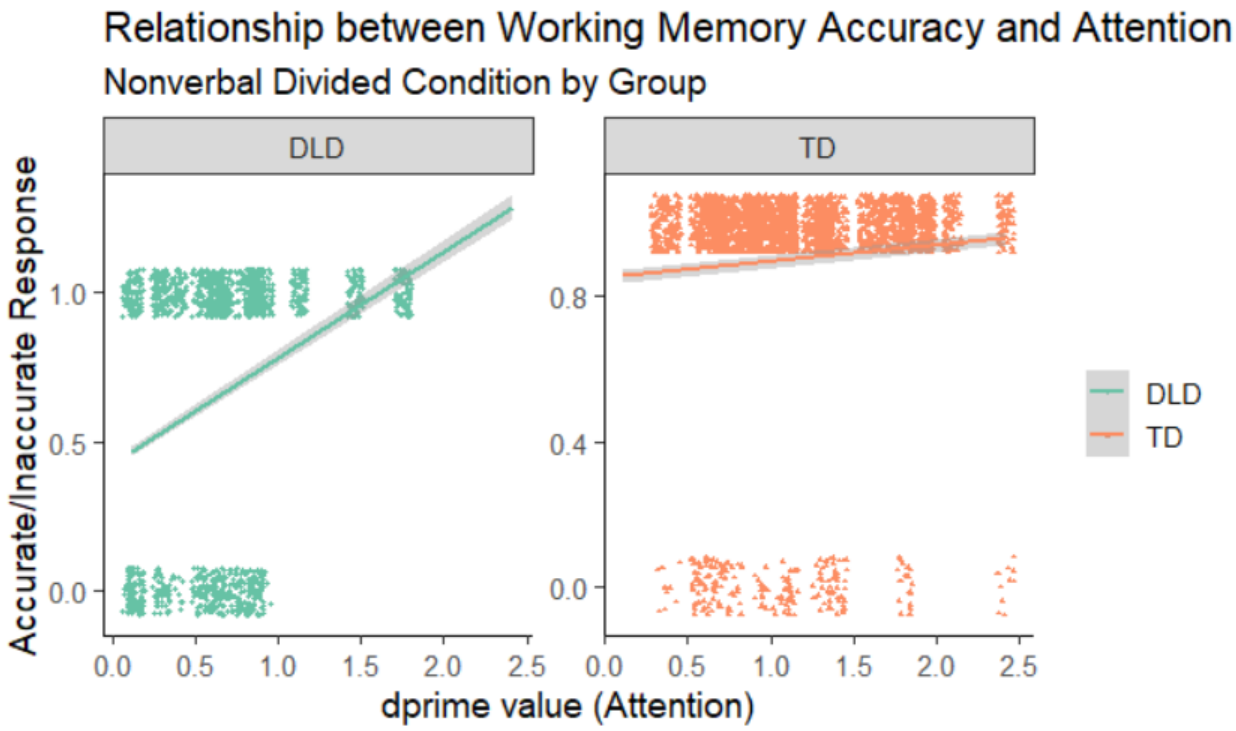
Attention

Accuracy

For the verbal-within condition, there was a significant effect of attention (b = 1.22; stat = 2.20; p < .05), indicating that relatively better attention was associated with better odds of a correct response by a factor of 3.4, and a significant effect of group (b = -1.92; stat = -1.97; p < .05), indicating worse odds of a correct response by a factor of 6.8 for the DLD than TD group. There was no significant group by attention interaction or significant effect of SES (p's > .09).

After removing chance-level performance, all results remained the same. For the verbal-divided condition, there was no significant effect of attention ($p = .34$). There was a significant effect of group ($b = -3.09$; stat = -3.05; $p < .01$), indicating worse odds of a correct response by a factor of 22.0 for the DLD group than the TD group, and no significant group by attention interaction or significant effect of SES (p's $> .06$). After removing chance-level performance, all results remained the same. For the nonverbal-within condition, there was no significant effect of attention, group, the group by attention interaction, or SES (p's $> .07$). I conducted follow up analyses based on descriptive performance patterns. These analyses showed a significant effect of attention in the DLD group ($b = 2.03$; stat = 3.06; $p < .01$), indicating relatively better attention was associated with better odds of a correct response by a factor of 7.6, and no significant effect of attention in the TD group ($p = .20$). After removing chance-level performance, all results remained the same. For the nonverbal-divided condition, there was no significant effect of attention ($p = .12$). There was a significant effect of group ($b = -3.32$; stat = -3.37; $p < .001$), indicating worse odds of a correct response by a factor of 27.8 for the DLD group than the TD group, and a significant group by attention interaction ($b = 2.60$; stat = 2.51; $p < .05$, see Figure 5). There was no significant effect of SES ($p = .25$). Follow-up analyses showed a significant effect of attention in the DLD group ($b = 3.35$; stat = 4.23; $p < .001$), indicating that relatively better attention was associated with better odds of a correct response by a factor of 28.6, and no significant effect of attention in the TD group ($p = .14$). After removing chance-level performance, all results remained the same. See Figure 5.3. For the distributed condition, there was a significant effect of attention ($b = 1.42$; stat = 3.15; $p < .01$), indicating that relatively better attention was associated with better odds of a correct response by a factor of

1.0, and no significant effect of group, the group by attention interaction, or SES (p's > .41). After removing chance-level performance, all results remained the same.



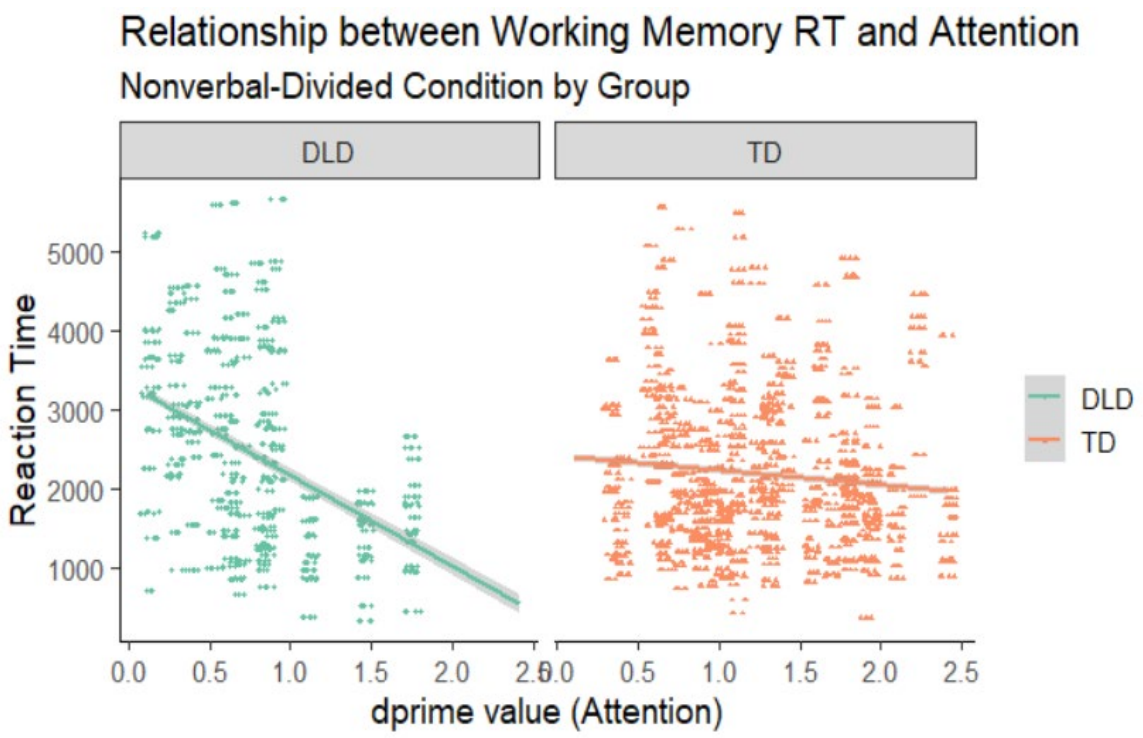
Note. Data points are jittered.

Figure 5.3. The significant group by attention interaction for accuracy in the nonverbal-divided condition.

Reaction Time

For the verbal-within condition, there was a significant effect of attention (b = -458.02; stat = -3.68; p < .001), indicating relatively better attention was associated with faster RT, and there was no significant effect of group, the group by attention interaction, or SES (p's > .42). I conducted follow up analyses based on descriptive performance patterns. These analyses showed no significant effect of attention in the DLD group (p = .18), and a significant effect of attention in the TD group (b = -465.73; stat = -4.10; p < .001), indicating relatively better attention was

associated with faster RT. After removing chance-level performance, all results remained the same. For the verbal-divided condition, there was no significant effect of attention, group, the group by attention interaction, or SES (p's > .05). After removing chance-level performance, all results remained the same. For the nonverbal-within condition, there was no significant effect of attention, group, the group by attention interaction, or SES (p's > .10). I conducted follow up analyses based on descriptive performance patterns. These analyses showed a significant effect of attention in the DLD group (b = -652.48; stat = -2.61; p < .01), indicating relatively better attention was associated with faster RT, and no significant effect of attention in the TD group (p = .40). After removing chance-level performance, all results remained the same. For the nonverbal-divided condition, there was no significant effect of attention (p = .21). There was a significant effect of group (b = 873.08; stat = 2.12; p < .05), indicating slower RT for the DLD group than the TD group, a significant interaction between group and attention (b = -1000.74; stat = -2.42; p < .05). There was no significant effect of SES (p = .47). Follow-up analyses showed a significant effect of attention in the DLD group (b = -1254.83; stat = -3.98; p < .001), indicating relatively better attention was associated with faster RT, and no significant effect of attention in the TD group (p = .25). After removing chance-level performance, all results remained the same. See Figure 5.4. For the distributed condition, there was no significant effect of attention, group, the group by attention interaction, or SES (p's > .09). After removing chance-level performance, all results remained the same. See Appendix D Table D.1 for complete output.



Note. Data points are jittered.

Figure 5.4. The significant group by attention interaction for RT in the nonverbal-divided condition.

Relative Importance of Each Individual Differences Predictor

Accuracy

For the verbal-within condition, the DLD group best performing model included matrix reasoning (BIC = 1523.6) and the best prediction model included sentence comprehension or d-prime (LOOIC = 1506.9), and the TD group best performing model included d-prime (BIC = 1517.1) and the best prediction model included matrix reasoning (LOOIC = 948.3). For the verbal-divided condition, the DLD group best performing model included sentence comprehension (BIC = 1372.2) and the best prediction model included sentence comprehension (LOOIC = 1325.0), and the TD group best performing model included sentence comprehension

(BIC = 1251.6) and the best prediction model included sentence comprehension and matrix reasoning (LOOIC = 227.5). For the nonverbal-within condition, the DLD group best performing model included d-prime (BIC = 1549.6) and the best prediction model included d-prime (LOOIC = 1553.1), and the TD group best performing model included matrix reasoning (BIC = 1708.6) and the best prediction model included d-prime (LOOIC = 1322.2). For the nonverbal-divided condition, the DLD group best performing model included d-prime (BIC = 1477.7) and the best prediction model included d-prime (LOOIC = 1485.0), and the TD group best performing model included d-prime (BIC = 1338.4) and the best prediction model included matrix reasoning (LOOIC = 622.9). For the distributed condition, the DLD group best performing model included sentence comprehension and matrix reasoning (BIC = 1382.1) and the best prediction model included sentence comprehension (LOOIC = 1353.5), and the TD group best performing model included d-prime (BIC = 1614.5) and the best prediction model included d-prime (LOOIC = 1078.5).

Reaction Time

For the verbal-within condition, the DLD group best performing model included sentence comprehension or matrix reasoning (BIC = 16348) and the best prediction model included sentence comprehension (LOOIC = 16282.0), and the TD group best performing model included d-prime (BIC = 36840) and the best prediction model included d-prime (LOOIC = 36738.1). For the verbal-divided condition, the DLD group best performing model included d-prime (BIC = 19016) and the best prediction model included d-prime (LOOIC = 18946.4), and the TD group best performing model included sentence comprehension (BIC = 38172) and the best prediction model included d-prime (LOOIC = 38071.0). For the nonverbal-within condition, the DLD group best performing model included matrix reasoning (BIC = 17418) and the best prediction

model included sentence comprehension, matrix reasoning, and d-prime (LOOIC = 17338.6), and the TD group best performing model included matrix reasoning (BIC = 35859) and the best prediction model included sentence comprehension, matrix reasoning, and d-prime (LOOIC = 35737.7). For the nonverbal-divided condition, the DLD group best performing model included d-prime (BIC = 16780) and the best prediction model included d-prime (LOOIC = 16700.3), and the TD group best performing model included matrix reasoning (BIC = 36992) and the best prediction model included sentence comprehension (LOOIC = 36855.0). For the distributed condition, the DLD group best performing model included matrix reasoning (BIC = 18828) and the best prediction model included d-prime or sentence comprehension and matrix reasoning (LOOIC = 18748.1), and the TD group best performing model included sentence comprehension or matrix reasoning (BIC = 37602) and the best prediction model included sentence comprehension (LOOIC = 37490.1). See Table 5.2.

Table 5.2. Model selection results. All models also include age and SES. Note that multiple imputation mixed-effects model *p*-values are included in this table in order to integrate model selection and statistically significant findings.

Condition	Model	BIC	LOOIC	Selected Model	*p*-value
Verbal Within					
Accuracy – DLD Group					
	Sentence Comprehension	1527.4	1506.9	LOOIC	NS
	Matrix Reasoning	1523.6	1507.8	BIC	< .01
	d'	1526.0	1506.9	LOOIC	< .05†
	Sentence Comprehension + Matrix Reasoning	1530.9	1507.3		
	Sentence Comprehension + Matrix Reasoning + *d'*	1535.1	1507.5		
Accuracy – TD Group					
	Sentence Comprehension	1518.2	948.5		NS
	Matrix Reasoning	1518.9	948.3	LOOIC	NS
	d'	1517.1	949.1	BIC	< .05†
	Sentence Comprehension + Matrix Reasoning	1526.0	947.9		
	Sentence Comprehension + Matrix Reasoning + *d'*	1532.5	948.5		
Reaction Time – DLD Group					

	Sentence Comprehension	16348	16282.0	BIC/LOOIC	NS
	Matrix Reasoning	16348	16281.6	BIC	NS
	d'	16350	16281.2		NS
	Sentence Comprehension + Matrix Reasoning	16353	16281.5		
	Sentence Comprehension + Matrix Reasoning + *d'*	16360	16281.8		
Reaction Time – TD Group					
	Sentence Comprehension	36848	36738.3		NS
	Matrix Reasoning	36850	36738.7		NS
	d'	36840	36738.1	BIC/LOOIC	< .001
	Sentence Comprehension + Matrix Reasoning	36855	36739.0		
	Sentence Comprehension + Matrix Reasoning + *d'*	36854	36738.0		
Verbal Divided					
Accuracy – DLD Group					
	Sentence Comprehension	1372.2	1325.0	BIC/LOOIC	< .05 [x]
	Matrix Reasoning	1369.3	1325.4		< .01 [x]
	d'	1376.1	1325.6		NS
	Sentence Comprehension + Matrix Reasoning	1373.5	1325.4		
	Sentence Comprehension + Matrix Reasoning + *d'*	1380.8	1324.8		
Accuracy – TD Group					
	Sentence Comprehension	1251.6	228.8	BIC	< .001 [x]
	Matrix Reasoning	1254.7	229.0		NS [x]
	d'	1253.4	228.0		NS
	Sentence Comprehension + Matrix Reasoning	1259.3	227.5	LOOIC	
	Sentence Comprehension + Matrix Reasoning + *d'*	1264.2	228.3		
Reaction Time – DLD Group					
	Sentence Comprehension	19017	18945.9		< .05
	Matrix Reasoning	19018	18945.5		NS
	d'	19016	18946.4	BIC/LOOIC	NS
	Sentence Comprehension + Matrix Reasoning	19024	18945.7		
	Sentence Comprehension + Matrix Reasoning + *d'*	19030	18945.9		
Reaction Time – TD Group					
	Sentence Comprehension	38172	38071.2	BIC	NS
	Matrix Reasoning	38174	38071.8		NS
	d'	38174	38071.0	LOOIC	NS
	Sentence Comprehension + Matrix Reasoning	38177	38071.7		
	Sentence Comprehension + Matrix Reasoning + *d'*	38184	38071.6		
Nonverbal Within					
Accuracy – DLD Group					
	Sentence Comprehension	1553.8	1554.4		NS
	Matrix Reasoning	1553.5	1553.8		< .001†
	d'	1549.6	1553.1	BIC/LOOIC	< .01
	Sentence Comprehension + Matrix Reasoning	1559.6	1554.2		
	Sentence Comprehension + Matrix Reasoning + *d'*	1560.4	1553.3		

Accuracy – TD Group					
	Sentence Comprehension	1721.2	1322.6		NS
	Matrix Reasoning	1708.6	1322.6	BIC	< .001†
	d'	1720.3	1322.2	LOOIC	NS
	Sentence Comprehension + Matrix Reasoning	1715.7	1322.3		
	Sentence Comprehension + Matrix Reasoning + *d'*	1722.5	1323.4		
Reaction Time – DLD Group					
	Sentence Comprehension	17423	17338.7		NS
	Matrix Reasoning	17418	17339.2	BIC	NS
	d'	17421	17339.5		< .01
	Sentence Comprehension + Matrix Reasoning	17424	17339.5		
	Sentence Comprehension + Matrix Reasoning + *d'*	17426	17338.6	LOOIC	
Reaction Time – TD Group					
	Sentence Comprehension	35860	35739.7		NS
	Matrix Reasoning	35859	35739.3	BIC	NS
	d'	35860	35739.3		NS
	Sentence Comprehension + Matrix Reasoning	35866	35738.2		
	Sentence Comprehension + Matrix Reasoning + *d'*	35873	35737.7	LOOIC	
Nonverbal Divided					
Accuracy – DLD Group					
	Sentence Comprehension	1487.6	1485.4		< .05
	Matrix Reasoning	1485.5	1485.6		< .01
	d'	1477.7	1485.0	BIC/LOOIC	< .001 [x]
	Sentence Comprehension + Matrix Reasoning	1491.2	1485.6		
	Sentence Comprehension + Matrix Reasoning + *d'*	1480.2	1485.4		
Accuracy – TD Group					
	Sentence Comprehension	1342.4	624.4		NS
	Matrix Reasoning	1342.2	622.9	LOOIC	NS
	d'	1338.4	623.0	BIC	NS [x]
	Sentence Comprehension + Matrix Reasoning	1350.0	624.4		
	Sentence Comprehension + Matrix Reasoning + *d'*	1353.4	624.9		
Reaction Time – DLD Group					
	Sentence Comprehension	16782	16701.1		< .05
	Matrix Reasoning	16784	16700.7		NS
	d'	16780	16700.3	BIC/LOOIC	< .001
	Sentence Comprehension + Matrix Reasoning	16789	16700.7		
	Sentence Comprehension + Matrix Reasoning + *d'*	16791	16699.8		
Reaction Time – TD Group					
	Sentence Comprehension	36998	36855.0	LOOIC	NS
	Matrix Reasoning	36992	36855.2	BIC	< .05
	d'	36997	36855.3		NS
	Sentence Comprehension + Matrix Reasoning	37000	36854.4		
	Sentence Comprehension + Matrix Reasoning + *d'*	37007	36855.3		

Distributed					
Accuracy – DLD Group					
	Sentence Comprehension	1383.0	1353.5	LOOIC	< .05†
	Matrix Reasoning	1383.4	1354.1		< .01 [x]
	d'	1386.9	1354.5		< .01†
	Sentence Comprehension + Matrix Reasoning	1382.1	1353.9	BIC	
	Sentence Comprehension + Matrix Reasoning + *d'*	1385.7	1353.8		
Accuracy – TD Group					
	Sentence Comprehension	1618.9	1080.7		< .05†
	Matrix Reasoning	1618.7	1080.1		NS [x]
	d'	1614.5	1078.5	BIC/LOOIC	< .01†
	Sentence Comprehension + Matrix Reasoning	1624.9	1080.1		
	Sentence Comprehension + Matrix Reasoning + *d'*	1623.8	1080.0		
Reaction Time – DLD Group					
	Sentence Comprehension	18838	18749.1		< .05 [x]
	Matrix Reasoning	18828	18748.3	BIC	< .001 [x]
	d'	18839	18748.1	LOOIC	NS
	Sentence Comprehension + Matrix Reasoning	18835	18748.1	LOOIC	
	Sentence Comprehension + Matrix Reasoning + *d'*	18842	18748.5		
Reaction Time – TD Group					
	Sentence Comprehension	37602	37490.1	BIC/LOOIC	NS [x]
	Matrix Reasoning	37602	37491.2	BIC	NS [x]
	d'	37603	37490.9		NS
	Sentence Comprehension + Matrix Reasoning	37607	37490.7		
	Sentence Comprehension + Matrix Reasoning + *d'*	37614	37490.9		

Note. *d*' = d-prime on the continuous processing task (i.e., selective/sustained attention); Sentence Comprehension = Accuracy on the sentence comprehension task; Matrix Reasoning = t-score on the Matrix Reasoning subscale from the Wechsler Abbreviated Intelligence Scale, Second Edition (WASI-II); Log-score Stacking = each model's predictive log score (i.e., the weighted combination of predictions from all specified models); LOOIC = Leave-one-out cross validation information criterion; *p*-value = *p*-value from multiple imputation mixed effects models; [x]indicates a significant group by predictor interaction; †indicates the effect was significant across groups.

Discussion

I examined how individual differences in verbal, nonverbal, and attentional abilities relate to working memory performance in children with DLD relative to age-matched TD peers using the serial-order-in-a-box – complex span model as my theoretical framework. The experimental paradigm varied the domain of an interference processing task and recall items in order to examine how individual differences predict the effects of interference. My first

analytical step was to characterize these relationships via statistical models and my final analytical step was to compare the relative importance among individual differences predictors in accounting for working memory performance. I used model selection information to determine which model had the best performance given my data and the best ability to predict performance beyond my data. In order to interpret results, I will integrate statistically significant findings with predictors found to be important based on model selection, focusing on relationships where groups present with different patterns. See Table 5.3 for hypothesis confirmation information.

I hypothesized group differences in relationships between working memory performance and verbal, nonverbal, and attentional abilities (See Table 5.3 for information on hypotheses confirmation). I measured verbal abilities using a language processing task, nonverbal abilities using a nonverbal cognition subscale, and attention using a continuous processing task. I predicted a stronger relationship between nonverbal cognition and performance on verbal working memory tasks (i.e., word recall) for the DLD group, and a stronger relationship between language processing and performance nonverbal working memory tasks (i.e., shape location recall) for the TD group. I found that these predictions were borne out in the data for nonverbal cognition, but not for language processing. I also predicted that attention, as measured by a continuous processing task, would be related to working memory performance regardless of the domain of task demands, potentially reflecting relative abilities in temporal processing. This prediction was borne out in the data based on the finding that attention was important for nonverbal recall in the DLD group and for verbal recall in the TD group. These patterns align with prior work indicating temporal processing weakness in DLD that may be related to their deficits in verbal processing (Lukács & Kemény, 2015; Mayor-Dubois, Zesiger, van der Linden, & Roulet-Perez, 2014; Tallal et al., 1996).

Table 5.3. Hypothesis Confirmation

Hypothesis	Result	Confirmed - Statistically		Confirmed - Importance	
		Acc	RT	DLD	TD
Verbal-within	*Verbal-within*				
Sentence Comprehension*Group		-	-	-	-
Matrix Reasoning*Group	Matrix Reasoning*Group	+/-	-	-	-
Continuous Processing Task*Group	Continuous Processing Task*Group	+/-	+/-	-	+
Verbal-divided	*Verbal-divided*				
Sentence Comprehension*Group	Sentence Comprehension*Group	+*	+/-	+	+
Matrix Reasoning*Group	Matrix Reasoning*Group	+*	-	-	-
Continuous Processing Task*Group		-	-	-	-
Nonverbal-within	*Nonverbal-within*				
Sentence Comprehension*Group		-	-	-	-
Matrix Reasoning*Group	Matrix Reasoning*Group	+/-	-	-	-
Continuous Processing Task*Group	Continuous Processing Task*Group	+/-	+/-	+	-
Nonverbal-divided	*Nonverbal-divided*				
Sentence Comprehension*Group	Sentence Comprehension*Group	+/-	+/-	-	-
Matrix Reasoning*Group	Matrix Reasoning*Group	+/-	+/-	-	-
Continuous Processing Task*Group	Continuous Processing Task*Group	+*	+*	+	-
Distributed	*Distributed*				
Sentence Comprehension*Group	Sentence Comprehension*Group	-	+*	+/-	+/-
Matrix Reasoning*Group	Matrix Reasoning*Group	+/-	+*	+	-
Continuous Processing Task*Group	Continuous Processing Task	-	-	-	+

Note. Sentence Comprehension = verbal ability measure; Matrix Reasoning = nonverbal ability measure; Continuous Processing Task = attention measure; * indicates a significant group difference in the relationship between the predictor and outcome measure; - indicates that the hypothesis was not confirmed; + indicates that the hypothesis was confirmed; +/- indicates that the hypothesis was partially confirmed; Acc = Recall accuracy; RT = Recall reaction time.

When considering model selection and statistically significant patterns for the DLD group, I demonstrated an important role for language processing with verbal-divided accuracy (i.e., nonverbal interference and verbal recall), and an important role for nonverbal cognition with distributed reaction time (i.e., verbal-nonverbal interference and recall). I also showed an important role for attention for nonverbal-divided performance (i.e., verbal interference and nonverbal recall) and nonverbal-within accuracy (i.e., nonverbal interference and nonverbal recall). When considering model selection and statistically significant patterns for the TD group, I demonstrated an important, but negative, role for language processing with verbal-divided

accuracy, and an important role for nonverbal cognition for nonverbal-divided reaction time. I also showed an important role for attention for verbal-within reaction time (i.e., verbal interference and recall) and distributed accuracy. Beyond these relationships, there was modest evidence of a group difference in the relationship between language processing and distributed reaction time, suggesting a facilitative relationship in the DLD group, but not the TD group. Interestingly, there was little evidence suggesting that multiple individual differences predictors (e.g., language processing *and* nonverbal cognition) explained performance to a greater degree than a single predictor (e.g., language processing).

My key findings suggest positive role for nonverbal cognition in performance on tasks with verbal-nonverbal interference and recall (i.e., auditory-word location judgment + word-image location recall) in DLD, but in performance on tasks with verbal interference and nonverbal recall (i.e., nonword judgment + shape location) in TD peers. The role of language processing was less straightforward. There was a positive role for language processing in performance on tasks with nonverbal interference and verbal recall for the DLD group, and a negative role for language processing in performance on tasks with nonverbal interference and verbal recall for the TD group. There was also modest evidence of a positive role for language processing in performance on tasks with verbal-nonverbal interference and recall in the DLD group, but not the TD group. Thus, the DLD group drew upon language processing and nonverbal cognition to facilitate performance with mixed-domain tasks. The TD group also drew upon language processing and nonverbal cognition, but appeared to draw on language processing regardless of whether language processing facilitated performance. With regard to attention, children with DLD drew upon attention to facilitate nonverbal recall (i.e., shape location),

whereas the TD group drew upon attention to facilitate verbal recall (i.e., words) and verbal-nonverbal recall (i.e., word-image location). This group difference may underscore an important factor in verbal processing difficulty in DLD.

Individual Differences and Working Memory in DLD

Language Processing versus Nonverbal Cognition

My findings broadly align with prior work demonstrating relationships between individual differences in language and nonverbal cognition skills and performance on processing tasks in children with DLD (Adams & Gathercole, 2000; Blom & Boerma, 2020; Botting & Conti-Ramsden, 2001; Marton, 2008; Thordardottir, 2008; Vugs et al., 2013; Vugs et al., 2017), as well as with prior work showing differences in these relationships in children with DLD relative to TD peers (Arslan et al., 2020; Botting et al., 2013; Blom & Boerma, 2019; Larson et al., 2019). Specifically, prior research suggests that children with DLD recruit nonverbal cognition (e.g., using eye gaze to 'placehold' a location) to engage in tasks that draw on processing (Arslan et al., 2020; Botting et al., 2013; Blom & Boerma, 2019; Larson et al., 2019), consistent with the current findings. There is ample evidence of associations between language processing and performance on verbal working memory tasks (Archibald & Gathercole, 2006, 2007; Ellis Weismer et al., 1999; Montgomery et al., 2010; Thordardottir, 2008; Vugs et al., 2017) and nonverbal working memory tasks (Vugs et al., 2013; Smolak et al., 2020; Windsor et al., 2008; Vugs et al., 2013) in children with DLD. There is some evidence that these relationships differ from TD peers, such as group differences in predictive relationships between language processing and an executive function composite measure (i.e., includes working memory; Blom & Boerma, 2019) and inhibition (i.e., related to working memory performance

per the SOB-CS model; Larson, Kaplan, et al., 2020), and group differences in the use of verbal strategies on a visual short-term memory task (Arslan et al., 2020). I also showed DLD versus TD group differences in the effect of interference, especially verbal interference, on verbal and nonverbal recall (Chapter 3) and the role of *free time* (i.e., the active-removal mechanism governing the effect of interference under the SOB-CS model; Oberauer et al., 2012) in performance on verbal recall tasks (Chapter 4). In fact, evidence from neuroimaging studies suggests that children with DLD have different neural activation patterns than TD peers, potentially reflecting adaptive use of intact versus impaired pathways (Ellis Weismer et al., 2005; Herbert et al., 2005; Njiokiktjien et al., 2001).

Also consistent with the current findings, TD children have been shown to draw on language skills (e.g., self-talk) to engage in tasks that draw on processing (Alderson-Day & Fernyhough, 2015; Arslan et al., 2020; Fatzer & Roebers, 2012; Larson et al., 2019; Marcovitch & Zelazo, 2009). The Hierarchical Competing Systems Model suggests that language, in the form of verbal mediation, underlies developmental advancement in goal-directed behavior (e.g., working memory, inhibition; Marcovitch & Zelazo, 2009). Nevertheless, when processing was divided between nonverbal interference and verbal recall in the current study, relatively better language processing was associated with poorer accuracy for the TD group. It is possible that verbal strategies did not facilitate performance on this task because the interference phase was nonverbal in nature, rather than each phase involving both verbal and nonverbal features. Additionally, there was modest evidence of DLD versus TD group differences in the relationship between language processing and reaction time on a task that involved verbal-nonverbal interference and recall. Specifically, there was a positive relationship for the DLD group and a negative relationship for the TD group. Convergingly, other work from my lab has shown a link

between relatively better language skills and slower planning (i.e., a complex goal-directed skill) on a nonverbal task for a TD group, yet a link between relatively better language skills and faster planning for a DLD group (Larson et al., 2019). These relationships were present in the absence of DLD versus TD group differences in accuracy on a task where group differences were anticipated based on prior work (e.g., Lidstone et al., 2012). These patterns suggest that verbal strategies may negatively affect reaction time and accuracy when a processing task involves nonverbal task demands.

The current findings coupled with prior work underscore a nuanced relationship between language processing and performance on tasks that draw on processing in children with DLD and TD peers. This relationship appears to differ depending on the domain of task demands and the measure of performance (e.g., accuracy versus reaction time), as well as DLD versus TD group status. Collectively, there appears to be a facilitative role for language processing and nonverbal cognition in DLD in the presence of verbal and nonverbal processing demands, suggesting that children with DLD recruit language processing and nonverbal cognition to facilitate performance (Arslan et al., 2020; Botting et al., 2013; Blom & Boerma, 2019; Ellis Weismer et al., 1999; Larson et al., 2019; Montgomery et al., 2010; Vugs et al., 2017). In contrast, the role of language processing may be primary for TD children, albeit a role that is not obviously facilitative. When TD children have slower reaction time on a task, this performance pattern may signal verbal strategy use which is thought to facilitate their performance accuracy (Fatzer & Roebers, 2012; Marcovitch & Zelazo, 2009), but may not actually be facilitative or may even be associated with poorer performance on tasks with nonverbal components (e.g., Larson et al., 2019).

Attention

For the DLD group, I found evidence of an important role for attention in performance on tasks with verbal interference and nonverbal recall (i.e., nonword judgment + shape location recall), and in performance on tasks with nonverbal interference and recall (i.e., face/nonface judgment + shape location recall). For the TD group, my findings supported an important role for attention and in performance on tasks with verbal interference and recall (i.e., nonword judgment + word recall) and in performance on tasks with verbal-nonverbal interference and recall (i.e., auditory word location judgment + word-image location recall). Notably, children with DLD drew upon attention for recall involving nonverbal items whereas TD peers drew upon attention for recall involving verbal items and verbal-nonverbal items.

Smolak et al. (2020) showed relationships among attention, language skills, and nonverbal working memory in children with DLD, but not TD peers. They argue for the possibility of a mediating role of attention in the relationship between nonverbal working memory and language skills. My findings are broadly consistent with this hypothesis. I showed that attention was important for inhibiting verbal interference during nonverbal working memory performance for children with DLD, and this link was present in the absence of a link between language processing and performance. I also showed an important role for attention in performance on tasks with nonverbal interference and recall. The link between attention and nonverbal recall may signal the use of attentional refreshing – a nonverbal strategy closely related to attention (Vergauwe & Langerock, 2017). Attentional refreshing brings an item into the focus of attention, thus increasing its temporal distinctiveness (i.e., serial order information; Cowan, 1988; 2010; Oberauer et al., 2012; Vergauwe & Langerock, 2017). In children with DLD, prior research posits a facilitative role of nonverbal strategies in general, but has not yet

examined attentional refreshing in particular, on tasks that draw on nonverbal processing (e.g., Arslan et al., 2020; Botting et al., 2013; Larson et al., 2019). Likewise, several studies link attention and working memory performance in DLD (Kapa et al., 2017; Marton, 2008; Schul et al., 2004), and many theories of working memory posit a key role for attention (Baddeley & Hitch 1994; Cowan, 2014; Oberauer et al., 2012). The current study also found modest evidence of a role for nonverbal cognition and performance on tasks involving nonverbal recall in my DLD group, further suggesting a stronger link between nonverbal and attentional strategies than verbal and attentional strategies.

In TD peers, attention appeared to be facilitative for verbal and verbal-nonverbal recall. This finding illustrates the possibility of better verbal recall performance for the DLD group if they recruited attention to a greater degree than observed in the current study. Prior work demonstrates relationships among attention, language, and working memory (Ebert & Kohnert, 2011; Marton, 2008; Smolak et al., 2020) and poor attention abilities in DLD (Mueller & Tomblin, 2012; Redmond & Ash, 2014). One interpretation of my findings for the TD group is that TD children drew upon attention under high temporal processing demands in order to facilitate performance. In fact, there was evidence of a negative relationship between language processing and performance with nonverbal interference and verbal recall in the TD group when attention did not appear to be as important to performance. These findings may reflect a mediating effect of attention on the relationship between language processing and performance on verbal working memory tasks. Indeed, attention is linked with temporal processing under the SOB-CS model (Oberauer et al., 2012), and verbal processing depends on temporal processing (Hsu & Bishop, 2011; Gillam, Cowan, & Day, 1995; Tallal et al., 1996).

Summary

Taken together, patterns related to language processing and nonverbal cognition suggest that children with DLD adaptively recruited intact versus impaired abilities to facilitate processing performance. In contrast, TD children may have recruited language processing regardless of whether language processing facilitated processing. Patterns related to attention suggest that children with DLD recruited attention on working memory tasks tapping a relatively less impaired domain, nonverbal working memory, but to a lesser degree on working memory tasks tapping a relatively more impaired domain, verbal working memory. Conversely, TD children appeared to recruit attention to facilitate performance on tasks tapping verbal working memory. These findings may highlight a key area of weakness in verbal processing for children with DLD. That is, attention may be recruited to a lesser degree in verbal than nonverbal processing in DLD, potentially contributing to their verbal processing difficulty.

Theoretical and Clinical Implications

The SOB-CS allows for the possibility of strategy use, although this model does not explicitly make claims about strategy use (e.g., verbal mediation). Instead, the roles of verbal, nonverbal, and attentional abilities under the SOB-CS model are related to the degree of distinctiveness in feature representation (Oberauer et al., 2012). Relative strengths in language processing are associated with high distinctiveness in verbal feature representation (e.g., sound patterns in words), relative strengths in nonverbal cognition are associated with high distinctiveness in nonverbal feature representation (e.g., location), and relative strengths in attention are associated with high distinctiveness in temporal feature representation (i.e., serial properties).

Findings for the DLD group align with the role of individual differences under the SOB-CS model. Relatively better language processing and nonverbal cognition were associated with relatively better performance on tasks involving verbal-nonverbal interference and recall, and nonverbal interference and verbal recall. Indeed, the DLD group had higher accuracy in these two conditions relative to other conditions (Table 2.3) and may have been engaging in adaptive use of their relative abilities. On the other hand, relatively better attention was associated with relatively better performance on tasks requiring nonverbal recall, but not on tasks requiring verbal recall, potentially implicating diminished recruitment of attention in their verbal processing difficulty. Findings for the TD group for nonverbal and attentional abilities, but not language processing, also align with the SOB-CS model. Relatively better nonverbal cognition and attention were associated with relatively better performance whereas relative better language processing was associated with relatively poorer accuracy in the verbal-divided condition. These patterns were present when task demands involved nonverbal task demands and verbal recall, although overall performance in this condition was not substantially worse than other conditions (Table 2.3). When attention was recruited during performance on tasks with verbal recall, there was no association between language processing and performance for the TD group, potentially suggesting a more facilitative role of attention than language in verbal working memory. Additionally, attention was important across groups when verbal and nonverbal task demands were present at each phase of the task (i.e., verbal-nonverbal interference and recall).

For both groups, it is possible that the extent to which they were able to switch from processing interference in one domain to recalling items in another domain on mixed domain tasks was governed by their attention abilities. This interpretation aligns with the view that my attention task (i.e., the continuous processing task) taps sustained *and* selective attention,

implicating the ability to voluntarily switch attention from one task demand to another as well as inhibit nontarget responses (Finneran et al., 2009; Ebert & Kohnert, 2011; Kapa et al., 2017). However, there was evidence that attention was important for performance on within-domain tasks as well. Another possibility is that the extent to which they were able to actively maintain task goals (e.g., serial recall for the recall phase) and inhibit alternative task goals (i.e., judgment for the interference phase) was governed by their attention abilities (Kane & Engle, 2004; Miyake et al., 2000; Miyake & Friedman, 2004; Tiego et al., 2018). This hypothesis aligns with the Hierarchical Model of Inhibitory Control (Tiego et al., 2018). Yet, this explanation provides limited explanation for differences in the role of attention related to the domain of task demands. In contrast, the SOB-CS model is able to account for the role of attention through its relationship with encoding, which may clarify how the role of attention varied on within- versus mixed-domain interference.

Under the SOB-CS model, attention is related to sequential displacement of representations in working memory, and therefore to temporal distinctiveness. By default, a currently active representation is the focus of attention and is available for further processing (e.g., removal; Oberauer et al., 2012). If an item is not attended to, it will not be encoded (i.e., associated with a serial position) properly, and therefore will have a less robust serial position representation. It is possible that because verbal information is particularly dependent on millisecond timescales (Hsu & Bishop, 2011 Gillam, Cowan, & Day, 1995; Tallal et al., 1996), verbal information is also more dependent on attention than nonverbal information in typically developing individuals (Bo & Seidler, 2009). However, the relative importance of verbal versus nonverbal temporal properties may be associated with individual differences in language

processing and nonverbal cognition (Donolato, Giofre, & Mamarella, 2017), as well as to the particular demands of the task.

My finding of an important relationship between attention and nonverbal recall in the DLD group, but between attention and verbal recall in the TD group, is consistent with this view and may signal difficulty in engaging attention for verbal processing in DLD. Children with DLD have been shown to have difficulty with temporal processing, and this difficulty with temporal processing may be related to their difficulty with verbal processing (Lukács & Kemény, 2015; Mayor-Dubois et al., 2014; Tallal et al., 1996). Given that attention is linked with temporal processing under the SOB-CS model and that many children with DLD have poor attention relative to TD peers (Finneran et al., 2009; Mueller & Tomblin, 2012; Redmond & Ash, 2014; Smolak et al., 2020), these patterns suggest important interrelationships among attention, temporal processing, and verbal processing in DLD. My finding of an important relationship between attention and verbal recall in the TD group is also consistent with this interpretation and the view of attention according to the SOB-CS model. Indeed, I demonstrated an important role for attention in the presence of heightened verbal interference for TD children – verbal recall paired with verbal interference. Moreover, when TD children drew upon attention for verbal recall, there was no association between language processing and performance.

The role of attention in working memory performance may also further clarify the effect of *free time* (i.e., the mechanism governing the degree of interference in working memory according to the SOB-CS model; Oberauer et al., 2012) observed in Chapter 4. I showed that relatively more *free time* was associated with poorer accuracy in the verbal-within domain condition for the DLD group, but with better accuracy for the TD group. The coupling of a high nonresponse rate and poor accuracy on the verbal interference task when paired with verbal

recall suggests diminished attention and encoding of verbal items for children in the DLD group. This interpretation is supported by my finding in the current study that attention was related to performance in the verbal-within condition for the TD group, but not the DLD group. Moreover, poor encoding in DLD (Leonard et al., 2019; McGergor et al., 2017) may be related to inefficient in inhibition of verbal interference (Bjorklund & Harnishfeger, 1990; Marton et al., 2007).

According to the SOB-CS model, the duration of attention to an item is associated with the strength of encoding for that item. Strong encoding leads to greater interference than weak encoding. If encoding strength is weak, due to poor attention to an item, the degree of interference is also weak and the effect of *free time* is less relevant to working memory performance. Thus, this framework would suggest that when children with DLD recruit attention on a working memory task, faster processing speed (e.g., more *free time* between cognitive operations) may diminish the effect of interference on recall performance. When children with DLD do not recruit attention on a working memory task, faster processing speed may be unassociated with the effect of interference on recall. Instead, there is a greater likelihood of poor overall recall due to poor encoding and poor representation of serial information (e.g., recalling items in the correct sequence). This pattern is more likely to be observed on verbal working memory tasks than nonverbal working memory tasks in DLD, although this hypothesis requires further exploration. Together, the SOB-CS model is able to account for interrelationships among processing speed and inhibition of interference in working memory performance, but also for the important role of attention. Using this framework, I have revealed new insights into processing in general and verbal processing in particular in children with DLD, as well as new avenues for future investigation.

Clinical Implications

Children with DLD may benefit from increasing the role of attention in verbal processing. This increase may be achieved by coupling verbal processing with nonverbal processing, given evidence of a relationship between attention and nonverbal recall, as well as verbal-nonverbal (i.e., word-image location) recall in the current study. For instance, incrementally decreasing nonverbal cues when targeting passive sentence structures may be associated with a maintenance of attention to the verbal components of the task. That is, attention may be maintained due to experience using attention within the context of targeting passive sentence structures. One example may be to sequentially: 1) use images depicting a dog chasing a cat and a cat chasing a dog, 2) use images of a dog and a cat individually, 3) use written sentences, and 4) use written sentences as feedback for an accurate production. This approach may also allow children with DLD to draw on relative strengths in the nonverbal domain to supplement passive sentence production with visual images, and potentially create new or alternative pathways to continue engaging nonverbal cognition.

Limitations and Future Directions

My measures of verbal and attentional abilities involved tasks that have been employed in prior research (Finneran et al., 2009; Robertson & Joanisse, 2010; Robertson & Gallant, 2019) and my measure of nonverbal ability is a well-validated standardized scale (Wechsler, 2011). However, each ability is tapped by a single measure of that ability, rather than a composite scale or multiple measures (e.g., sentence and grammatical morpheme comprehension for verbal ability). As a result, performance on these measures of verbal, nonverbal, or attentional abilities should not be interpreted as comprehensive accounts of these abilities. Rather, my analysis of

how individual differences in these abilities relate to working memory performance is a preliminary step in understanding how relative abilities are drawn upon to engage in processing performance. Future work should use more comprehensive measures of these abilities to examine the degree to which relationships observed in the current work are specific to a component of verbal, nonverbal, or attentional ability or are evident regardless of the particular measure of that ability. It is also important to note that these measures may tap a secondary skill in addition to the primary skill being measured. For instance, the sentence comprehension task may also draw on nonverbal or attentional abilities even though the primary skill being measured is verbal ability. Future work should also aim to disentangle the degree to which a given measure is a pure account of a given skill.

There are important limitations related to my participant sample and analytical approach. Most relevant to the current study, my approach to model selection involves two approaches to model comparison, yet there are other approaches to comparing models. First, the two approaches I employed provide different kinds of information – best performance given the current data via BIC and best predictive accuracy beyond the current data via LOOIC. I integrated across these approaches in order to determine which statistically significant results were most important to working memory performance. Thus, results that I found to be important in this study met stringent criteria for model performance, model prediction, and statistical significance. A predictor that was statistically significant could therefore be considered not important under my analytical approach. Additionally, there are other means of conducting model selection, such as Bayesian Model Averaging. Bayesian Model Averaging has the advantage of assigning a value to each predictor under analysis that indicates the likelihood of that predictor being in the true model of performance. This approach, however, assumes that the

true model of performance is included in the set of models examined (Kaplan, 2021). I did not adopt this assumption because my a priori goal was to analyze a small set of potential predictors. Future work may benefit from adopting an approach that aims to identify a likely true model of working memory performance by accounting for verbal, nonverbal, and attentional abilities, as well as other skills thought to be related to working memory performance (e.g., motor sequencing). Finally, it is possible to interpret additional effects from my analyses. I chose to focus on relationships that differ between DLD and TD groups and that were associated with the strongest evidence of importance. Future work may consider investigating relationships that did not differ between groups or that had modest evidence of importance in order to further characterize relationships between individual differences and working memory performance in DLD. See Chapter 2 for additional limitations related to my participant sample and analytical approach.

Lastly, there may be limitations related to my remote-based procedures. Most pertinent to the current study, it is possible that attention was an important factor in my findings due to the increased attentional demands in a remote-based study relative to a lab-based study. For instance, I found parent-reported elevated symptoms of Attention-Deficit/Hyperactivity Disorder (ADHD) in many TD and DLD participants in the absence of ADHD diagnoses in these participants. It is possible that this elevated ADHD symptomology is related to an extended period of home quarantine due to the COVID-19 pandemic, involving remote-based schooling, parents/caregivers working from home, and fewer opportunities for childcare/support. Thus, future work should examine the role of attention relative to language processing and nonverbal cognition in working memory performance in a lab-based environment in order to resolve this

outstanding question. See Chapter 3 for additional limitations related to remote-based data collection.

Conclusions

Using the serial-order-in-a-box – complex span model as my theoretical framework, the current study examined the role of individual differences in language processing, nonverbal cognition, and attention in working memory performance on tasks with varied verbal and nonverbal demands. I used statistical significance to characterize relationships and model selection to determine whether an individual differences predictor was important to performance. My findings for the TD group suggest that TD children drew upon language processing regardless of whether language processing facilitated performance under mixed-domain task demands. They also drew upon attention to facilitate verbal recall, potentially reflecting an important facilitative role for attention in verbal recall. In contrast, my findings for the DLD group suggest that children with DLD adaptively drew upon language processing and nonverbal cognition to facilitate performance under mixed-domain task demands. They drew upon attention to facilitate nonverbal recall (i.e., shape location), but not verbal recall (i.e., words). This finding suggests that attention may be recruited to a lesser degree in verbal than nonverbal processing in DLD, potentially representing a contributing factor in verbal processing difficulty.

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Chapter 6: General Discussion

In the current dissertation, I compared children with Developmental Language Disorder (DLD) to their age-matched typically developing (TD) peers on: 1) the role of domain in working memory performance by varying the domain (i.e., verbal versus nonverbal) of task demands, 2) the relationship between working memory performance and *free time*, a key mechanism posited by my theoretical framework, and 3) how individual differences in language processing, nonverbal cognition, and attention were related to working memory performance. Study 1, "The Role of Domain in Working Memory Performance," extended prior work that examined how performance differed when task demands were primarily within a single domain (e.g., a verbal interference judgment task and verbal recall items), divided between domains (e.g., a verbal interference judgment task and nonverbal recall items), and distributed across domains (e.g., a verbal-nonverbal interference judgment task and verbal-nonverbal recall items) with the goal of understanding how different types of interference affect working memory performance. Study 2, "The Impact of *Free Time* on Working Memory Performance," tested the active-removal mechanism responsible for diminishing interference in working memory according to the serial-order-in-a-box – complex span (SOB-CS) computational model (Oberauer, Lewandowsky, Farrell, Jarroled, & Greaves, 2012) in children with DLD for the first time. Study 3, "Individual Differences and Working Memory Performance," built on Studies 1 and 2 by examining how performance on experimental tasks of language processing and attention, and a standardized scale of nonverbal cognition predicted working memory performance. Study 3 also examined the degree to which each of these individual differences predictors was found to be important to performance based on model selection analysis. My participants included a total of 55 school-age children, 21 children with DLD and 34 age-

matched TD peers ages 9-13 years. The overarching goal of this work was to integrate three primary processing-based hypotheses of DLD, verbal working memory (Archibald & Gathercole, 2006, 2007; Ellis Weismer, Evans, & Hesketh, 1999), processing speed (Kail, 1994; Miller et al., 2001), and inefficient inhibition (Bjorklund & Harnishfeger, 1990; Marton, Kelmenson, & Pinkhasova, 2007), by examining performance on working memory tasks using the SOB-CS model as my theoretical framework.

Overall Summary

In each study, I demonstrated a role for the three processing-based hypotheses of DLD: verbal working memory (Archibald & Gathercole, 2006, 2007; Ellis Weismer et al., 1999), processing speed (Kail, 1994; Miller et al., 2001), and inefficient inhibition ((Bjorklund & Harnishfeger, 1990; Marton et al., 2007). However, none of these hypotheses entirely accounted for behavioral patterns in DLD in prior work (e.g., Ebert & Kohnert, 2011; Schul et al., 2004; Vugs et al., 2013) or in the current body of work when considered separately. Study 1 showed worse nonverbal than verbal working memory performance in children with DLD, indicating that a verbal working memory account may be less able to explain deficits in DLD than a general working memory account, and little evidence of slower reaction time (i.e., a measure of processing speed) in the DLD group relative to the TD group, indicating that processing speed does not fully explain DLD. There was also a key role for verbal interference in performance on verbal and nonverbal working memory tasks, but inconsistent evidence that the degree of verbal and nonverbal interference (e.g., high versus low interference) was associated with working memory performance. This latter finding suggests that inefficient inhibition of interference is not the primary processing-based factor in DLD. The SOB-CS model adds to the explanatory coverage of these hypotheses because it accounts for the relationship between time-based

processes and interference in working memory performance across verbal and nonverbal domains. It also contributes to explaining performance due to its view that relative verbal and nonverbal abilities are associated with the distinctiveness of an item's representation in working memory (e.g., strength of feature activation). For instance, verbal interference would be expected to have a greater effect on verbal recall for the DLD group than the TD group given the DLD group's weakness in language. However, there was a disproportionate effect of verbal interference on verbal and nonverbal performance, as well as a lack of clear benefit to minimizing within-domain interference, which necessitated further examination of the SOB-CS model's key mechanism – *free time*.

In Study 2, I further demonstrated the importance of considering nonverbal working memory in addition to verbal working memory, as well as evidence of inconsistent DLD versus TD group differences in reaction time and interference effects. I found a facilitative role of *free time* in performance on verbal working memory tasks and on nonverbal working memory tasks involving within-domain interference. These findings are consistent with the SOB-CS model, and suggest that *free time* may be more closely linked with verbal than nonverbal working memory, except under heightened interference. However, when verbal recall was paired with verbal interference, relatively more *free time* appeared to be associated with poorer accuracy for the DLD group, but with better accuracy for the TD group. I hypothesized that this effect may be related to the role of attention according to the SOB-CS model.

Thus, Study 3 examined how individual differences in attention, language processing (i.e., verbal abilities), and nonverbal cognition (i.e., nonverbal abilities) related to working memory performance, with a focus on group differences. I measured attention with a continuous processing task, language processing with a sentence comprehension task, and nonverbal

cognition with the matrix reasoning subscale from the Wechsler Abbreviated Intelligence Scale, Second Edition (Wechsler, 2011). In particular, I showed that children with DLD recruited their relative abilities in language processing and nonverbal cognition differently than TD peers, suggesting adaptive use of intact versus impaired processing skills in DLD. I also showed that attention was important to performance for verbal recall paired with verbal interference for the TD group, but not the DLD group. This finding signaled a possible explanation for patterns related to verbal interference in Studies 1 and 2, and a potential contributing factor in the DLD group's verbal processing deficits. This interpretation is preliminary and requires further examination for several reasons. First, my remote-based approach to data collection may introduce attentional factors not present in prior studies examining working memory in children with DLD (see Chapter 5). Second, attention was not manipulated in my experimental paradigm and only one measure of attention was included in my analyses for this study (see also Chapter 2 for information on parent reported Attention-Deficit/Hyperactivity Disorder symptoms). Lastly, according to the SOB-CS, attention is closely linked with encoding and temporal processing, which are also areas of weakness in DLD (Gillam, Cowan, & Day, 1995; Leonard et al., 2019; Lukács & Kemény, 2015; Mayor-Dubois, Zesiger, van der Linden, & Roulet-Perez, 2014; McGergor, Gordon, Eden, Arbisi-Kelm, & Oleson, 2017; Tallal et al., 1996), yet I did not examine these associations directly.

To further explain why attention may be an important contributing factor in verbal processing, it is important to further clarify how attention is linked to encoding and temporal processing under the SOB-CS. According to the SOB-CS model, attention is key to appropriate encoding, which involves binding an item to a context position in time (i.e., serial position; Oberauer et al., 2012). Attention is therefore particularly important for representing temporal

properties of the input. In the absence of attention to an interference or recall item, the roles of *free time* and interference in working memory become less relevant to explaining performance. Rather, a breakdown may occur earlier in processing, at the level of binding an item to a serial position in time. Notably, processing-based hypotheses of DLD are less able to account for interrelationships among factors found to be important in the current work than the SOB-CS model, such as interrelationships between processing speed, interference, and attention in working memory. The SOB-CS model provides an integrated explanation for behavioral patterns observed in the current body of work. Accordingly, the SOB-CS model is a productive step forward in accounting for processing-based factors in DLD.

Processing-Based Factors in DLD

Although the current body of work showed that none of the primary processing-based hypotheses of DLD fully accounted for processing performance, there was clear evidence of weaknesses in the DLD group that reflect each of these hypotheses. Researchers across disciplines have called for integrated theories of various phenomena, such as accounting for interrelationships among working memory, attention, and the role of domain (e.g., Archibald, 2018; Kane & Engle, 2002; Marton, 2008; Montgomery et al., 2016; Norman, 1968, Oberauer et al., 2012) and adopting an interaction-based approach to development and developmental disabilities (e.g., Ellis Weismer, 2013; Karmiloff-Smith, 2005; Spencer et al., 2009; Vissers, Koolen, Hermans, Scheper, & Knoors, 2015). The current dissertation represents a step toward integrating the three primary processing-based hypotheses of DLD by adopting a framework, the SOB-CS model, that accounts for each of these factors. Importantly, the SOB-CS model does not represent a causal theory of DLD, rather it represents a framework which integrates key areas of

weakness observed in DLD to describe complex processing. The SOB-CS model may be a guide for advancing causal theories of DLD.

Toward a Model of Processing in DLD

The current body of work suggests that DLD is not solely a disorder of language, rather there are important domain-general differences in cognitive processes in children with DLD relative to same-age TD peers. These group differences in cognitive processes, however, appear to give rise to disproportionate weakness in language ability relative to nonverbal cognition. I provide evidence that interrelationships among working memory, processing speed, and inhibition of interference are important factors in DLD. My findings also showed that these factors are related to individual differences in language processing and nonverbal cognition, further suggesting a domain-general account of DLD. However, interrelationships among working memory, processing speed, and inhibition of interference also depended on attention when there were heightened verbal processing demands in my work. Thus, my integrated account of DLD must involve an attention and encoding bottleneck, in particular for verbal information. This attention bottleneck determines the extent to which an item is bound to a context position and serial properties of information are recalled correctly. This bottleneck also determines the extent to which downstream interference affects processing performance. Beyond attention and encoding, my integrated account of DLD must involve different patterns of activation relative to TD peers that reflect differences in how children with DLD draw on language processing and nonverbal cognition. I would expect that activation strength is weaker and activation is more diffuse for verbal than nonverbal features in DLD. As a result, interference between verbal items is more likely than between nonverbal items. Finally, children with DLD may not have diminished unfilled intervals of time than TD peers across processing

tasks, but they may depend on unfilled intervals to inhibit interference to a greater degree than TD peers. I saw this effect for recall involving verbal features. It is possible that children with DLD will have diminished unfilled intervals in at least some processing tasks based on prior showing slowed reaction time on processing tasks (Kail, 1994; Leonard et al., 2007; Leonard, Ellis Weismer, Weber-Fox, & Miller, 2014; Miller, Kail, Leonard, & Tomblin, 2001) and the current evidence of links between processing speed and having unfilled intervals of time on processing tasks. Furthermore, this type of processing may reflect spaced learning (i.e., time between learning events) which has been consistently shown to lead to better learning than massed learning approaches (i.e., learning events presented in immediate succession), potentially due to the role of forgetting (e.g., consolidating relevant information into long-term memory and removing irrelevant information from further processing; Vlach, 2014; see also Gordon, 2020).

I may also speculate how these interrelationships among working memory, processing speed, and inhibition of interference play causal roles in the language deficits in DLD. The key processing-based differences relative to TD peers appear to be in attention, encoding, and activation patterns. With regard to attention, children with DLD may attend to verbal information to a lesser degree when the verbal information is particularly challenging, as in the case of verbal recall paired with verbal interference. This hypothesis is consistent with the Goldilocks Effect posited by Kidd, Piantadosi, and Aslin (2012) which suggests that infants selectively sample (e.g., attend to) information in their environment. If information in the environment is too easy, such as being very frequently occurring or having very high salience, or if information is too difficult, such as being very infrequently occurring or having very low salience, it has a lesser likelihood of being sampled than information at a more moderate level of difficulty (Kidd et al., 2012; see also desirable difficulties work, such as Eskenazi & Nix, 2021 and Maddox & Balota,

2015). Importantly, the Goldilocks Effect is not considered to be specific to verbal information. However, it is possible that children with DLD have a lower threshold for desirable difficulty with verbal than nonverbal information, leading to downstream effects on language development. For instance, children with DLD have been shown to require more exposures to a novel word in order to learn the word relative to TD peers (Alt, 2011; Leonard et al., 2019), and this exposure might be particularly important with challenging verbal task demands (e.g., referent naming versus referent identification; Alt & Plante, 2006). It is also possible that children with DLD respond differently to aspects of complexity than TD peers, such as work showing an advantage in novel word learning for TD children, but not children with DLD, when words had high rather than low phonological probability (e.g., frequently occurring phonological patterns; Gray, Pittman, & Weinhold, 2014). Requiring additional exposures or responding to complexity differently than TD peers has the potential to explain a variety of behavioral patterns in DLD related to verbal information, but does not clarify the disproportionate weakness in language relative to nonverbal skills in DLD. While there may be an important Goldilocks Effect (Kidd et al., 2012) in children with DLD that differs from TD peers, this explanation does not clarify why verbal information is disproportionately affected in DLD.

An additional consideration is encoding differences in DLD relative to TD peers. Difficulty with encoding verbal information is thought to affect language learning in DLD (e.g., McGregor, Gordon, Eden, Arbisi, & Oleson, 2017), but encoding nonverbal information is less well studied in this population. Some studies suggest that nonverbal encoding (e.g., nonverbal strategies) is used to a greater degree in DLD than TD (Arslan, Broc, & Mathy, 2020; Botting, Psarou, Caplin, & Nevin, 2013; Larson, Gangopadhyay, Kaushanskaya, & Ellis Weismer, 2019), but nonverbal cues may not mediate the effect of verbal complexity (e.g., in a word learning

task; Alt & Plante, 2006). Domain-general deficits in encoding could disproportionately affect verbal processing due to encoding involving binding an item to a serial position in time (Oberauer et al., 2012) and verbal information being more dependent on serial processing than nonverbal information (Hsu & Bishop, 2011 Gillam, Cowan, & Day, 1995; Tallal et al., 1996). Over time, if verbal items are not robustly bound to serial positions, language development may be delayed or deviant relative to typical development. For instance, learning word boundaries in connected speech requires identifying probabilistic boundaries between words (e.g., happy/baby versus ha/pyba/by; Saffran, Aslin, & Newport, 1996), which may only be identifiable if phonological patterns are represented in correct serial positions (e.g., happy versus pyha; note that this is an extreme example in order to highlight serial position). In this scenario, additional exposures may be required to identify word boundaries and the effect of phonologically infrequent patterns would be less clear (e.g., sequence learning; Conway et al., 2011). Indeed, a meta-analysis of statistical learning in DLD indicated poorer detection of statistical patterns (e.g., probabilistic word boundaries) relative to TD peers, suggesting that statistical learning deficits are related to their language deficits (Lammertink, Boersma, Wijnen, & Rispens, 2017). Critically, nonverbal information involves serial and statistical information as well (e.g., temporal events; Fiser & Aslin, 2002) and the degree to which temporal properties are privileged with verbal or nonverbal information is associated with individual differences in language and nonverbal skills (Donolato, Giofre, & Mamarella, 2017). Thus, encoding may flexibly account for patterns of behavior across verbal and nonverbal domains through the relative robustness of item plus serial position binding.

Finally, another breakdown in processing may be related to activation patterns. The current work has shown that there are differences in the relationships among processing and

relative abilities in language processing, nonverbal cognition, and attention, as have other prior studies (e.g., Dispaldro et al., 2013; Larson et al., 2019; Larson, Kaplan, Kaushanskaya, & Ellis Weismer, 2020). Neuroimaging work suggests differences in neural activation in DLD relative to TD peers, potentially indicating the use of intact rather than impaired pathways in DLD (Ellis Weismer, Plante, Jones, & Tomblin, 2005; Herbert et al., 2005; Njiokiktjien, Rijke, & Jonkman, 2001). Thus, this evidence implicates differences in the degree to which children with DLD activate verbal and nonverbal processing units relative to TD peers. Specifically, children with DLD may activate more nonverbal processing units and may have weaker encoding strength of activated verbal processing units than TD peers. Verbal processing may be associated with diffuse activation patterns in DLD, reflecting less co-activation in neighboring verbal processing units, coupled with greater activation of nonverbal processing units (e.g., due to nonverbal encoding or nonverbal strategies). These patterns would underscore less efficient processing and less robust verbal item representations than TD peers. Furthermore, children with DLD may recruit nonverbal processing units under task demands where TD children recruit verbal processing units, potentially affecting nonverbal recall in DLD. Patterns of activation that diverge from those present in typical development may suggest compensatory or inefficient processing (Ellis Weismer et al., 2005; see arguments for neurodevelopmental disorders as disorders of neural networks, such as Di Martino et al., 2013; Vertes & Bullmore 2015). While it is difficult to speculate on specific patterns of deficits associated with compensatory or inefficient activation patterns, it may be possible to use computational modeling to systematically vary differences in patterns of activation in order to yield behavioral patterns observed in DLD.

The SOB-CS Model versus Processing-Based Hypotheses

There are a few advantages of the SOB-CS model being a computational model over and above theories based primarily on behavioral patterns. Computational modeling involves simulating complex systems (e.g., behavior) and adjusting key variables to answer theoretical questions (National Institute of Biomedical Imaging and Bioengineering, 2021). This approach to understanding behavior and disorders has been adopted in literature from psychology (e.g., to examine therapeutic effects in varied disorders, Mansell & Huddy, 2020, and literacy development; Chang, Monaghan, & Welbourne, 2019) and educational psychology (e.g., teaching and learning; Laamb & Premo, 2015), as well as audiology (e.g., neurophysiological correlates of tinnitus; Schaette & Kempter, 2012). There is also computational modelling of language development, such as grammatical aspect acquisition (Li & Shirai, 2000) and word learning (Fazly, Alishahi, & Stevenson, 2010; McMurray, 2007; see also MacWhinney, 2010). Computational modeling circumvents many issues associated with examining behavior in participant samples, such as difficulty identifying the active ingredient in a therapy (Mansell & Huddy, 2020), and it may contribute to identifying and explaining causal relationships (Herd & Miles, 2019; National Institute of Biomedical Imaging and Bioengineering, 2021).

Although the SOB-CS is not a computational model of DLD, it is a computational model of working memory and it includes important factors in DLD. Thus, there is the potential for this model to be used to further identify causal factors in DLD or even to create a causal model of DLD, beyond describing processing more generally. For instance, if computational modelers and behavioral experts in DLD collaborate, they could adjust variables in the SOB-CS model to mimic DLD patterns of processing speed, interference effects, and working memory performance. These adjustments could also reflect language-based breakdowns in DLD, such as

disproportionate weakness in syntax, or areas of weakness beyond language, such as attentional deficits. Taken together, the current body of work supports further use of the SOB-CS model as an account of processing speed, inhibition of interference, and working memory in DLD more so than it supports the use of a single processing-based hypothesis of DLD. This conclusion aligns with interaction-based views of development and developmental disorders, such as Neuroconstructivism (Karmiloff-Smith, 2005) and Developmental Systems (Spencer et al., 2009; see also the Epigenetic Landscape posited by Waddington, 1957), given that it favors interrelationships among cognitive processes rather than a breakdown in a single cognitive process that gives rise to broad patterns of deficits.

Conclusions

In the current dissertation, my aim was to address three primary gaps in the literature. The first gap in the literature was that three primary processing-based hypotheses of DLD – limited verbal working memory, slow processing speed, and inefficient inhibition of interference – have been examined separately rather than under an integrated framework. I addressed this gap by using the SOB-CS model as my framework because it posits a time-based mechanism that governs the degree of interference in working memory performance. The second gap was that prior studies did not use a fully-crossed experimental design to examine the role of domain in working memory performance in DLD relative to TD peers. The current work extended prior work by accounting for performance when processing was within a single domain (e.g., verbal interference and recall), divided between domains (e.g., verbal interference and nonverbal recall), and distributed across domains (i.e., verbal-nonverbal interference and recall). The final gap that I addressed was that no prior studies have examined how individual differences in

verbal, nonverbal, and attentional abilities relate to working memory performance in children with DLD relative to TD peers.

My findings support a role for verbal working memory, processing speed, and inhibition in processing performance for children with DLD, yet these roles were incomplete when considered separately. I showed that children with DLD had poorer verbal and nonverbal working memory performance than TD peers, and that verbal interference affected performance on verbal and nonverbal working memory tasks to a greater degree than nonverbal interference. Consistent with the SOB-CS model, I also showed modest benefits of cross-domain task demands relative to within-domain task demands for both groups. The disproportionate effect of verbal interference was clarified further by examining *free time*, the active-removal mechanism governing the effect of interference on working memory per the SOB-CS model. *Free time* (e.g., unfilled pauses) appeared to facilitate performance regardless of the domain of task demands, except in the case of verbal interference paired with verbal recall for children with DLD. Under these task demands, TD children recruited attention during performance, but children with DLD did not. Thus, I argue that poor attention and encoding accounted for performance to a greater degree than the effect of *free time*. Specifically, the breakdown at an earlier phase of processing may have been responsible for performance patterns to a greater degree than interference for verbal recall. In contrast, children with DLD drew upon attention during nonverbal recall, an area that is less impaired than verbal recall in this population. Additionally, my examination of individual differences indicated that children with DLD recruited relative skills in language processing and nonverbal cognition during working memory performance. It is possible that children with DLD adaptively recruit language processing and nonverbal cognition to facilitate working memory performance, but recruit attention to facilitate nonverbal working memory

performance. Thus, the lack of an important relationship between attention and verbal working memory performance may represent a contributing factor in verbal processing difficulty observed in children with DLD. Together, this body of work demonstrated a role for each of the processing-based hypotheses of DLD, but that an integrated model of these factors, the SOB-CS model, better explained processing performance. Thus, the SOB-CS model may be used in future work to advance our understanding of processing in DLD. It may also have the long-term potential to inform causal theories of DLD.

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Appendix A: Additional Figures Depicting Components of the SOB-CS Model

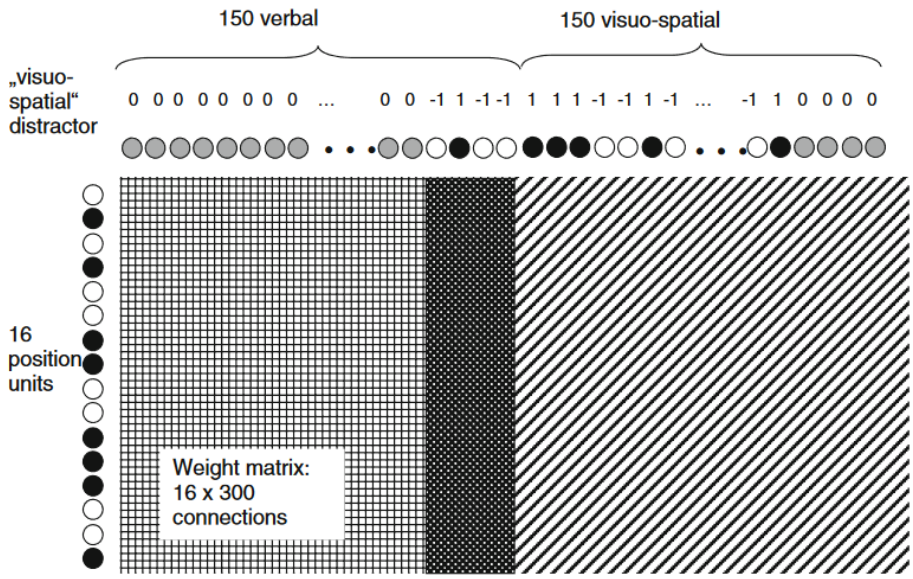

Figure A.1. The item-layer architecture of the SOB-CS model (adapted with permission from Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012, p. 804). Note that I use the term "verbal" in a consistent manner with Oberauer et al., but I use the term "nonverbal" in place of Oberauer et al.'s term "visuospatial."

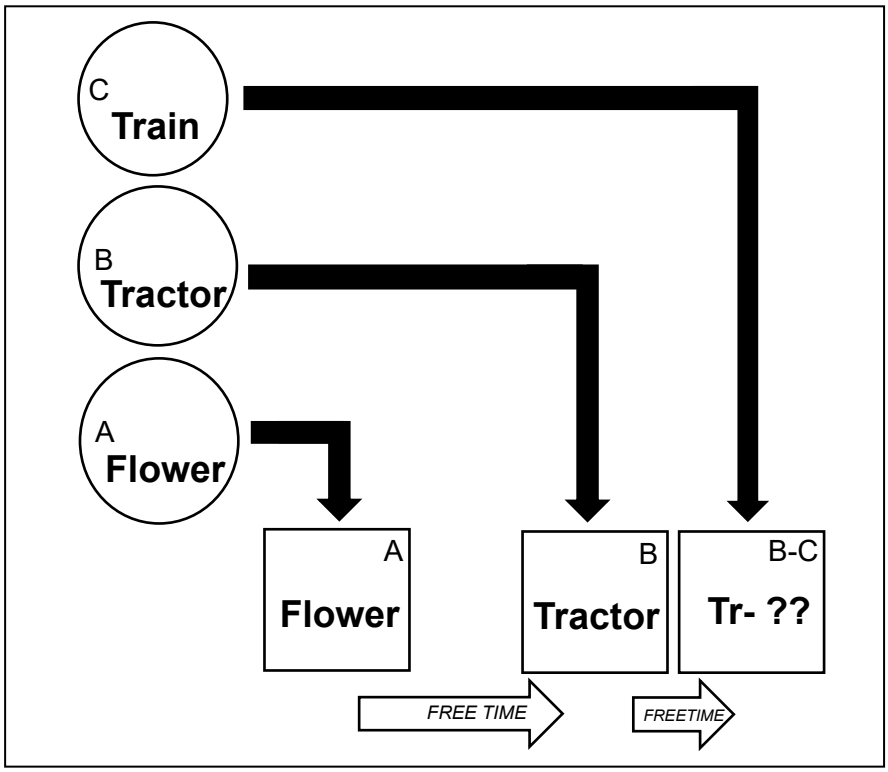

Figure A.2. An interpretation of SOB-CS with verbal stimuli.

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Appendix B: Additional Methods and Descriptive Performance Information

Table B.1. Westfell et al. (2014) crossed random-effects power calculation (see https://jakewestfall.shinyapps.io/crossedpower/ for power analysis website).

Variable	Value
Design	Stimuli-within-condition
Standardization	Unstandardized
Mean difference	0.25
Contrast codes	0.5
Residual variance	2
Participant intercept variance	0.2†
Stimulus intercept variance	0.2†
Participant-by-stimulus variance	0.1†
Participant slope variance	0.1†
Stimulus slope variance	0.2†
Total number of participants	55
Total number of stimuli	300
Power	0.88
Effect size d	0.15

†These values are standard input values as I did not have a clear hypothesis indicating the need for different values.

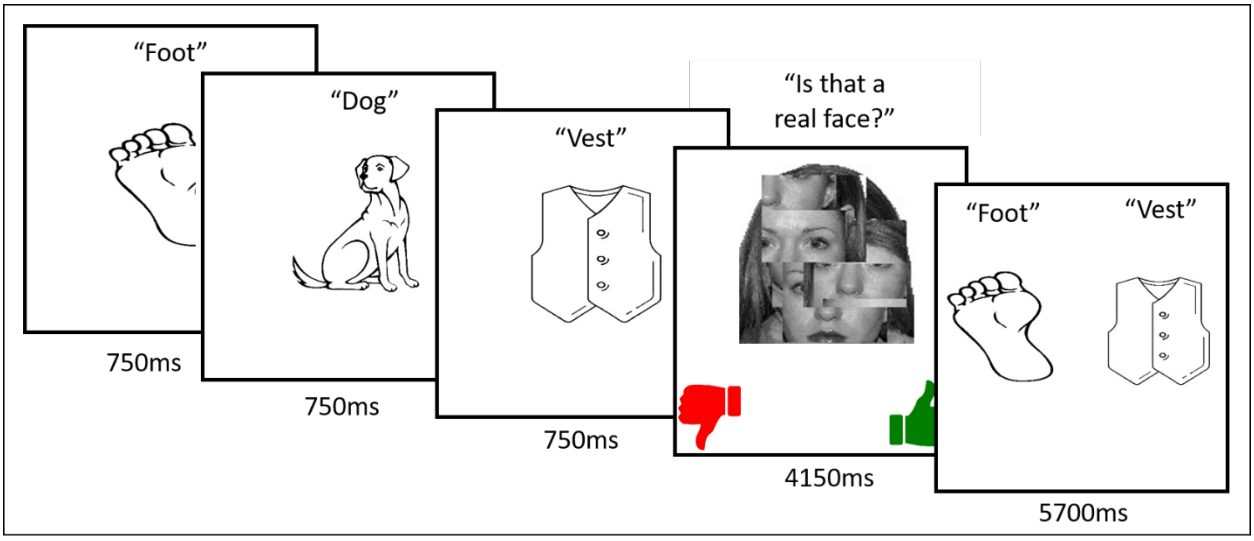

Figure B.1. Verbal divided-domain condition trial example.

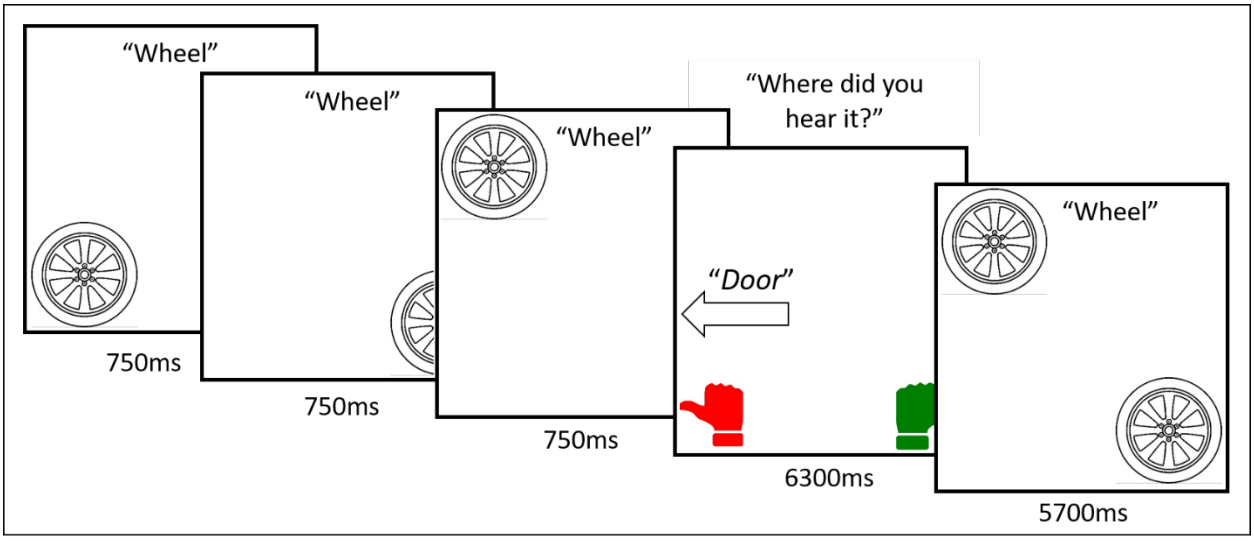

Figure B.2. Distributed-domain condition trial example

Table B.2. Verbal recall stimuli comparisons.

Feature	Verbal-Within	Verbal-Divided	Distributed	
Syllables				VW<VD *p*-value = 0.84
Mean (SD)	1.36(0.48)	1.38(0.53)	1.47(0.52)	VD>D *p*-value = 0.56
Range	1-2	1-3	1-2	VW<D *p*-value = 0.47
Frequency				VW<VD *p*-value = 0.31
Mean (SD)	0.004(0.005)	0.003(0.003)	0.003(0.003)	VD<D *p*-value = 0.84
Range	0.001-0.024	0.001-0.014	0.001-0.010	VW<D *p*-value = 0.24
Category	NA	NA	NA	VW-VD *p*-value = 0.84
				VD-D *p*-value = 0.57
				VW-D *p*-value = 0.68
Source	NA	NA	NA	VW-VD *p*-value = 1.00
				VD-D *p*-value = 0.73
				VW-D *p*-value = 0.73

Note: Frequency based on the CHILDES database (MacWhinney, 2000; Warren corpora); Categories included: Animals (e.g., rabbit), Toys (e.g., ball), Places (e.g., jungle), Outdoors (e.g., tree), Food (e.g., sandwich), Small Household Items (e.g., camera), Large Household Items (e.g., TV), Body Parts (e.g., head), Clothing (e.g., shirt), People (e.g., nurse), Vehicles (e.g., bus), and Routines (e.g., dinner). Sources included: CHILDES database (MacWhinney, 2000; Warren corpora; Warren-Leubecker & Bohannon, 1984) or the MacArthur-Bates Communicative Development Inventories (Fenson et al., 2007).

Table B.3. Verbal interference phase stimuli comparisons.

Feature	Verbal-Within	Nonverbal-Divided	
Syllables (all)			
Mean (SD)	1.33(0.49)	1.07(0.26)	VW>NVD *p*-value = 0.07
Range	1-2	1-2	
Frequency (nonwords)			
Mean (SD)	259.12(297.92)	666.17(737.83)	VW<NVD *p*-value = 0.18
Range	40-917	0-1741	
Category (true words)	NA	NA	VW-NVD *p*-value = 0.80
Source (true words)	NA	NA	VW-NVD *p*-value = 0.80

Note: Words and nonwords collapsed for syllable count; Frequency for words was only available for two stimuli, thus it was not analyzed, and frequency for nonwords is the summed frequency of phonological neighbors based on the ARC Nonword Database (Rastle, Harrington, & Coltheart, 2002) Categories included: Animals, Toys, Places, Outdoors, Food, Small Household Items, Large Household Items, Body Parts, Clothing, People, Vehicles, and Routines. Sources included: CHILDES database (MacWhinney, 2000; Warren corpora; Warren-Leubecker & Bohannon, 1984) or the MacArthur-Bates Communicative Development Inventories (Fenson et al., 2007).

Table B.4. Number of participants falling at or below chance recall performance by group and condition.

Condition	TD (n = 34)	DLD (n = 21)
Verbal-within	0	6
Verbal-divided	1	3
Nonverbal-within	0	5
Nonverbal-divided	0	8
Distributed	0	4

Note. 2 DLD participants at chance in 4 conditions; 3 DLD participants at chance in 3 conditions; 1 DLD participant at chance in all conditions; 1 DLD participant at chance in 2 conditions.

Table B.5. Information on non-response rates by group and condition.

Condition	TD (4%)†	DLD (n = 8%)†	
Verbal-within	5%	12%	$p < .001$***
Verbal-divided	2%	4%	$p = .05$
Nonverbal-within	2%	4%	$p = .12$
Nonverbal-divided	5%	10%	$p < .01$**
Distributed	4%	10%	$p < .001$***

†Percent non-responses across conditions

*significant difference at $p < .05$; **significant difference at $p < .01$; ***significant difference at $p < .001$

Table B.6. Correlations among participant characteristics and performance accuracy on working memory tasks.

	Age	SES	NVIQ	Lang	Con-t	VW	VD	NW	ND	D
Age	-	0.13	0.08	0.09	0.14	0.26	0.10	0.19	0.10	0.32
SES	0.13	-	0.34	0.35	-0.12	0.13	0.15	0.23	0.14	0.13
NVIQ	0.08	0.34	-	0.71	-0.27	0.51	0.45	0.56	0.55	0.53
Lang	0.09	0.35	0.71	-	-0.33	0.56	0.43	0.53	0.60	0.48
Con-t	0.14	-0.12	-0.27	-0.33	-	-0.37	-0.33	-0.24	-0.42	-0.28
VW	0.26	0.13	0.51	0.55	-0.37	-	0.69	0.56	0.72	0.69
VD	0.10	0.15	0.45	0.43	-0.33	0.69	-	0.60	0.58	0.60
NW	0.19	0.23	0.56	0.53	-0.24	0.56	0.60	-	0.73	0.66
ND	0.10	0.14	0.55	0.60	-0.42	0.72	0.58	0.73	-	0.75
D	0.32	0.13	0.53	0.48	-0.28	0.69	0.60	0.66	0.75	-

Note. Age = years; SES = socioeconomic status (maternal education); Lang = Core Language standard scores on the Clinical Evaluation of Language Fundamentals, 5th Edition (Wiig, Semel, & Secord, 2013); Con-t = Conners-3 abbreviated parent interview (i.e., a screening for Attention-Deficit/Hyperactivity Disorder (Conners, 2008); VW = Verbal within domain condition; VD = Verbal divided domain condition; NW = Nonverbal within domain condition; D = Distributed domain condition.

Table B.7. Correlation tables for experimental tasks across groups and by group.

A) Correlations of experimental task performance across groups.

	VW	VD	NW	ND	D	SentComp	*d*'	MatrixReas
VW	-	0.69	0.56	0.72	0.69	0.43	0.45	0.51
VD	0.69	-	0.60	0.58	0.60	0.35	0.27	0.45
NW	0.56	0.60	-	0.73	0.66	0.39	0.45	0.56
ND	0.72	0.58	0.73	-	0.75	0.52	0.43	0.55
D	0.69	0.60	0.66	0.75	-	0.63	0.52	0.53
SentComp	0.43	0.34	0.39	0.52	0.63	-	0.43	0.38
d'	0.45	0.27	0.45	0.43	0.52	0.43	-	0.29
MatrixReas	0.51	0.45	0.56	0.55	0.53	0.38	0.29	-

B) Correlations of experimental task performance for the TD group.

	VW	VD	NW	ND	D	SentComp	*d*'	MatrixReas
VW	-	0.27	0.18	0.09	0.30	0.12	0.30	0.01
VD	0.27	-	0.27	-0.01	-0.02	-0.22	-0.01	0.01
NW	0.18	0.27	-	0.41	0.46	-0.07	0.24	0.48
ND	0.09	-0.01	0.41	-	0.46	0.03	0.02	0.18
D	0.30	-0.02	0.46	0.46	-	0.36	0.47	0.17
SentComp	0.12	-0.22	-0.07	0.03	0.36	-	0.04	-0.03
d'	0.30	-0.01	0.24	0.02	0.47	0.04	-	0.05
MatrixReas	0.01	0.01	0.48	0.18	0.17	-0.03	0.05	-

C) Correlations of experimental task performance for the DLD group.

	VW	VD	NW	ND	D	SentComp	*d*'	MatrixReas
VW	-	0.80	0.61	0.83	0.73	0.26	0.34	0.60
VD	0.80	-	0.69	0.73	0.79	0.41	0.26	0.59
NW	0.61	0.69	-	0.83	0.67	0.45	0.48	0.43
ND	0.83	0.73	0.84	-	0.78	0.49	0.57	0.57
D	0.73	0.79	0.67	0.78	-	0.62	0.46	0.60
SentComp	0.26	0.41	0.45	0.49	0.62	-	0.54	0.32
d'	0.34	0.26	0.48	0.57	0.46	0.54	-	0.09
MatrixReas	0.60	0.59	0.43	0.57	0.60	0.32	0.09	-

Note. VW = Verbal within domain condition; VD = Verbal divided domain condition; NW = Nonverbal within domain condition; D = Distributed domain condition; Sentence Comprehension = Accuracy on the sentence comprehension task; MatrixReas = t-score on the Matrix Reasoning subscale of the Wechsler Abbreviated Intelligence Scale, second Edition (WASI-II; Wechsler, 2011); *d*' = d-prime from the continuous processing task, a measure of sustained/selective attention.

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Appendix C: Differences in Significant Effects Between Imputed and Non-Imputed Analyses

Table C.1. Summary of *differences* in significant effects between analyses with raw data (outliers removed) and imputed analyses.

Study	Model	Raw data effect	Imputed data effect
Study 1			
	Recall Accuracy ~ (verbal within vs. nonverbal within)*Group + SES + Interference Accuracy Verbal Within	Verbal within vs. nonverbal within (*b* = -0.32; chi-sqr = 1.24^5; *p* <.001***); SES (*b* = 0.01; chi-sqr = 194.62; *p* <.001***); Interference Accuracy Verbal Within (*b* = 2.75; chi-sqr = 9.29^6; *p* <.001***); (verbal within vs. verbal divided)*Group (*b* = 0.54; chi-sqr = 3.86^5; *p* <.001***)	Verbal within vs. nonverbal within (*b* = -0.39; stat = -0.99; *p* = .32); SES (*b* = 0.01; stat = 0.12; *p* = .91); Interference Accuracy Verbal Within (*b* = 0.57; stat = 0.99; *p* = .33); (verbal within vs. verbal divided)*Group (*b* = 0.64; stat = 1.07; *p* = .29)
	Recall Accuracy ~ (verbal within vs. verbal divided)*Group + SES + Interference Accuracy Verbal Within	Interference Accuracy Verbal Within (*b* = -0.08; chi-sq = 5.92; *p* < .05*)	Interference Accuracy Verbal Within (*b* = 0.37; stat = 0.65; *p* = .52)
	Recall Accuracy ~ (nonverbal within vs. nonverbal divided)*Group + SES	Nonverbal within vs. nonverbal divided (*b* = 0.67; chi-sqr = 3.81; *p* = .05)	Nonverbal within vs. nonverbal divided (*b* = 0.68; stat = 2.01; *p* < .05*)
	Recall Accuracy ~ (verbal divided vs. distributed)*Group + SES + Interference Accuracy Distributed	Interference Accuracy Distributed (*b* = 3.14; chi-sqr = 10.53; *p* < .01**)	Interference Accuracy Distributed (*b* = 1.39; stat = 1.94; *p* = .06)
	Recall RT ~ (nonverbal divided vs. distributed)*Group + SES + Interference Accuracy Distributed	Nonverbal divided vs. distributed (*b* = -148.16; t-value = -1.52; *p* = .13); Group (*b* = 541.72; t- value = 2.50; *p* < .05*)	Nonverbal divided vs. distributed (*b* = -247.34; stat = -2.27; *p* < .05*); Group (*b* = 414.25; stat = 1.88; *p* = .06)
Study 2			
	Verbal Within Condition: Recall Accuracy ~ Free Time*Group + SES	Group (*b* = -.18; chi-sqr = 6.10^4; *p* < .001***); SES (*b* = -.19; chi-sqr = 6.70^4; *p* < .001***)	Group (*b* = -0.14; stat = -0.17; *p* = .86); SES (*b* = -0.18; stat = -1.42; *p* = .16)
	Verbal Divided Condition: Recall Accuracy ~ Free Time*Group + SES	Free Time*Group (*b* = 0.00; chi-sqr = 3.17; *p* = .08)	Free Time*Group (*b* = 0.00; stat = 2.97; *p* < .01*)

	Verbal Divided Condition: Recall RT ~ Free Time*Group + SES	Group (b = 291.69; t-value = 1.59; p = .21)	Group (b = 447.07; stat = 2.03; p < .05*)
	Distributed Condition, DLD Group: Recall Accuracy ~ Free Time	Free Time (b = 0.00; chi-sqr = 4.25; p < .05*)	Free Time (b = 0.00; stat = 1.96; p = .05)
Study 3			
	Verbal Within Condition: Recall Accuracy ~ Sentence Comprehension*Group + SES	Group (b = -1.88; chi-sqr = -2.82; p < .01**)	Group (b = -3.94; stat = -1.34; p = .18)
	Verbal Within Condition: Recall Accuracy ~ Attention*Group + SES	SES (b = -0.19; chi-sqr = 4.58^4; p < .001***); Attention*Group (b = 0.57; chi-sqr = 4.03^5; p < .001***)	SES (b = -0.17; stat = -1.69; p = .09); Attention*Group (b = 0.49; stat = 0.50; p = .62)
	Verbal Divided Condition: Recall Accuracy ~ Matrix Reasoning*Group + SES	Group (b = -0.06; chi-sqr = 0.01; p = .29)	Group (b = -6.41; stat = -2.73; p < .01*)
	Verbal Divided Condition, TD Group: Recall Accuracy ~ Sentence Comprehension	Sentence Comprehension (b = -3.87; chi-sqr = 1.85; p = .17)	Sentence Comprehension (b = -3.95; stat = -4104.44; p < .001***)
	Nonverbal Divided Condition: Recall Accuracy ~ Matrix Reasoning*Group + SES	Group (b = -1.57; chi-sqr = 5.96; p < .05*)	Group (b = -4.27; stat = -1.67; p = .09)
	Distributed Condition: Recall RT ~ Sentence Comprehension*Group + SES	Group (b = 343.01; t-value = 1.53; p = 13)	Group (b = 2682.90; stat = 2.90; p < .01**)
	Distributed Condition: Recall RT ~ Matrix Reasoning*Group + SES	Group (b = 538.86; t-value = 1.34; p = 19); Matrix Reasoning*Group (b = -293.82; t-value = -0.72; p = 47)	Group (b = 1643.60; stat = 2.21; p < .05*); Matrix Reasoning*Group (b = -30.04; stat = -2.15; p < .05*)
	Distributed Condition, DLD Group: Recall RT ~ Sentence Comprehension	Sentence Comprehension (b = 1645.00; t-value = -1.69; p = .11)	Sentence Comprehension (b = -2294.18; stat = -2.59; p < .05*)

*significant difference at p < .05; **significant difference at p < .01; *** significant difference at p < .001

Appendix D: Full Multiple-Imputation Mixed-Effects Model Results from Study 3

Table D.1. Study 3 multiple imputation mixed-effects model results for analyses of recall accuracy and reaction time regressed on sentence comprehension, matrix reasoning, or attention, group, and the interaction between group and the individual differences predictor. Where the interaction between group and an individual differences predictor was significant, I reported follow up within-group regression. I also reported follow up analyses conducted based on descriptive performance patterns.

Condition	Predictor	*b estimate*	test-statistic	*p-value*
Language Processing – Accuracy				
Verbal-within				
	Sentence Comprehension	0.06	0.02	$p = .98$
	Group	-3.94	-1.34	$p = .18$
	SES	-0.15	-1.27	$p = .20$
	Group*Sentence Comprehension	2.67	0.73	$p = .46$
Verbal-divided				
	Sentence Comprehension	-4.02	-1.54	*$p = .12$*
	Group	-7.61	-2.96	$p < .01$**
	SES			$p = .43$
	Group*Sentence Comprehension	8.10	2.54	$p < .05$*
DLD Group	Sentence Comprehension	4.01	2.50	$p < .05$*
TD Group	Sentence Comprehension	-3.95	-4104.44	$p <$ .001***
Nonverbal-within				
	Sentence Comprehension	-1.02	2.53	$p = .69$
	Group	-3.67	-1.48	$p = .14$
	SES	0.11	1.10	$p = .27$
	Group*Sentence Comprehension	3.66	1.18	$p = .24$
Nonverbal-divided				
	Sentence Comprehension	0.50	0.17	$p = .87$
	Group	-4.23	-1.47	$p = .14$
	SES	-0.10	-0.88	$p = .38$
	Group*Sentence Comprehension	3.32	0.92	$p = .36$
DLD Group	Sentence Comprehension	3.99	2.06	$p < .05$*
TD Group	Sentence Comprehension	0.79	0.29	$p = .78$
Distributed				
	Sentence Comprehension	4.53	2.22	$p < .05$*
	Group	-0.47	-0.23	$p = .82$
	SES	0.04	0.49	$p = .62$

	Group*Sentence Comprehension	0.63	0.24	$p = .81$
Language Processing – RT				
Verbal-within				
	Sentence Comprehension	329.97	0.50	$p = .62$
	Group	1168.09	1.75	$p = .08$
	SES	-22.17	-0.81	$p = .42$
	Group*Sentence Comprehension	-1448.28	-1.72	$p = .08$
Verbal-divided				
	Sentence Comprehension	363.12	0.58	$p = .56$
	Group	1190.73	1.86	$p = .06$
	SES	19.81	0.77	$p = .44$
	Group*Sentence Comprehension	-1396.49	-1.71	$p = .09$
DLD Group	Sentence Comprehension	-1133.93	-2.06	$p < .05$*
TD Group	Sentence Comprehension	295.15	0.49	$p = .62$
Nonverbal-within				
	Sentence Comprehension	710.71	0.90	$p = .37$
	Group	1128.79	1.41	$p = .16$
	SES	16.21	0.50	$p = .62$
	Group*Sentence Comprehension	-1233.92	-1.21	$p = .23$
Nonverbal-divided				
	Sentence Comprehension	-92.96	-0.09	$p = .93$
	Group	1405.89	1.30	$p = .19$
	SES	21.05	0.46	$p = .64$
	Group*Sentence Comprehension	-1696.34	-1.26	$p = .21$
DLD Group	Sentence Comprehension	-1936.63	-2.43	$p < .05$*
TD Group	Sentence Comprehension	-180.49	-0.16	$p = .87$
Distributed				
	Sentence Comprehension	976.41	1.09	$p = .28$
	Group	2682.90	2.90	$p < .01$**
	SES	20.15	0.54	$p = .59$
	Group*Sentence Comprehension	-3185.35	-2.71	$p < .01$**
DLD Group	Sentence Comprehension	-2294.18	-2.59	$p < .05$*
TD Group	Sentence Comprehension	911.92	1.16	$p = .25$
Nonverbal Ability – Accuracy				
Verbal-within				
	Matrix Reasoning	0.00	0.10	$p = .92$

	Group	-5.76	-2.22	$p < .05$*
	SES	-0.18	-1.58	$p = .12$
	Group*Matrix Reasoning	0.08	1.60	$p = .11$
DLD Group	Matrix Reasoning	0.08	3.15	p < .01**
TD Group	Matrix Reasoning	-0.00	-0.07	$p = .94$
Verbal-divided				
	Matrix Reasoning	-0.01	-0.31	$p = .76$
	Group	-6.41	-2.73	$p <$ .001***
	SES	-0.09	-0.83	*p = .41*
	Group*Matrix Reasoning	0.10	2.34	$p < .05$*
DLD Group	Matrix Reasoning	0.09	3.31	$p < .01$**
TD Group	Matrix Reasoning	-0.01	-0.39	$p = .69$
Nonverbal-within				
	Matrix Reasoning	0.11	3.91	$p <$ .001***
	Group	3.09	1.55	$p = .12$
	SES	0.04	0.44	$p = .66$
	Group*Matrix Reasoning	-0.07	-1.79	$p = .07$
Nonverbal-divided				
	Matrix Reasoning	0.02	0.66	$p = .51$
	Group	-4.27	-1.67	$p = .09$
	SES	-0.15	-1.23	$p = .22$
	Group*Matrix Reasoning	0.05	1.07	$p = .29$
DLD Group	Matrix Reasoning	0.09	3.50	p < .001***
TD Group	Matrix Reasoning	0.02	0.55	$p = .58$
Distributed				
	Matrix Reasoning	0.04	1.42	$p = .15$
	Group	-3.06	-1.54	$p = .12$
	SES	-0.03	-0.37	$p = .71$
	Group*Matrix Reasoning	0.05	1.43	$p = .15$
Nonverbal Ability – RT				
Verbal-within				
	Matrix Reasoning	-7.77	-0.95	$p = .34$
	Group	244.12	0.39	$p = .70$
	SES	-17.23	-0.61	$p = .54$
	Group* Matrix Reasoning	-3.50	-0.29	$p = .77$
Verbal-divided				
	Matrix Reasoning	-10.56	-1.38	$p = .17$

	Group	32.73	0.05	$p = .96$
	SES	25.44	0.95	$p = .34$
	Group*Matrix Reasoning	1.49	0.13	$p = .90$
Nonverbal-within				
	Matrix Reasoning	-12.78	-1.41	$p = .16$
	Group	551.01	0.80	$p = .42$
	SES	28.75	0.92	$p = .36$
	Group*Matrix Reasoning	-10.69	-0.84	$p = .40$
Nonverbal-divided				
	Matrix Reasoning	-29.61	-2.25	$p < .05$*
	Group	-709.51	-0.74	$p = .46$
	SES	40.57	0.88	$p = .38$
	Group*Matrix Reasoning	15.49	0.88	$p = .38$
DLD Group	Matrix Reasoning	-16.05	-1.21	$p = .23$
TD Group	Matrix Reasoning	-27.61	-2.26	$p < .05$*
Distributed				
	Matrix Reasoning	-16.68	-1.74	$p = .08$
	Group	1643.60	2.21	$p < .05$*
	SES	39.69	1.19	$p = .23$
	Group*Matrix Reasoning	-30.04	-2.15	$p < .05$*
DLD Group	Matrix Reasoning	-45.72	-4.32	$p <$ .001***
TD Group	Matrix Reasoning	-14.72	-1.60	$p = .11$
Attention – Accuracy				
Verbal-within				
	Attention	1.22	2.20	$p < .05$*
	Group	-1.92	-1.97	$p < .05$*
	SES	-0.17	-1.69	$p = .09$
	Group*Attention	0.49	0.50	$p = .62$
Verbal-divided				
	Attention	-0.53	-0.95	$p = .34$
	Group	-3.09	-3.05	$p < .01$*
	SES	-0.05	-0.50	$p = .62$
	Group*Attention	1.74	1.83	$p = 0.07$
Nonverbal-within				
	Attention	0.70	1.41	$p = .16$
	Group	-1.67	-1.81	$p = .07$
	SES	0.10	1.01	$p = .31$
	Group*Attention	1.43	1.50	$p = .14$
DLD Group	Attention	2.03	3.06	$p < .01$**
TD Group	Attention	0.77	1.28	$p = .20$
Nonverbal-divided				

	Attention	0.85	1.57	$p = .12$
	Group	-3.32	-3.37	$p < .001$***
	SES	-0.12	-1.14	$p = .25$
	Group*Attention	2.60	2.51	$p < .05$*
DLD Group	Attention	3.35	4.23	$p < .001$***
TD Group	Attention	1.00	1.47	$p = .14$
Distributed				
	Attention	1.42	3.15	$p < .01$**
	Group	-0.68	-0.82	$p = .41$
	SES	0.01	0.09	$p = .93$
	Group*Attention	0.66	0.74	$p = .46$
Attention – RT				
Verbal-within				
	Attention	-458.02	-3.68	$p < .001$***
	Group	-141.91	-0.60	$p = .55$
	SES	-19.73	-0.79	$p = .43$
	Group*Attention	88.37	0.37	$p = .71$
DLD Group	Attention	-360.75	-1.36	$p = .18$
TD Group	Attention	-465.73	-4.10	$p < .001$***
Verbal-divided				
	Attention	-236.54	-1.96	$p = .05$
	Group	288.97	1.21	$p = .23$
	SES	22.07	0.92	$p = .36$
	Group*Attention	-292.91	-1.21	$p = .23$
Nonverbal-within				
	Attention	-130.35	-0.83	$p = .41$
	Group	437.54	1.48	$p = .14$
	SES	17.46	0.56	$p = .58$
	Group*Attention	-460.17	-1.61	$p = .11$
DLD Group	Attention	-652.48	-2.61	$p < .01$**
TD Group	Attention	-131.66	-0.84	$p = .40$
Nonverbal-divided				
	Attention	-264.11	-1.25	$p = .21$
	Group	873.08	2.12	$p < .05$*
	SES	30.69	0.73	$p = .47$
	Group*Attention	-1000.74	-2.42	$p < .05$*
DLD Group	Attention	-1254.83	-3.98	$p < .001$***
TD Group	Attention	-257.99	-1.16	$p = .25$

Distributed				
	Attention	-217.54	-1.17	$p = .24$
	Group	607.60	1.68	$p = .09$
	SES	17.04	0.46	$p = .65$
	Group*Attention	-432.67	-1.19	$p = .24$

Note. Test-statistic = chi-sq for accuracy and t-value for reaction time; Group = Typically Developing vs. Developmental Language Disorder group comparison; Sentence Comprehension = Accuracy on the sentence comprehension task; NS = not significant; Matrix Reasoning = t-score on the Matrix Reasoning subscale from the Wechsler Abbreviated Intelligence Scale, Second Edition (WASI-II; Wechsler, 2011); *significant difference at $p < .05$; **significant difference at $p < .01$; *** significant difference at $p < .001$

References

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