Relationship Between the Verbal Working Memory System and Subtypes of Reading Disability

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Abstract

Across both research and clinical settings, memory deficits have been acknowledged as one of the major characteristics associated with developmental dyslexia. As such, a great number of studies have been conducted over the years to understand the complex relationships among dyslexia, verbal short-term memory (VSTM), and the central executive (CE). The results, however, have been mixed, potentially because few studies have differentiated subtypes of dyslexia within the samples. Further, many of the studies have focused on word-level and connected-text level reading deficits, resulting in a limited understanding of the relationship between memory and sublexical (or subword) deficits. Exploring memory in relation to subtypes may help to clarify and extend our knowledge of how specific sublexical core reading components (in particular, naming speed) interact with VSTM and CE. In the present study, the double-deficit hypothesis (DDH; Wolf & Bowers, 1999) was used to classify children with reading disabilities (RD) into subtypes (*N*=134, ages 7-9). The four subtypes were: phonological awareness deficits only (PD; *n*=33), naming speed deficits only (NSD; *n*=34), combined deficits (DD; *n*=39), and a group of children that do not fall neatly within the DDH framework but, who experience fluency deficits in connected text (unclassified readers, UcRD; *n*=28). The main purpose of the study was to assess whether RD subtypes under the DDH have distinct patterns of VSTM and CE functioning. The results established that children with sublexical deficits (PD, NSD, and DD) all have weaknesses in their verbal working memory systems. Further, there were no significant differences in VSTM and CE profiles across the subtypes. The implications of these findings in terms of the theory, assessment, and intervention of reading disabilities are discussed.

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Introduction

In alphabetic scripts, developmental dyslexia is typically characterized by a core deficit in phonological processing, which is defined as a difficulty in recognizing and manipulating the sounds of language (Stanovich, 1986). There has been robust evidence in both behavioral and neuroimaging studies of dyslexia to support the notion that phonological processing deficits underlie reading disabilities (e.g., Eden & Zeffiro, 1998; Share & Stanovich, 1995; Snowling, 1981; Temple, 2002). As a result, the phonological processing core deficit has become a widely accepted explanation for reading impairment in children. There has been evidence assembled over the years, however, to suggest that dyslexia is associated with cognitive processing deficits that go beyond the phonological core deficit. Accordingly, the area of cognition most notably linked to reading disabilities is memory.

In the learning disabilities literature memory deficits have long been acknowledged as a major characteristic of reading disabilities (e.g., De Jong, 1998; Gathercole & Baddeley, 1993; Jorm, 1983; Mann, Liberman, & Shankweiler, 1980; Perfetti, 1985; Siegel & Ryan, 1989; Swanson, Cooney, & McNamara, 2004; Swanson, Zheng, & Jerman, 2009). As such, a great number of studies have been conducted over the past three decades to understand the complex relationship between dyslexia and memory deficits. Although the research has been mixed, generally it indicates that children with reading disabilities perform poorly on verbal short-term memory (VSTM) and central executive (CE; or "working memory") tasks compared to skilled readers. Further, longitudinal studies indicate that VSTM and CE deficits persist throughout childhood and into adulthood for individuals with reading disabilities, meaning that they do not improve with development (e.g., Siegel, 1994; Swanson & Sachse-Lee, 2001). Thus, there is ample data to suggest that a relationship exists between deficits in the verbal working memory system (i.e., VSTM and CE) and dyslexia.

Most of the studies in the memory-reading literature have included children characterized largely by word recognition deficits (i.e., at the word level) and/or reading comprehension deficits (i.e., at the connected-text level). No studies (to the author's knowledge) have explored the verbal working memory system (i.e., VSTM and CE) in children with other well-established sources of reading impairment, such as naming speed deficits (or sublexical fluency deficits). Naming speed deficits are considered to be a second core underlying deficit in dyslexia, which manifest into reading fluency difficulties and ultimately reading comprehension problems (Badian, 1997; Kirby, Parrila, & Pfeiffer, 2003; Wolf & Bowers, 1999). Children with naming speed deficits are slower readers because they struggle with accessing and retrieving orthographic-phonological codes (or letter-sound correspondence), which results in poor reading fluency. Naming speed ability is typically indexed by rapid automatic naming (RAN) tasks. Specifically, RAN tasks require an individual to rapidly and continuously name sets of familiar visual stimuli (e.g., letters, digits, colors, or objects). Accordingly, RAN tasks capture a great many of the language, cognitive, and perceptual components underlying reading fluency.

Although naming speed deficits are well established in the reading disability literature, they have been under-studied relative to phonological processing deficits. Consequently, there are a limited number of studies that have examined naming speed deficits in relationship to VSTM and CE processing (e.g., Amtmann, Abbott, & Berninger, 2006). This is important because theoretically VSTM and/or CE are involved in RAN performance (e.g., Amtmann et al., 2006) and therefore implicated in naming speed deficits. Thus, one of the aims of this study is to evaluate VSTM and CE functioning in children characterized by naming speed deficits.

A practical framework to use for assessing the relationships among VSTM, CE, and naming speed deficits is the double-deficit hypothesis (DDH). The DDH is based on the work of Wolf and Bowers (1999; 2000; Bowers & Wolf, 1993) who demonstrated that there were children with reading disabilities that had poor naming speed skills, but intact phonological awareness abilities. They also recognized that for these children (with naming speed deficits) phonological processing reading interventions were not effective. Therefore, based on this and other evidence, they asserted that naming speed deficits may represent another core underlying deficit in reading disabilities, separate (in large part) from phonological awareness difficulties.

Subsequently, in a seminal paper Wolf and Bowers (1999) contended that a more differentiated view of reading failure (beyond the phonological processing core deficit) was needed and introduced the double-deficit hypothesis (DDH). Accordingly, Wolf and Bowers suggested that most children with reading disabilities fall into three subtypes: those with phonological awareness deficits only (PD; struggle with accuracy in subword processing), naming speed deficits only (NSD; have difficulty with fluency-related subprocesses), and combined deficits in PD and NSD, also known as double-deficits (DD; are considered to be the most severely reading impaired). More recently a fourth group of children that do not fall neatly within the DDH, but who experience fluency issues in connected text, has been added to the model (Ullman et al., 2009). They are identified with unclassified reading disabilities (UcRD). More details about each subtype's reading profile will be discussed later. It is important to note that Wolf and Bowers conceptualized the double-deficit hypothesis as a heuristic, rather than a conclusive explanation for reading failure. Further, they proposed the DDH to help the learning disability field acknowledge that phonological processing is not the only factor that affects dyslexia.

There are no studies that have examined VSTM and CE functioning according to the double-deficit hypothesis subtypes. Assessing memory within the DDH framework will allow for a general exploration of the relationships among VSTM, CE, and two core underlying deficits in dyslexia, that is, naming speed and phonological awareness deficits. Accordingly, if children with naming speed deficits only and children with phonological awareness deficits only have VSTM and/or CE impairments, this would provide evidence that memory is (perhaps) a common underlying factor among the different pathways to reading disabilities. Moreover, within the DDH context, it can be tested whether children with different sources of reading disability (i.e., PD, NSD, DD, and UcRD) have distinct VSTM and CE profile patterns. If so, this would suggest that the verbal working memory system is differentially involved in reading deficits. Therefore, the subtype approach would help further our understanding of the relationship between memory and reading disabilities and perhaps inform the design of reading interventions for children with different reading-memory deficit profiles. Thus, the present dissertation seeks to elucidate the relationships among VSTM, CE, and naming speed deficits, in particular, in dyslexia by using the DDH framework.

There is one overarching aim in the dissertation:

> To determine the nature of VSTM and/or CE profiles in children characterized by naming speed deficits only (NSD), phonological awareness deficits only (PD), combined deficits (DD), and unclassified reading disabilities (UcRD).

Thus, the following research question will guide the analysis for the study: Do different subtypes of reading disability, as classified by the double-deficit hypothesis, have significantly different verbal working memory system (VSTM and/or CE) profiles?

There are six chapters in the dissertation. Chapter 1 consists of a brief history about working memory and a review of Baddeley and Hitch’s model in order to introduce the reader to the constructs involved in working memory. Chapter 2 summarizes the nature of the relationship between VSTM and reading disabilities by discussing key topics from the literature. Similarly, Chapter 3 considers the relationship between CE and reading disabilities by discussing the main themes from the literature. Chapter 4 gives an overview about fluency, naming speed deficits, and the double-deficit hypothesis, including the subtypes. Chapter 5 describes the study, which includes the hypotheses, methods, and results. Finally, chapter 6 reviews the findings in relation to the hypotheses and discusses how the results may impact the theory, assessment, and remediation of dyslexia.

CHAPTER ONE

Overview of Memory

Until the late 1950's memory was defined as a unitary entity. By the 1960's, however, evidence began to surface that supported the existence of two memory systems (i.e., short-term memory, STM and long-term memory, LTM) (Brown, 1958; Peterson & Peterson, 1959; for a review see Baddeley, 2006). When the distinction was made between STM and LTM, different models were proposed to characterize the relationship between the two components. The most influential model introduced at the time was by Atkinson and Shiffrin (1968). In their model information from the environment was brought into a temporary sensory store and then transferred into a short-term store (STS). The STS consisted of a limited capacity and information was transferred into LTM if it was held for a certain period of time. Once the information was in the STS, it was used to carry out a range of cognitive tasks and transferred into and out of LTM.

In the 1970's, a new memory model was introduced that hypothesized there was more to memory than just the STS and LTM (Baddeley & Hitch, 1974). In the new model there were three-components that made up the memory system: the central executive (a limited capacity attentional control system), the phonological loop (or articulatory loop; a system that assists the central executive by holding and rehearsing sound and speech-based information), and a corresponding visuo-spatial sketchpad (a system that assists the central executive with non-verbalizable material). More recently, Baddeley (2000) added a fourth component to the model known as the episodic buffer. The episodic buffer is hypothesized to play an essential role in binding information together into chunks or episodes from each of the working memory components and LTM (see Figure 1).

Over the past thirty years, Baddeley and Hitch's multi-component working memory (WM) model has provided a useful framework for the empirical investigation of a wide range of constructs, including intelligence, reading, and reasoning (Miyake & Shah, 1999). Further, the model has been applied to understanding memory functioning in different learning-disabled populations including individuals with reading disabilities, math disabilities, and attention deficit hyperactivity disorder (ADHD).

1.1 A Note About Nomenclature

Before moving on to a more detailed discussion of Baddeley and Hitch's WM model, it is important to briefly note the terms used in the memory-reading literature because there are many inconsistencies. For instance, the term 'phonological loop' from the WM model is often referred to as 'verbal short-term memory (VSTM)' because phonological loop processes are represented in verbal STM measures (see Baddeley, Gathercole, & Papagano, 1998; Gathercole, 1998). Therefore, these two terms tend to be used interchangeably in the literature. Similarly, the central executive (CE) is commonly referred to as "working memory" because the elements measured in WM tasks include CE processing (e.g., attentional control processes) (e.g., Swanson, Zheng, & Jerman, 2009). Moreover, the term "working memory" is used broadly in both research and clinical contexts and may refer to different things. For instance, the term 'working memory' may refer to the entire working memory system (i.e., verbal STM, visual/spatial STM, CE, and episodic buffer), combinations of components (e.g., verbal STM and CE, or visual/spatial STM and CE), or individual components (e.g., the central executive).

Therefore, in order to prevent any misunderstandings in the present dissertation, the following nomenclature will be employed throughout: the terms phonological loop and verbal STM will be used interchangeably; the term central executive (CE) will be used to refer to the executive control system from Baddeley and Hitch's (1974) model; and the phrase verbal working memory system (VWMS) will refer to all of the verbal working memory components (i.e., verbal STM and CE) (see Figure 2).

1.2 The Multi-Component Working Memory Model

Short-term memory (STM)

The short-term memory system is used when small amounts of information are held passively (i.e., unchanged) for a short period of time. An example of an everyday STM task would be remembering a phone number (e.g., "987-222-6503"). Short-term memory is described as having two main components: the phonological loop and the visual-spatial sketchpad. There is also a third component known as the episodic buffer.

Phonological loop. The phonological loop or verbal short-term memory (VSTM) is the most thoroughly investigated and understood component of the multi-component working memory model. The phonological loop consists of two mechanisms: the phonological store and the subvocal articulatory system. The phonological store is specialized for the temporary storage of verbalizable material, including written and auditorally presented items, in addition to visual information that is nameable (e.g., objects).

The phonological store retains as much material as can be articulated (or spoken) by an individual within 1.5 to 2 seconds (Baddeley, 1986). After this time, information decays unless it is refreshed by the subvocal articulatory system (or the rehearsal process), which then lengthens the amount of time information is held in the phonological store. This system helps to retain verbal information in real time through covert (or inner-speech) rehearsal. It also appears to be the mechanism by which non-auditory stimuli (e.g., written text or objects) gain access to the phonological store, that is, through subvocal re-coding in the rehearsal system. Developmentally, the phonological loop steadily increases from preschool until adolescence (Siegel, 1994). On average, children four years of age can remember two to three items (or digits) and children twelve years of age can remember six items (Gathercole, 1998). Also, the spontaneous use of subvocal rehearsal does not occur until approximately 7 years of age (Gathercole & Hitch, 1993).

Evidence to support the notion that information is phonologically stored in the phonological loop (or VSTM) comes from the "phonological-similarity effect" (Baddeley, 1990). Briefly, the term 'phonology' refers to the smallest units of speech sounds within a language. The phonological-similarity effect is characterized by an individual having more difficulty remembering sequences of phonologically similar words (i.e., rhyming items) compared to sequences of non-similar words (i.e., non-rhyming items). That is, phonologically similar codes are harder to remember because the internal speech representations are easily confused (e.g., "bar, car, star, jar, tar") compared to phonologically distinguishable codes (e.g., "but, cat, sun, jump, tree"). The ability to recall information requires discrimination of codes and the more similar the codes, the more confusable and difficult it is to remember them. These results have been interpreted to suggest that items are stored phonologically in the phonological loop (Baddeley, 1990). For instance, if items were not encoded and stored phonologically, individuals would remember both lists of phonologically similar and non-similar words equally. Moreover, the phonological-similarity effect has been replicated in several other studies, confirming the notion that items are phonologically stored in the phonological loop (Gathercole & Baddeley, 1990; Halliday, Hitch, Lennon, & Pettipher, 1990).

The existence of a subvocal articulatory system or rehearsal mechanism is corroborated by the "word-length effect" (Baddeley, 1986, 1990). Accordingly, it is easier to remember a list of short words compared to a list of long words (at the same level of word frequency). It is suggested that lists of short words are easier to remember because they take less time to articulate, which allows for more time to rehearse and, therefore, prevents decay. For instance, an individual will have an easier time memorizing a list of short words, "put, ten, hat, nun," than a list of long words, "particular, tagging, household, napping," because they take a reduced amount of time to articulate. For this reason, the more rapidly items can be articulated, the greater the verbal short-term memory span. Therefore, Baddeley theorized that VSTM span, or the amount of information that can be held in VSTM, is a function of decay rate (i.e., a constant of 1.5 to 2 secs in the phonological store) and rehearsal rate (i.e., the number of words an individual can say per sec) put together.

Visuo-spatial sketchpad. The visuo-spatial sketchpad (VSP) is thought to be the visual parallel to the phonological loop in underlying processes: that is, the VSP also contains a store and rehearsal mechanism. The purpose of the VSP is to temporarily store non-verbal material (e.g., abstract shapes and spatial information). The VSP has proved difficult to study, as there is a lack of well-developed standardized measures of visuo-spatial knowledge that exists (compared to the language system). In terms of the organizational structure, researchers have hypothesized that there is a distinction between the visual and spatial aspects of the sketchpad system (see Milner, 1971; Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999). Further, some researchers suggest that the sketchpad is divided specifically into objects and location (e.g., Smith, Jonides, & Koeppe, 1996). For more detailed information on the theories about VSP see Pickering (2001).

Episodic buffer. The episodic buffer is the newest component introduced by Baddeley (2000). Over the years, behavioral and neuronal evidence has supported Baddeley and Hitch's original notion of there being separate processing systems for verbal and visual information (i.e., the phonological loop and visuo-spatial sketch pad). The multi-component WM model, however, did not account for "multi-modal" processing or general storage that can combine different kinds of information. Given this disparity, Baddeley proposed the addition of the episodic buffer to the working memory model. Essentially, the episodic buffer's function is to integrate information from different perceptual sources (or codes) and other memory systems into a single complex structure or episode. It is presumed to serve as an intermediary or "buffer" among the phonological loop, visuo-spatial sketchpad, and long-term memory (Baddeley & Wilson, 2002).

Central Executive

The central executive (CE) (also commonly referred to as working memory) is engaged in the simultaneous storage and processing (the manipulation or transformation) of information. Essentially, it is the ability to keep things in mind while performing complex tasks. An everyday example would be to read a story and comprehend it at the same time. To do this, an individual must read the words on the page and retain the information in short-term memory, while also processing the meaning of each word, analyzing the syntactic structure of the sentences, integrating information from each of the sentences, retrieving background knowledge from long-term memory to fill in the missing details, as well as monitoring/updating their interpretation of the text. Therefore, to read and comprehend text simultaneous storage and processing is necessary, which relies on the central executive.

The central executive essentially "regulates" the entire working memory system. There are four main functions the central executive is posited to perform, including: (1) directly controlling the activities of the phonological loop and visuo-spatial sketchpad (i.e., STM); (2) controlling encoding of information and retrieval strategies; (3) switching attention and suppression of irrelevant stimuli; and (4) retrieving information from long-term memory (LTM).

Baddeley (1986) initially characterized the central executive as an attentional control mechanism, which was based on the Supervisory Attentional System of Norman and Shallice (1986). Accordingly, Baddeley envisioned the central executive as a limited pool of general processing capacity (modality-free) that could perform any function outside of short-term memory. Essentially, CE was regarded as a 'catch all' for anything not explained by STM. The underlying mechanism(s) or processes that made up the central executive, however, were left undefined by Baddeley. Therefore, the identification and definition of the underlying mechanism(s) of the central executive has been an area of intense focus among memory researchers.

One of the main questions for researchers has been whether the central executive is a single executive controller or whether it is part of a larger integrated system made up of sub-systems or sub-processes. Baddeley has suggested that because of the 'variety and complexity' of executive deficits found in patients with frontal lobe damage, it is likely that the central executive is made up of sub-systems. He has also posited that the central executive may consist of a 'series of parallel but equal processes' that give the appearance of a central unitary controller (Baddeley, 1996).

In an attempt to understand the central executive, Baddeley broke it down into distinct features that an executive control system would have. For example, he postulated that the central executive is comprised of different sub-processes of attention, such as the ability to focus, divide attention, and switch it from one thing to another (Baddeley, 1996). Over the years, these elements of attention have been categorized into the following sub-processes: (a) updating and monitoring information (updating); (b) inhibiting irrelevant information (inhibition); and (c) shifting or switching between multiple tasks or operations (shifting) (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000).

Researchers have taken these postulated sub-processes (i.e., updating, inhibition, and shifting) and tried to determine if all of them act together in a unitary fashion or whether they play separate roles in executive tasks. For example, Miyake and colleagues (2000) examined the three sub-processes across an extensive battery of executive tasks (e.g., the Wisconsin Card Sorting Test, Tower of Hanoi, random number generation, operation span, and dual tasking) in a sample (N=137) of college-students (see Miyake et al., 2000 for detailed descriptions of tasks). Using confirmatory factor analysis they found that the sub-processes (i.e., updating, inhibition, and shifting) were moderately correlated with each other, but also separable. In addition, Miyake and colleagues demonstrated that the sub-processes contributed differentially to each of the executive tasks. For instance, updating was most strongly associated with random number generation (RNG) and operation span (a complex-memory span task); inhibition was important for RNG and Tower of Hanoi; and shifting strongly contributed to WCST. This suggests that updating, inhibition, and switching are part of a unitary system, but that they are also separable and independent entities as well.

Thus, Miyake and colleagues concluded that there is both a “unity and diversity” in the mechanisms that underlie the executive controller.

Other researchers have emphasized specific sub-processes as playing a major role in central executive functioning. For example, Engle and Kane (2004) suggest that inhibition or the suppression of irrelevant information is the key to CE performance, whereas some researchers support the notion that switching from one focus to another is significant (e.g., Barrouillet, Bernardin, & Camos, 2004), and still others propose that the ability to update and maintain information is essential for CE functioning (e.g., Miyake et al., 2000). Thus, a clear and complete conceptualization of the central executive remains elusive. As new approaches for analyses are developed (e.g., Miyake et al., 2000) and well-defined variables/measures are implemented in studies, a more concrete understanding of CE may be possible in the future.

CHAPTER TWO

VSTM and Dyslexia

For many years researchers have focused on understanding verbal short-term memory (VSTM) and its relationship to dyslexia. This is because a considerable number of studies have found a significant association between the two constructs (for reviews see Brady, 1991; Elbro, 1996; Wagner & Torgesen, 1987). It has been suggested that a strong link exists between dyslexia and VSTM because they both include phonological processes. For instance, poor phonological processing (i.e., the identification and manipulation of the smallest unit of sounds in spoken word, that is, phonemes) is a core component in reading disabilities. Similarly, in verbal short-term memory phonological processes are also involved because verbal information is phonologically encoded, stored in phonological form, and phonologically re-coded or rehearsed. Therefore, since dyslexia and VSTM both involve a great deal of phonological processing, it is reasonable to assume that they themselves are also interrelated.

The exact nature, however, of the relationship between dyslexia and VSTM has been ambiguous in the literature. In order to better understand the relationship I will first examine the links between poor VSTM and dyslexia, describe how VSTM is measured, explore the role(s) VSTM plays in reading development, review the possible underlying cause(s) of VSTM breakdown in dyslexia, and consider whether VSTM "causes" or contributes to dyslexia.

2.1 The Occurrence of VSTM Impairments in Dyslexia

Evidence of a relationship between verbal short-term memory capacity and dyslexia has come from studies involving digit, letter, real word, non-word and single-sentence recall tasks. Typical verbal short-term memory tasks require children to recall increasing strings of verbal items in sequential order (e.g., forward digit span). Findings from multiple studies have consistently shown that children with reading disabilities remember significantly fewer verbal items compared to skilled readers. Specifically, poor readers have difficulty temporarily storing auditorally presented strings of letters (e.g., Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1977), words (e.g., Katz & Deutsch, 1964; Mann, Liberman, & Shankweiler, 1980), and single sentences (e.g., Mattis, French, & Rapin, 1975; Perfetti & Goldman, 1976; Weinstein & Rabinovitch, 1971).

Researchers have also tested whether mode of presentation of verbal information affects poor readers' short-term memory recall. That is, if an item is presented visually, such as, a letter of the alphabet (picture of 'A') or a common object (picture of a ball), do children with reading disabilities still recall fewer items than skilled readers? The answer is yes. Regardless of the mode of presentation any information that is 'verbalizable' (or phonologically represented in language) is more difficult for poor readers to remember than typical readers (Shankweiler & Liberman, 1976). Researchers have, therefore, concluded that poor readers experience short-term memory deficits for verbalizable (i.e., linguistic) information.

Further evidence in support of a relationship between poor VSTM functioning and reading disabilities can be found in a comprehensive meta-analysis by O'Shaughnessy and Swanson (1998). Within the meta-analysis there were 33 studies (out of 155) that met strict criteria for inclusion (for details about the criteria please see O'Shaughnessy & Swanson, 1998). According to the results, students with reading disabilities (average age 11 years) significantly showed deficits in verbal STM performance compared to typical readers. Further, although the scope of the present paper does not include the relationship between visual-spatial STM and dyslexia, it is interesting to note that there were no significant differences between poor and good readers for memorization of non-verbal stimuli (i.e., stimuli that are not represented linguistically, such as, abstract shapes).

The VSTM-dyslexia relationship is also substantiated by research in other orthographies outside of the alphabetic script. For example, some researchers have tested whether VSTM deficits exist in syllabary (e.g., Japanese Kana) and logography based scripts (e.g., Japanese Kanji and Mandarin Chinese). Findings have shown that children with reading disabilities in syllabic and logographic scripts have poor verbal short-term memory (Mann, 1985; Ren & Mattingly, 1990). Therefore, these studies suggest that verbal short-term memory deficits may be common among poor readers of other languages. In conclusion, based on the accumulation of evidence, it appears a strong link exists between verbal STM deficits (i.e., difficulty with temporary storage of verbal information) and dyslexia.

2.2 Measuring Verbal Short-Term Memory

Tasks that tap into VSTM index temporary storage capacity, whereas tasks that tap into CE index concurrent storage and processing. In this section, I will discuss VSTM tasks and the most common ones used in clinical as well as research settings.

For clinical purposes, when diagnosing memory deficits in children Gathercole and Alloway (2006) suggest starting with subtests from standardized ability tests, such as the digits forward and digits backward span (the composite is known as “Digit Span”) on the Wechsler Intelligence Scale for Children, fourth edition (Wechsler, 2003). These tasks are common measures of the verbal working memory system and are used in clinical and research settings. The digits forward span (DFS) assesses verbal short-term memory (or the phonological loop). The task involves the auditory presentation of random digit sequences of increasing length (e.g., ‘2-4-7-9-3’) that the child must verbally recall in order. Other measures of VSTM, such as word span, follow the same format as DFS and include the auditory presentation of un-related single words of increasing set lengths (e.g., ‘goal, fish, lamp, car, cup’). The highest number of items recalled in the correct order determines VSTM capacity. The DFS and word span are both classic tasks that index verbal short-term memory storage capacity.

A task that is similar to the digits forward span is the digits backward span (DBS). The DBS, however, has been a subject of debate within the memory field. The DBS task is traditionally regarded as a central executive measure because it is posited to involve concurrent storage and processing. It has been questioned though, whether DBS actually taps into the executive-attentional capacity of CE or rather the storage aspect of VSTM. The digits backward span is similar to the DFS in that both involve the auditory presentation of random digit sequences of increasing length. They are distinct from each other, however, because the child must recall the digit sequences in the reverse order (e.g., if '4-8-5-2' is presented, then '2-5-8-4' is the correct recall response), as opposed to the same order. Some researchers argue that the reversal activity in the digits backward span may not necessarily involve simultaneous storage and processing. For instance, an individual could conceivably store all of the digits first then reverse the order of the digits, instead of simultaneously storing and reversing the digits at the same time. If this were the case, then DBS would not tap into central executive functioning; rather, it would tap into storage capacity only (or VSTM). Related to this is the contention that the processing activity (i.e., the reversal of numbers) is not demanding enough to engage CE capacity (Colom, Abad, Rebello, & Shih, 2005; Engle, Tuholski, Laughlin, & Conway, 1999). For these reasons, a number of researchers have suggested that the digits backward span task is similar in complexity to the forward recall task (e.g., Rosen & Engle, 1997).

Other researchers have reasoned that the mental reversal of numbers (the processing component) involves more than storage and that it does require executive-attentional processing or CE resources (e.g., Elliot, Smith, & McCulloch, 1997). Evidence to support this comes from studies that have found close relationships between performance on the digits backward span and performance on other central executive memory measures (e.g., listening recall and counting recall) (see Gathercole, Pickering, Ambridge, & Wearing, 2004; Oberauer, SuB, Schulze, Wilhelm, & Wittmann, 2000).

For instance, in a recent study St. Clair-Thompson (2010) specifically examined the relationships between digits backward span and other memory measures (e.g., short-term and central executive capacity) in both children and adults. Using confirmatory factor analysis, the author found that DBS loaded onto a working memory factor (CE) for children and onto a short-term memory factor for adults. These findings suggest that digits backward span is a good central executive measure for children (e.g., ages 6-8), but perhaps not for adults. The author reasoned that the cognitive resources employed in different memory tasks vary as a function of individual ability or developmental capacity. That is, children employ their attentional resources (i.e., CE capacity) when reversing sequences of digits in the DBS task because it is challenging for them developmentally. Whereas for adults, the task is less attentionally demanding (i.e., more routine) and, therefore, involves largely storage processing. Based on these findings, it appears that the digits backward span is an appropriate measure of central executive capacity for children, but not necessarily for adults. Thus, given that the present study will investigate memory in children (and not adults), the DBS task will be classified as a CE measure.

In general, Gathercole and Alloway (2006) assert that the digits forward and backward span tasks mainly serve only as preliminary markers of memory functioning and that additional memory tasks should be administered to make a clinical diagnosis. For instance, research has shown that digit span tasks (i.e., DFS and DBS) can be insensitive indices of the verbal working memory system in below average and typically developing children because they only identify individuals with severe weaknesses (i.e., >1SD below the mean) rather than those with mild or moderate issues (Baddeley, 1990; Daneman & Carpenter, 1980; Gathercole & Baddeley, 1993; Savage & Frederickson, 2006). In addition, some children with number-based processing problems may perform poorly on digits span tasks because of their difficulties with the numerical stimuli rather than memory issues per se.

One measure that is considered to be a more sensitive index of VSTM and that does not include numerical stimuli is nonword repetition (NWR). Nonword repetition consists of the examiner orally presenting multi-syllabic nonwords (e.g., ‘loddenapish’) that the child must repeat as accurately as possible. The test items start with one-syllable nonwords (e.g., ‘ral’) and eventually increase up to seven-syllable nonwords. The highest number of accurately repeated nonwords determines a child’s score. Nonword repetition has been associated with early reading acquisition (Masterson, Laxon, Carnegie, Wright, & Horslen, 2005), vocabulary ability (Gathercole, Service, Hitch, Adams, & Martin, 1999) and articulation rate.

In fact, some researchers suggest that the NWR task is a better measure of the phonological loop than the digits forward span task because it does not include any lexical or semantic information, which may influence performance (e.g., Gathercole, Willis, & Baddeley, 1991). There is, however, research that suggests nonword repetition measures more than the phonological loop because it may tap into LTM for stored phonological codes (e.g., Baddeley, Gathercole, & Papagno, 1998; Roodenrys & Stokes, 2001). For instance, nonwords (e.g., 'loddenapish') use the same letters and phonological representations as in real words. Although there are no LTM representations for non-words (because they are 'made-up' words used in experimental or clinical settings), the letters (orthography) and their sounds (phonology) are represented in LTM. Therefore, when a child temporarily stores a non-word, theoretically the orthographic-phonological codes of the letters are retrieved from LTM to support verbal short-term memory storage. Even though LTM may be involved in nonword repetition, the task is still considered to be one of the most sensitive measures of verbal short-term memory capacity.

2.3 What Role Does VSTM Play in Reading?

Research suggests that verbal STM may play a major role in the development of pre-reading skills, such as the acquisition of letter knowledge. In an alphabetic script, letter knowledge refers to a child's understanding about letters, such as the visual appearance of them and the corresponding sounds they make. Familiarity with letters is important for the development of decoding skills and is, therefore, a precursor to learning to read words. In fact, studies have shown that a child's letter knowledge in kindergarten significantly predicts later reading ability (e.g., De Jong & van der Leij, 1999; Lonigan, Burgess, & Anthony, 2000; Scarborough, 1998).

Links between VSTM and the acquisition of letter knowledge have been demonstrated in typically developing children (e.g., De Jong & Olson, 2004;

Treiman, Tincoff, Rodriguez, Mouzali, & Francis, 1998). For instance, De Jong and Olson (2004) followed a group of Dutch children for the first two years of kindergarten (accordingly, there are two years of kindergarten in the Dutch school system) starting at age 4.5 and ending at age 6. In the Dutch system children do not develop letter knowledge (i.e., letter-names and letter-sound knowledge) until their second year of kindergarten. Verbal short-term memory (indexed by nonword repetition) was measured at the beginning of the group's first year of kindergarten and letter knowledge was measured at the beginning and end of their second year of kindergarten. The results showed that there were substantial correlations between VSTM (at the beginning of kindergarten) and later letter knowledge in the fall and spring of the 2nd year of kindergarten (0.39 and 0.44 respectively). Hierarchical regression analyses demonstrated that verbal STM accounted for a significant amount of additional variance (7% in the fall and 10% in the spring of 2nd year of kindergarten) even after age, nonverbal intelligence, and vocabulary were controlled for. This study, therefore, indicates that VSTM is involved in letter knowledge acquisition in typically developing children.

Although there is a link between VSTM and letter knowledge in typical readers, no studies (to the author's knowledge) have directly examined this relationship in poor readers. Researchers hypothesize that children with dyslexia have difficulty with their early letter learning and letter knowledge in kindergarten because of their poor VSTM functioning. It is possible, perhaps, that VSTM plays more of a role in the acquisition of letter knowledge for poor readers than for typical readers. Longitudinal studies, however, are needed in children at risk for developing reading impairment to provide direct evidence that VSTM plays a significant role in poor readers' letter knowledge development. Thus, until more research is done, it remains unclear whether VSTM constrains letter knowledge acquisition in children with reading disabilities.

Another reading skill posited to be influenced by verbal STM is phonological recoding (or decoding). Phonological recoding is the sequential translation of letters (e.g., 'cat') into their corresponding sounds (/k/ -/a/-/t/). It is a fundamental reading skill that typical beginning readers use to decode (or identify) words and that skilled readers use when they encounter new or unfamiliar words. Conversely, poor readers struggle significantly with obtaining this skill. Essentially, phonological recoding serves as a self-teaching mechanism for learning the sound patterns of words (Baddeley, Gathercole, & Papagno, 1998). That is, successful phonological recoding of a word (or the sequential translation of letters into sounds) reinforces that word's letter-to-sound pattern and cements it in long-term memory.

It has been hypothesized that verbal short-term memory is important for phonological recoding to occur. For example, in phonological recoding each letter's sound must be temporarily stored or held in VSTM until the last letter has been translated and the entire sequence of sounds can be blended together to form a word. Direct evidence of a relationship between phonological recoding and VSTM comes from an early study that found a correlation of .65 between verbal short-term memory performance and decoding (Dreyer, 1989).

Indirect evidence of a VSTM-phonological recoding relationship may be found in children with reading disabilities. For example, poor phonological recoding ability and inefficient acquisition of letter-sound patterns (i.e., phonemic awareness) are common symptoms among children with reading disabilities (e.g., Mark, Shankweiler, Liberman, & Fowler, 1977). Also, it is well established in the literature that poor readers have impairments in verbal short-term memory. Therefore, it may be the case that impaired VSTM functioning affects or constrains the learning of letter-sound patterns in children with dyslexia, which results in poor phonological recoding skills (and subsequently poor word recognition ability) (e.g., Snowling & Hulme, 1989; Swanson & Berninger, 1995).

Verbal short-term memory has also been implicated at higher levels of reading, such as reading comprehension. The ability to understand what one reads is the central purpose of learning to read text. Verbal STM is posited to play a role in reading comprehension because individual words of sentences must be sequentially and temporarily retained for higher-level language processing to occur (e.g., syntactic analysis and extraction of meaning). In general, researchers theorize that verbal STM serves as a "bottleneck" to higher cognitive level processing (Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1977; Mann, Liberman, & Shankweiler, 1980; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). That is, if text is not adequately retained in verbal STM (e.g., due to poor phonological processing, information decay from inefficient word reading, or even poor semantic skills; Cain, 2006), then the information is restricted and cannot be transferred up through the verbal working memory system to CE for higher-level language processing to take place (e.g., Nation, Adams, Bowyer-Crane, & Snowling, 1999; Perfetti, 1985, 1994; Shankweiler, 1989). Thus, it is hypothesized that VSTM impairment indirectly leads to reading comprehension deficits.

Links between verbal STM and reading comprehension have been found in developmental studies involving children 9 and 14 years of age (Leather & Henry, 1994; Swanson & Howell, 2001; De Jonge & De Jong, 1996). For example, Swanson and Howell (2001) found correlations ranging from 0.30 to 0.40 between verbal STM and reading comprehension performance in typical readers, indicating a fairly strong relationship. In addition, the same research team found in a different study that STM (both verbal and visual-spatial tasks combined) contributed a significant amount of variance (R^2=0.51, p< .001) to reading comprehension in 9 and 14 year-old good and poor readers (Swanson & Ashbaker, 2000). Moreover, STM provided an additional 7% of prediction power in reading comprehension after age, articulation speed, and central executive measures had been accounted for in the regression model. Together, these findings suggest that verbal STM ability may be involved in reading comprehension performance in good and poor readers.

In order to further understand the nature of the relationship between verbal STM and reading comprehension, various research groups have focused on children with reading comprehension deficits (e.g., Nation, Adams, Bowyer-Crane, & Snowling, 1999; Swanson & Berninger, 1995). There are two subgroups of children that experience reading comprehension difficulties. One of the groups consists of children with both poor word reading and poor reading comprehension skills (they are described as having “general reading disabilities”). The other group is characterized as having age-appropriate word reading skills, but poor reading comprehension ability, which has been linked to poor language comprehension skills (Stothard & Hulme, 1996; Yuill & Oakhill, 1991). This second group is often referred to as “poor reading comprehenders” or described as having specific reading deficits.

Swanson and Berninger (1995) used these differences between the two groups to investigate the roles of VSTM and CE in relation to word reading and comprehension abilities. Accordingly, a double dissociation design was employed in which children with reading disabilities were divided into four groups: (1) low word recognition abilities/low reading comprehension abilities (i.e., word reading deficits and reading comprehension deficits), (2) low word recognition abilities/high reading comprehension abilities (i.e., word reading deficits only), (3) high word recognition abilities/low reading comprehension abilities (i.e., reading comprehension deficits only), (4) high word recognition abilities/high reading comprehension abilities (i.e., typical readers).

The results indicated that VSTM measures were related to word reading ability, but not to reading comprehension performance. In contrast, the CE measures were related to reading comprehension ability, but not to word reading ability. No significant interaction was found, which suggested that the children with both reading disabilities (poor word reading skills and poor reading comprehension) had combined memory impairments, that is, both VSTM and CE deficits. Therefore, according to Swanson and Berninger (1995), comprehension deficits are related to CE functioning specifically and not to VSTM functioning.

In the study, however, the authors noted that their findings did not rule out the possibility that the relationship between CE and reading comprehension could be mediated by word reading ability and therefore, indirectly by verbal STM processes. In their data though, the authors did not find support for this notion and concluded that word reading ability did not account for the relationship between CE and reading comprehension (for details see Swanson & Berninger, 1995, p. 106). The results in this study must be interpreted with caution, however, because two skills important for reading comprehension were not controlled for across participants, namely, vocabulary knowledge and fluency (at the sublexical and/or word levels).

There are some studies that have controlled for vocabulary knowledge and word reading ability in poor reading comprehenders as another way to assess the relationship between VSTM and reading comprehension. For instance, Stothard and Hulme (1992) showed that skilled and less skilled comprehenders did not differ in verbal STM performance when they were matched on vocabulary and word reading ability. Another study that controlled for word reading and vocabulary ability employed a VSTM word span task, which increased in the number of syllables to be recalled. According to the results, both good and poor comprehenders were similarly affected by syllable length, indicating that there was no difference in verbal STM ability between the two groups. Together these findings suggest that VSTM is not significantly related to reading comprehension when both vocabulary skills and word reading ability are taken into account. Thus, it appears that verbal STM may play a minor or an indirect role in overall reading comprehension.

Some authors though, suggest that it may be involved in basic reading comprehension skills (e.g., processes involved in understanding simple sentences). For instance, Cantor, Engle, and Hamilton (1991) suggest that VSTM may be important for understanding the literal meaning of individual phrases or sentences (i.e., basic comprehension), as opposed to the conceptual gist or overall meaning of entire passages. Other researchers posit that VSTM may be essential when word order is critical for meaning, such as, when information must be remembered in a sequential form (e.g., Crain, Shankweiler, Macaruso, & Bar-Shalom, 1990). More studies into the role of VSTM in basic reading comprehension skills may be helpful in furthering our knowledge of the relationship between VSTM and reading comprehension.

In summary, the evidence of verbal STM impairments in children with reading disabilities is marked. Specifically, verbal STM ability may influence the following reading skills in poor readers: the acquisition of letter knowledge (i.e., pre-reading skills), the development of phonological recoding (i.e., a self-teaching mechanism for learning sound patterns), word reading ability, and possibly basic reading comprehension.

Given that verbal STM deficits have been strongly associated with reading disabilities it is important to consider where they come from. That is, what is the underlying cause(s) of verbal short-term memory impairments in children with dyslexia?

2.4 What Causes VSTM Impairments in Dyslexia?

Various hypotheses have been presented in the literature to explain the underlying cause(s) of verbal STM deficits found in children with reading disabilities. Some of the most prevalent theories include: (1) weak phonological processing in dyslexia leads to poor encoding in VSTM, (2) the phonological store itself is inefficient, (3) slower articulation rates lead to a smaller store capacity, and (4) long-term memory (LTM) representations are of poorer quality, which affects reconstruction of items in VSTM. Although a substantial number of studies have been conducted over the years to determine the source of VSTM deficits in dyslexia, the results have been inconsistent.

In an attempt to bring some consistency to the debate a researcher recently investigated the four main hypotheses from the literature to determine which of them best account for the verbal STM breakdown in dyslexia (Kibby, 2009). The results from the study were revealing; however, to understand them fully it is necessary to review each of the hypotheses.

First, a brief review of the structure of verbal STM is appropriate. Verbal short-term memory (the phonological loop) consists of two components: a phonological store and a subvocal articulatory system (or rehearsal loop). It is posited that only verbalizable information (i.e., anything that can be verbally articulated) is phonologically encoded into the store. The phonological store retains as much material as can be spoken within 1.5 to 2 seconds unless it is refreshed by the subvocal articulatory system (SVA; Baddeley, 1986). The SVA system sub-vocally rehearses the verbal information in order to prevent it from fading from the store. Long-term memory also supports the retention of information in the verbal STM store by accessing prior knowledge to reconstruct phonological codes when needed.

The first hypothesis identifies the initial process of encoding as an area of breakdown in VSTM. It has been suggested that children with dyslexia have difficulty encoding information into VSTM because of their poor phonological awareness abilities (i.e., their inability to identify and manipulate units of sound). Essentially, this hypothesis assumes that poor phonological skills underlie the verbal STM deficits in dyslexia.

The second hypothesis proposes that the breakdown occurs in the storage component of VSTM. Some studies have found poor readers show no phonological-similarity effect, that is, they find it equally difficult to remember words that are phonologically similar and dissimilar. Researchers have interpreted this finding to mean that their phonological store is defective (e.g., Liberman et al., 1977; Mann et al., 1980; Shankweiler et al., 1979). Others, however, have demonstrated that the phonological-similarity effect is intact in children with reading disabilities (RD) when the list length is shortened (i.e., controlling for floor effects) (e.g., Hall, Wilson, Humphreys, Tinzmann, & Bowyer, 1983; Holigan & Johnson, 1988; Johnston, 1982). In a more recent study, Kibby, Marks, Morgan, and Long (2004) found that the list length did not appear to have an effect on the presence or absence of the phonological-similarity effect in children with reading disabilities. They instead found that the length of the words themselves affected the phonological-similarity effect. That is, when the length of the words was shortened, and there were fewer phonemes to process per word, children with RD showed the phonological-similarity effect (i.e., they had more difficulty recalling phonologically similar words compared to dissimilar words).

According to these findings, children with reading disabilities do, in fact, have intact phonological stores, but their phonological stores function with less efficiency, especially when greater phonological processing is required.

The third hypothesis suggests that slow articulation rate is the cause of VSTM deficits in children with RD. According to Baddeley (1986), memory span is determined by decay rate and rehearsal rate. Decay rate is defined as a constant of 1.5 to 2 seconds and rehearsal rate is based on the number of words an individual can articulate per second. Therefore, the faster the articulation rate, the more time there is to rehearse items and the larger the memory span. In contrast, the slower the articulation rate, the less time there is to rehearse and the smaller the memory span. A reduced memory span results in a less efficient VSTM system overall. Prior research has shown that children with RD have slower articulation rates (McDougall et al., 1994, 2002; Roodenrys & Stokes, 2001), while others have found no differences in poor readers' articulation rates (e.g., Kibby et al., 2004). Thus, it is unclear in the literature whether poor readers actually have slower articulation rates or not.

The fourth hypothesis posits that poorer or fewer quality long-term memory (LTM) representations (of phonological knowledge) is the source of VSTM deficits in RD. Long-term memory helps to expand VSTM span by providing phonological representations of stored words to support retrieval. That is, phonological structure knowledge stored in LTM is used to reconstruct words (or to complete the pattern) when they have partially decayed in the loop (Hulme, Maughan, & Brown, 1991). In addition, studies examining the role of LTM representations in verbal short-term memory capacity have found that both poor and typical readers have comparable LTM contributions when the stimuli are familiar (high frequency) words. When the stimuli, however, are unfamiliar (low frequency) words poor readers have a reduced verbal STM span compared to typical readers. This suggests that poor readers may have fewer and/or inferior quality LTM representations. It has been hypothesized that poor readers may have inferior LTM representations because of their limited reading experiences and/or poor vocabulary knowledge (Torgesen, 1998; Bishop & Snowling, 2004).

In Kibby's study (2009), all four of the hypotheses were examined. The study included a sample of 18 children with reading disabilities (identified using the discrepancy model) and 18 children with typical reading development between the ages of 9 to 14. The participants were matched on age, grade, gender, nonverbal intelligence and socioeconomic status (SES). The two groups, however, had significantly different verbal IQs (VIQ) (e.g., RD = 97.33; typical readers = 110.44). Therefore, the author treated VIQ as a covariate in the analyses in an attempt to statistically control for its influence on group performance differences.

An experimental task was used in the study to assess verbal STM. The measure required participants to memorize lists of five items that were presented orally by a computer and then to recall them in serial order. The task was divided into two blocks. One block assessed the phonological store using the phonological-similarity effect (rhyming vs. non-rhyming items). The other block assessed the sub-vocal articulatory (or rehearsal system) using the word length effect (shorter vs. longer words). Also within the task, different types of stimuli were used including high-frequency words (e.g., ‘shoe’), low-frequency words (e.g., ‘plateau’), and non-words (e.g., ‘cafo’) to evaluate the effect of word familiarity on VSTM. Articulation rate was measured according to the time it took participants to repeat a pair of stimuli out loud five times as quickly as possible. The times were recorded and averaged to yield a measure of articulation rate (i.e., item spoken per second). Phonological processing was assessed using a phonological awareness measure (i.e., a phoneme deletion task, say “/blut/” without the “/t/” sound; McDougall et al., 1994) and a phonological decoding task (i.e., the Word Attack subtest from the WJ-R; Jastak & Wilkinson, 1984). For more detailed descriptions of each of the measures used in the study please refer to Kibby (2009).

The results from the study were revealing in that each of the four hypotheses were correct depending on the type of stimuli presented (i.e., rhyming vs. non-rhyming items, shorter vs. longer-word items, and high-frequency vs.

low-frequency vs. non-word items). Kibby concluded that there were "multiple contributors" to the VSTM deficit associated with dyslexia. Specific findings from the study are briefly presented below with regards to each of the four hypotheses.

Recall that the first hypothesis stated poor phonological encoding results in a reduced VSTM span. The author predicted that non-word lists (e.g., nort, gite, moke) would result in the greatest group differences in VSTM span because encoding non-words depends mostly on phonological processing, as there are no LTM phonological representations for them. Findings from the study supported this hypothesis. The results showed that poor phonological awareness was related to a reduced VSTM span in children with reading disabilities when phonological processing of items was required. That is, phonological awareness was a strong predictor of non-word VSTM performance, but not real word VSTM. This is consistent with the literature (e.g., Kibby & Cohen, 2008; Kibby et al., 2004; Liberman et al., 1977; Mann et al., 1980; Wagner et al., 1994).

The second hypothesis theorized that an inefficient phonological store leads to poor VSTM functioning. It was predicted that the RD group would not show a phonological-similarity effect, that is, they would find it equally difficult to remember words that were phonologically similar and dissimilar (i.e., items that rhymed and items that did not rhyme). In the literature, the absence of a phonological-similarity effect is considered to be an indication of an inefficient phonological store. The results from the study were consistent with the hypothesis. That is, children with reading disabilities found it equally difficult to remember rhyming and non-rhyming lists of words compared to typical readers, indicating that the RD group had inefficient phonological stores. Moreover, when verbal IQ and articulation rate were controlled for, there was still a three-way significant interaction between group membership, item frequency, and phonological-similarity effect, suggesting that poor readers' inefficient phonological stores are not solely due to slow articulation rates or individual differences in verbal intelligence. The author interpreted these results to mean that children with RD have reduced efficiency in their phonological stores.

The third hypothesis stated that slow articulation rates in poor readers lead to inefficient VSTM functioning (McDougall et al., 1994; Roodenrys & Stokes, 2001). Recall that memory span is a function of articulation rate (AR). Therefore, a slow articulation rate results in a reduced memory span and subsequently poor VSTM. In this study, the author did not find significant group differences between the RD group's articulation rates and typical readers' articulation rates. Given that it is unclear in the literature whether poor readers actually have slower articulation rates, Kibby suggested that perhaps only some children with RD have slow articulation rates. In terms of the relationship between articulation rate and verbal STM functioning, the results showed that AR predicted VSTM performance in both groups. Additionally, AR was a significant covariate in the phonological-similarity and the word-length blocks. Thus, the findings suggest that articulation rate plays a role in VSTM functioning for poor and typical readers.

The fourth hypothesis posited that poor LTM representations are the main cause of VSTM deficits in reading disabilities. Children with dyslexia may have inferior LTM representations (i.e., fewer and lower quality) because of their limited reading experience and/or poor vocabulary knowledge. The author predicted that there would be no differences in memory span for high frequency (familiar) words because both groups should have similar LTM memory representations for them. Kibby, however, predicted that there would be significant group differences for both low-frequency words (e.g., plateau) and non-words (e.g., 'cafo'). Further, it was proposed that the non-words condition would show the greatest difference between the two groups. This is because it is posited that there are no LTM representations for non-words, which means a greater emphasis would be put on phonological processing skills. The findings in the study supported the hypothesis. There were no differences between the RD group and typical readers for high-frequency words, but there were group differences for low-frequency words and non-words. The comparable performance between the groups on high frequency words suggests that children with reading disabilities have intact VSTM functioning for familiar words (Kibby & Cohen, 2008; Lee & Obrzut, 1994; McDougall & Donohoe, 2002). The author conjectured that it could be because poor readers tend to encode, store, and retrieve words by their meaning, and they could use this strategy for recalling familiar words. In contrast, children with reading disabilities performed poorly on low frequency words and non-words, perhaps because of their inferior LTM representations.

In relation to the poor readers' LTM representations, the author noted that the RD group had lower verbal IQs compared to the typical readers. Kibby posited that the low VIQs in the RD group might be a contributing factor to their poor LTM representations because verbal IQ indexes vocabulary and acquired knowledge. In the analysis, she found that verbal IQ predicted VSTM performance for low-frequency items (i.e., items that do not have LTM representations) in poor and typical readers, indicating that VIQ may play a role in LTM representations. When verbal IQ was statistically controlled for, however, the group differences on low frequency words remained, suggesting that VIQ is not the only factor in LTM representations. Therefore, more research is needed into this area to identify the factors that affect LTM representations.

In summary, Kibby (2009) suggests that there are multiple factors that contribute to the VSTM deficits found in children with reading disabilities. For instance, it appears that poor phonological processing plays a major role in the encoding *and* storage of verbal material in VSTM. Also, even though the children with RD in the study did not have slower articulation rates, Kibby asserts that perhaps only some poor readers have slower articulation rates that affect VSTM capacity (since articulation rates for all of the participants predicted VSTM). Further, poor LTM representations of phonological knowledge may reduce the functioning of VSTM. Finally, findings from the study suggest that the ability to encode, store, and retrieve familiar words (i.e., high frequency words) is intact in children with reading disabilities, perhaps because poor readers make use of their semantic knowledge about words.

Although the results from Kibby's study are compelling, it is important to note there are limitations to the findings. First, the sample size of the study was quite small (controls *n*=18; RD *n*=18) and therefore, the results may not be generalized to the entire reading disability population. Further, only the discrepancy model was used to identify children with reading disabilities and not a low achievement model, which may have excluded a major portion of the RD population. Moreover, the developmental range of the child participants (i.e., 9-14 years of age) was quite large, which may have introduced more variability into the data. Lastly, the typical and poor readers were not matched on verbal IQ, that is, children with reading disabilities had lower VIQs than controls. Thus, more studies are needed to corroborate these findings.

2.5 Do VSTM Impairments Cause or Contribute to Dyslexia?

It is clear from the literature that verbal STM deficits are strongly associated with dyslexia. For example, VSTM impairments are commonly found among children with reading disabilities, VSTM functioning is significantly correlated with reading performance, and VSTM plays a role in various reading components (e.g., letter knowledge and phonological recoding). Therefore, some researchers have hypothesized that verbal STM impairments may actually cause reading disabilities, while others suggest that it may only be a contributing factor or merely a correlating variable.

In an attempt to decipher the relationship between VSTM deficits and dyslexia Pennington, Van Orden, Kirson, and Haith (1991) conceptualized six ways in which the two could be related and reviewed data from various studies accordingly. The six hypotheses included the following: (1) VSTM deficits are a primary symptom (i.e., VSTM deficits are a prerequisite for dyslexia); (2) a contributing symptom (i.e., VSTM deficits are a facilitator of dyslexia); (3) a secondary symptom (i.e., VSTM deficits are a consequence of dyslexia); (4) a correlated symptom (i.e., VSTM deficits are a correlate of dyslexia); (5) a reciprocal causation symptom (i.e., VSTM deficits are both a cause and a consequence of dyslexia); and (6) an artifactual symptom (i.e., VSTM deficits are artifactually related to dyslexia). Pennington and colleagues reviewed both cross-sectional (e.g., Conners & Olson, 1990; Felton, Wood, Brown, Campbell & Harter, 1987; Pennington, Van Orden, Smith, Green, & Haith, 1991) and longitudinal studies (e.g., Bradley & Bryant, 1985; Jorm, Shore, MacLean, & Matthews, 1984; Mann, 1984; Mann & Ditunno, 1990; Mann & Liberman, 1984) to assess the causal nature between VSTM deficits and dyslexia (i.e., the six possible ways that VSTM deficits may be related to dyslexia).

In the cross-sectional studies reviewed by Pennington and colleagues the results were inconsistent among the dyslexic samples. For example, some performed similarly on VSTM tasks compared to peer age (CA) and reading age (RA) controls, while other samples performed significantly worse than CA and/or RA controls (Conners & Olson, 1990; Pennington et al., 1990). They interpreted these results to mean that verbal STM deficits may only characterize a subgroup of dyslexics, or that the deficits are not persistent across development (both children and adults made up the samples), or lastly that a bias in the sampling may have resulted in an artifactual deficit in dyslexia (support for this comes from a study that contrasted dyslexia and ADHD (see Felton, Wood, Brown, Campbell & Harter, 1987).

Pennington and colleagues evaluated the longitudinal studies to explore whether VSTM deficits are a prerequisite for dyslexia (e.g., Bradley & Bryant, 1985; Jorm, Shore, MacLean, & Matthews, 1984; Mann, 1984; Mann & Ditunno, 1990; Mann & Liberman, 1984). Some of the major findings from each of the studies were as follows. In Bradley and Bryant (1985) VSTM performance (pre-readers ages 4 or 5) was inconsistent in predicting later reading skill when age, verbal intelligence, and general IQ at final testing were removed from the regression equation. In addition, VSTM performance at time 1 did not predict reading ability at time 2, whereas reading ability at time 2 predicted VSTM performance at time 3. Given the findings, the authors concluded that VSTM ability is a result of reading skill rather than a cause.

Two other longitudinal studies (e.g., Mann, 1984; Mann & Liberman, 1984) found a significant correlation between VSTM performance and later reading skill (.39 and .55 respectively), suggesting that VSTM ability is a correlating symptom. Another study, Mann and Ditunno (1990), tested cohorts of kindergarteners in the fall (or spring) and then again in first grade (fall or spring). Verbal STM was only predictive of one of the kindergarten cohorts and it added only 2% to the variance in reading ability. Similarly, Jorm and colleagues (1984) found that VSTM measures accounted for only 6% of the variance in later word naming skill. Together, the longitudinal studies suggest that VSTM ability plays a role in reading skill, but that it may not be a primary symptom or cause of dyslexia.

Based on the studies Pennington and colleagues examined, they concluded that VSTM deficits are not a prerequisite for dyslexia. Consistent with the literature, many of the studies indicated that phonological awareness is the primary deficit in dyslexia because it accounts for significant variance in later reading ability and predicts later reading skills compared to VSTM. They suggested that more research is needed to determine whether verbal STM deficits are secondary (i.e., a consequence of dyslexia) and/or artifactual (i.e., artifactually related to dyslexia) in relation to dyslexia because the findings were mixed. Therefore, according to Pennington and colleagues' (1991) review of longitudinal and cross-sectional studies it appears that VSTM deficits in dyslexia are best defined as contributing (i.e., a facilitator of dyslexia) and correlating symptoms (i.e., a correlate of dyslexia).

2.6 Summary

Over the past thirty years a great deal has been learned about the relationship between verbal short-term memory and individual differences in reading ability. For instance, we know that a majority of children with reading disabilities experience verbal short-term memory (VSTM) deficits. Further, some studies indicate that VSTM is significantly related to word reading difficulties and might play and indirect role in reading comprehension problems. Moreover, the research suggests that VSTM is important in the acquisition of letter knowledge (i.e., pre-reading skills) and phonological recoding (i.e., the ability to decode words), both of which are considered to be fundamental to reading development. Lastly, VSTM may be involved in basic reading comprehension (i.e., understanding the literal meaning of individual phrases or simple sentences).

Given that verbal short-term memory impairments are so prevalent in children with reading disabilities, researchers have tried to understand where the breakdown occurs. Multiple hypotheses have been proposed, however, there has been a lack of consensus in the literature. A recent study (Kibby, 2009) though, suggests that there are multiple factors that contribute to VSTM deficits in dyslexia. These include weak phonological processing skills, which affects encoding and storage in VSTM; slower articulation rates (in some LD-readers), which leads to a smaller VSTM capacity; and poor representations of phonological knowledge in LTM, which reduces VSTM functioning. Therefore, poor VSTM in dyslexia may result from various factors.

Finally, researchers have questioned over the years whether VSTM causes dyslexia. So far in the literature, both longitudinal and cross-sectional studies support the notion that deficits in VSTM do not solely cause dyslexia, but instead contribute to and correlate with reading disabilities (Pennington et al., 1991). Thus, overall it appears that VSTM is an important factor in reading disabilities.

CHAPTER THREE

The Central Executive and Dyslexia

The central executive (CE), commonly referred to as "working memory," is considered to be the most important and flexible component of Baddeley and Hitch's (1974) working memory model. For instance, the central executive has been implicated in complex cognitive tasks such as decision-making, mental arithmetic, writing, language and reading comprehension (Gathercole, Alloway, Willis, & Adams, 2006; Swanson & Siegel, 2001). Essentially, any task that requires the simultaneous storage and manipulation (or processing) of information involves CE memory.

As discussed in the Chapter 1, the central executive is a generalized (i.e., modality-free) limited-capacity entity that controls and coordinates the activities of the entire working memory system. Specifically, CE controls encoding and retrieval strategies in both verbal STM and visual-spatial STM. The central executive is posited to regulate the working memory system using three executive functions: (1) updating and monitoring; (2) inhibition of non-relevant information; and (3) shifting (or switching attention) between processes (Miyake et al., 2000). Additionally, the central executive is responsible for connecting and retrieving information from long-term memory (LTM).

3.1 The Occurrence of CE Deficits in Dyslexia

A number of studies over the years have shown that children with reading disabilities suffer from (verbally based) central executive deficits compared to typical readers (Siegel & Ryan, 1989; Swanson, 1999; Swanson & Alexander, 1997; Swanson & Sachse-Lee, 2001; Gathercole, Alloway, Willis, & Adams, 2006). For instance, in a recent meta-analysis of the memory-reading literature, Swanson, Zheng, and Jerman (2009) found that children with reading disabilities were significantly impaired on CE measures (and verbal STM) compared to typical readers. The mean effect size (i.e., differences calculated between typical and atypical reader performance in CE) was in the moderate range (e.g., -.61), indicating that poor readers struggle with CE deficits. Furthermore, the research suggests that verbal central executive difficulties (just like VSTM impairments) persist throughout childhood and into adulthood for individuals with reading disabilities (e.g., Siegel, 1994).

In the reading disability field, however, researchers have questioned whether the central executive is merely a proxy for general verbal ability (i.e., verbal IQ). For example, some suggest that verbal IQ drives the relationship between CE and reading ability because CE and verbal IQ tend to be positively correlated (Nation, Adams, Bowyer-Crane, & Snowling, 1999; Stothard & Hulme, 1992). Various studies have shown though, that the central executive is "dissociable" from verbal IQ (Cain, Oakhill, & Bryant, 2004; Gathercole, Alloway, Willis, & Adams, 2006, Swanson & Ashbaker, 2000). For instance, when the effects of verbal IQ are statistically controlled for, a significant relationship still exists between CE and reading ability. Therefore, the research suggests that CE is not simply a substitute for verbal IQ in relation to reading ability.

Additionally, various researchers have also questioned whether CE deficits in dyslexia are mediated by poor phonological processing skills, which are strongly associated with reading ability and linked to VSTM functioning. Findings from multiple studies, however, have demonstrated that when phonological processing performance is controlled for statistically, CE deficits still persist in poor readers (e.g., Gathercole et al., 2006; Swanson, 1999a).

In relation to this, researchers have also debated over whether VSTM functioning mediates the relationship between CE and reading ability. The reasoning follows that the central executive and verbal STM share variance with each other (are interconnected) in the verbal working memory system because CE regulates VSTM functioning (e.g., Baddeley & Hitch, 1974). Therefore VSTM may underlie the relationship between CE and reading ability. This is an important issue, which will be addressed further in a later section (3.6).

In this chapter, I will review how CE is measured, the relationship between the central executive and reading (specifically, reading comprehension and word recognition), the nature of CE as it relates to reading disabilities (i.e., domain general or specific?), and finally whether CE "causes" or contributes to dyslexia.

3.2 Measuring the Central Executive

The central executive (CE) is most commonly indexed by complex-memory span (CMS) tasks, which involve the simultaneous storage and processing (or manipulation/transformation) of information. Verbal complex-memory tasks have been shown to be highly predictive of academic achievement in children, including in math (e.g., Bull & Scerif, 2001; Gathercole & Pickering, 2000), reading comprehension (e.g., Gathercole, Pickering, Knight, & Stegmann, 2004; Swanson, 1994), and language comprehension (e.g., Cain, Oakhill, & Bryant, 2004; Seigneuric, Ehrlich, Oakhill, & Yuill, 2000). The CMS task is a powerful predictor of academic achievement because it captures the ability to store and process information at the same time, which is fundamental to learning.

The most influential complex-memory span task to date, and the one upon which all others are based, is Daneman and Carpenter's reading span task (1980). The original task consisted of participants reading aloud a series of unrelated sentences (the processing component), while also remembering the last word to each sentence (the storage component). For example, the participant would read four sentences and at the end of the series then recall the last word to each sentence in order. The task started with one or two sentences and gradually increased until the participant was unable to read the sentences and recall the words correctly. Therefore, a participant's 'working memory span' or central executive capacity was determined by the highest series of sentences they could read while correctly maintaining the final words in order.

Since the inception of the complex-reading span task many different versions have been used in research studies. Most of them vary in the processing activity. For instance, some verbal CMS tasks involve less cognitively demanding activities, such as, listening to or reading a sentence. Whereas others require more cognitively demanding processing, such as, judging the veracity of sentences (e.g., listen to a sentence then judge whether the statement is correct or not and answer ‘yes’ or ‘no’); answering questions about sentences read (e.g., the child reads the sentence, “Johnny went to the movies,” then they are asked, “Where did Johnny go?”); filling in the last word to a simple sentence (e.g., the child listens to the sentence, “Milk is bought at the ________” and they must complete the sentence); or solving oral arithmetic problems (e.g., The child is asked, “5+4-6=?”). Since the levels of processing have not been controlled for among different verbal CMS tasks, it has been difficult to interpret research results and to compare findings across studies.

One way to address this issue is to use standardized versions of CMS tasks across research studies. For example, there is one working memory test battery developed by British psychologists that is standardized for children, which includes three verbal complex-memory span measures (e.g., listening recall, counting recall, and backward-digit recall) (i.e., Working Memory Test Battery for Children; Pickering & Gathercole, 2001). Perhaps if standardized measures were utilized in research studies more often (as opposed to unique experimental versions) there would be greater consistency in findings and a clearer understanding of central executive memory.

In terms of clinical use, it is important to consider the ‘mode’ of processing involved in a CMS task and the population of children being assessed. For instance, in the case of a child with a reading disability, a complex-memory span task that involves reading as the process activity (e.g., read a set of sentences then recall the last word of each sentence) is not ideal because a poor performance on the task may reflect their difficulty with reading rather than a CE memory problem. The same is true for children with number-based processing difficulties. For example, if the complex-memory span task involves oral arithmetic problem solving, then the child's performance may be confounded by their lack of facility with numbers. Therefore, when using complex-memory span tasks to assess CE functioning, particularly in clinical populations (i.e., those with reading and/or math disabilities), it is important to take into account the 'mode' of processing in the CMS task.

Although complex-memory span tasks are the most common measures used in research to index central executive functioning, there is no clear consensus as to what exactly is being measured. For example, given that both a 'process' component and a 'storage' component are posited to occur simultaneously in a CMS task, it is difficult to decipher how much of each is being captured. In addition to this, researchers are uncertain of the specific executive processes that are implicated in a CMS task. The most common executive processes hypothesized to be involved include the ability to update/monitor incoming information, to shift or switch attention between mental sets, and to inhibit irrelevant information (Miyake, 2001). Even though the underlying mechanisms of CMS tasks are not well understood, they remain powerful predictors of academic achievement.

In addition to CMS tasks, there are other alternative measures that have been used in research and clinical settings to index central executive functioning. For instance, the digits backward span (DBS) is a standardized sub-test found in most intelligence tests (e.g., WISC-IV; Wechsler, 2003) and is frequently used (aside from CMS tasks) to assess CE. It is similar to complex-memory span tasks because it includes both storage and a processing component (e.g., digit sequences are read aloud to the child and the child must recall the digit sequences in reverse order). There has been debate, however, as to whether it actually taps into central executive functioning (see Chapter 2). Other tasks that have been used to index CE measures include, the Wisconsin Card Sorting Task (Palmer, 2000), dual processing tasks (e.g., Kibby, Marks, Morgan, & Long, 2004), and executive attention-related tasks (e.g., Roodenrys, Koloski, & Grainger, 2001).

All of these tasks though, have the same validity issues as complex-memory span tasks. That is, it is unclear what exactly is being captured by the measures. Therefore, there is no central executive task to date in which the underlying mechanisms are well defined and understood. Thus, additional research is needed to delineate the specific processes involved in CE tasks.

3.3 CE and Reading Comprehension

The purpose of the central executive is to store and process information concurrently, which requires the coordination of both lower and higher-order processes. Similarly, the ability to comprehend text also requires the coming together of lower and higher-order reading processes. Therefore, it is not surprising that CE has been strongly linked to, and is considered to be a key predictor of reading comprehension (Daneman & Carpenter, 1980; Engle, Cantor & Carullo, 1992; Friedman & Miyake, 2004; Gathercole, Brown & Pickering, 2003).

Over thirty years ago, Daneman and Carpenter (1980) demonstrated that a significant correlation exists between complex reading span tasks and reading comprehension performance in typical college-aged students. Since then, numerous studies have shown that performance on complex-memory span tasks (using verbal and numeric information) not only correlate with reading comprehension, but also predict reading ability in good and poor readers (e.g., Swanson, 2003; Swanson & Howell, 2001).

Moreover, studies have demonstrated statistically that the central executive contributes unique variance, separate from verbal short-term memory's influence, to individual differences in reading comprehension (Swanson, 1994, Swanson & Berninger, 1995). Additionally, one study indicated that the central executive explains significant variance in reading comprehension after the contribution of other important factors are taken into account, such as, word reading ability, vocabulary knowledge and verbal IQ (Cain, Oakhill, & Bryant, 2004). Thus, it is clear from the literature that the central executive is significantly associated with individual differences in reading comprehension.

3.4 How is CE Involved in Reading Comprehension?

Although the research demonstrates that there is a relationship between CE and reading comprehension, it is of value to discuss how CE is involved in reading comprehension. First, one must understand the complex processes involved in reading comprehension itself.

Reading comprehension can be defined simply as the ability to understand written text or to extract "meaning from reading." The actual act of gathering meaning from text, however, is not so simple. Reading comprehension involves a complex interplay between various levels of language (e.g., analysis of syntactic structure and semantics), reading (e.g., phonological awareness, naming speed, orthographic and morphological knowledge), long-term memory (e.g., vocabulary and background knowledge), the verbal working memory system (both VSTM and CE), and higher-level comprehension processes (e.g., inference making, anaphoric processing, use of context, monitoring/updating). Therefore, reading comprehension is comprised of both lower-level and higher-level processes.

The specific steps involved in reading comprehension consist of the following: decoding and accessing the meaning of each word (decoding and semantics); analyzing the syntactic structure of the sentences (syntax); integrating the information from each of the sentences (integration); identifying correct referents for pronouns (anaphoric processing); incorporating general knowledge to fill in missing details (make inferences); using surrounding text to decipher the meaning of ambiguous words or phrases (use of context); and finally monitoring whether the text has been interpreted correctly (monitor/update) (Cain, 2006). All of these steps together allow a reader to create a running "mental model" or a meaning-based representation of the text (Gernsbacher, 1990; Kintsch, 1998).

In the reading literature, the central executive is hypothesized to be integral to constructing mental models of text. Theoretically, a reader must store the 'just-read' word in verbal STM while concurrently computing the syntactic structure of the sentence, integrating (or linking) the next word or phrase, inhibiting irrelevant information, and retrieving information from LTM (e.g., vocabulary and background knowledge). The central executive is posited to be important for all of these processes to take place.

The exact mechanisms that underlie the relationship between CE and reading comprehension, however, have yet to be identified in the literature. One theory suggests that CE may be important for higher-level comprehension skills associated with meaning-based construction (e.g., text integration, inference, comprehension monitoring, anaphoric processing or use of context). This is because higher-level comprehension skills are posited to rely on central executive resources.

Higher-level comprehension skills are important for reading comprehension; particularly as word reading ability becomes more automatic in development. For instance, studies have shown that higher-level comprehension skills (namely, inference making, comprehension monitoring, and understanding story structure) in typical readers ages 8-11 years contribute unique variance to reading comprehension even after word reading and verbal skills have been accounted for (Cain, Oakhill, & Bryant, 2004). Thus, they are considered to play a fundamental role in creating coherent mental models of text.

There are relatively few studies that have directly assessed the relationships among higher-level comprehension skills, CE, and reading comprehension in typical and/or atypical readers. For typical readers, there is one study that investigated all three variables longitudinally (i.e., at ages 8, 9, and 11) with a sample size of 102 children (Cain et al., 2004). The authors first assessed whether CE and higher-level comprehension skills (specifically, comprehension monitoring, inference making, and knowledge of story structure) were significantly related to each other. The correlational analysis demonstrated that comprehension monitoring (at ages 8, 9, and 11; $r = .25$ to $.40$, $p < .01$), inference making (at ages 9 and 11; $r = .34$ to $.42$, $p < .01$), and knowledge of story structure (as indexed by a story title task at ages 8, 9, and 11; $r = .31$ to $.36$, $p < .01$) were significantly related to verbal CE capacity (indexed by a sentence span task). The authors interpreted this to mean that a significant relationship exists between CE capacity and specific higher-level comprehension skills.

Secondly, the authors examined whether CE mediated the relationship between the higher-level comprehension skills and reading comprehension performance. They performed a fixed-order hierarchical multiple regression analysis in which word reading accuracy, vocabulary, and verbal ability (verbal IQ) were entered first, followed by verbal CE measures (e.g., the digit backward span task and the sentence span task), and lastly the higher-level comprehension skills (e.g., inference-making or comprehension monitoring). The outcome variable was reading comprehension performance. The authors postulated that if verbal CE underlied the relationship between higher-level comprehension skills and reading comprehension, then once CE was taken into account (added into the equation) the higher-level comprehension skills would not contribute additional variance to the prediction of reading comprehension.

The results, however, showed that both inference making and comprehension monitoring contributed significant variance to reading comprehension at each time point (i.e., at ages 8, 9, and 11) even after verbal CE was accounted for. Cain and colleagues interpreted this to mean that although inference making and comprehension monitoring tasks involve some form of simultaneous storage and processing, performance on them does not completely depend on CE resources. Therefore, even though there is a relationship between CE and higher-level comprehension skills (as indicated by the significant correlations), it appears that CE is not the sole mediator between particular higher-level comprehension skills (i.e., inference making and comprehension monitoring) and reading comprehension performance.

It is important to note that the results in this study were based on typical readers and not children with reading disabilities. There are no known studies that have examined this in atypical readers. Therefore, it is not clear whether the relationship between CE and higher-level comprehension skills is the same or different for poor readers. It could be, for instance, that for children with reading disabilities CE mediates the relationship between higher-level comprehension skills and reading comprehension performance because of their weaknesses in CE functioning. That is, CE impairments may limit higher-level comprehension skills and therefore lead to reading comprehension deficits. Until studies, however, are conducted in children with reading disabilities it cannot be determined whether this is the case.

3.5 CE and Word Recognition

Both the central executive (e.g., Daneman & Carpenter, 1980; Engle, Cantor & Carullo, 1992; Friedman & Miyake, 2004) and word recognition (Perfetti & Hart, 2001; Shankweiler, Lundquist, Dreyer, & Dickenson, 1996) are considered to be strong predictors of reading comprehension. Given that CE and word recognition are related to reading comprehension, it may be the case that a relationship exists between CE and word recognition as well.

Accordingly, word recognition is defined as the ability to identify written words accurately and quickly (automatically) with little to no effort on the reader's part. Identifying words automatically allows an individual to read connected-text fluently and to comprehend written text.

In order to understand how CE and word recognition may be associated, it is important to describe how word recognition occurs. Identifying written words involves the coming together of multiple processes in a rapid and efficient manner, as in reading comprehension. For example, it includes the activation of phonological awareness (i.e., knowledge of syllables, phonemes, etc.), decoding (i.e., letter-sound correspondence), semantics (i.e., activation of contextually appropriate word meaning), and sight recognition (i.e., visual recognition of familiar words such as 'the').

In terms of the verbal working memory system, it is hypothesized that the following memory processes occur in word recognition. For example, the visual word form (or orthographic pattern) is encoded into VSTM, then relevant letter-to-sound knowledge is retrieved from LTM, the letters are sequentially decoded into sounds and then re-blended together to identify the word, and lastly, the word's meaning (semantic processing) is activated and retrieved from LTM. Further, if the word-form is familiar (e.g., 'the') then theoretically it may be held in VSTM as a visual match is made from LTM and the sound representation of the word, as well as the word's meaning, is retrieved. Thus, it is possible that the central executive, whose purpose is to maintain information while processing the same/or other information, regulate STM processing, and retrieve information from LTM, is involved in word-level recognition (or reading).

The majority of studies that have examined CE and reading have focused on the relationship between CE and reading comprehension. Consequently, there are very few studies that have reported on the relationship between CE and word recognition specifically (e.g., Bayliss, Jarrold, Baddeley, & Leigh, 2005; Georgiou, Das, & Hayward, 2008; Leather & Henry, 1994; Swanson & Alexander, 1997; Swanson & Ashbaker, 2000; Swanson & Howell, 2001).

The studies involving skilled readers have shown that CE contributes significant variance to word recognition. For instance, in one study by Georgiou, Das, and Hayward (2008) they examined the contribution of CE (as well as phonological awareness and rapid naming speed) to word reading and reading comprehension performance in children ages 8-10 years. In a hierarchical regression analysis, Georgiou and colleagues found that a sentence span task (Daneman & Carpenter, 1980) and a sentence question span task (an experimental complex-span task that involves more processing than storage), both contributed 9% to 12% respectively of the variance to word recognition after controlling for age. When other well-established predictors of word recognition, such as, phonological awareness and rapid naming were entered into the regression equation, however, CE no longer accounted for significant unique variance in word recognition. Together, these results suggest that CE is a predictor of word recognition, but that it does not account for unique variance beyond the effects of phonological awareness and rapid naming in skilled readers.

Similarly, Leather and Henry (1994) found that a listening span task and a counting span task (common CE measures) both significantly predicted word-reading accuracy (indexed by the Neale Analysis of Reading Ability; Neale, 1966) in 7 year-old skilled readers. That is, when age and vocabulary were controlled for, the listening span accounted for 31% and the counting span accounted for 19% of the variance in word reading accuracy. Therefore, it appears that in skilled readers, CE does contribute unique variance to word recognition beyond vocabulary.

In studies that have investigated LD-reader groups, it appears that CE also plays a role in word recognition performance. For example, Swanson & Alexander (1997) included both skilled readers and LD-readers from ages 8-12 years to determine the processes that best predict reading performance (i.e., word recognition and reading comprehension). Word recognition was indexed by the Reading Recognition subtest of the Kaufman Test of Educational Achievement (Kaufman & Kaufman, 1985). For the central executive, six different complex-span tasks were included in the study in order to provide both reliable and generalizable indicators of the construct (e.g., sentence span, visual-spatial span, counting span, and three dual-demand tasks). Most of the complex-memory tasks were subsumed under a general working memory system component known as the “g-component.” The g-component was comprised primarily of working memory (CE) measures as well as modular processes (e.g., phonemic deletion, orthographic choice, and semantic choice; for more details concerning how these factors loaded onto the g-component, see Swanson & Alexander, 1997). Even though the g-component consisted of both general and modular processes, the authors asserted that it indexed a general working memory resource system (i.e., CE).

The findings from the study were different for the skilled readers versus the LD-readers. For the skilled readers the phonological awareness component (made up of phonological choice and pseudoword repetition) best predicted word recognition performance (i.e., 6% of the variance), whereas in the LD-readers the g-component (general working memory system) significantly predicted word recognition performance (i.e., 10% of the variance) after age was controlled for.

The authors concluded that word reading recognition is most likely an automatic and rapid process for skilled readers, which means that it is less cognitively (or attentionally) demanding for them and therefore, would not require central executive capacity. These results support the findings from the Georgiou, Das, and Hayward (2008) study discussed earlier in this section, which found that CE did not account for unique variance in word recognition for skilled readers when other well-established variables such as, phonological awareness and naming speed, were taken into account.

In terms of the LD-readers, Swanson and Alexander concluded that word recognition is a labored and cognitively demanding activity for poor readers because their skills are not automatic and are inefficient just like in beginning readers. Therefore, for LD-readers the ability to recognize words demands more attention and/or cognitive resources, which requires the central executive.

In another study (Swanson & Ashbaker, 2000), LD-readers were matched with typical readers who were either at the same age or at the same reading-level. Accordingly, there were a total of three groups in the study: the LD-readers (15 years), the chronologically age matched peers (15 years) and the reading-level matched participants (7-9 years). The purpose of the study was to assess the contribution of CE, short-term memory and speech rate to individual differences in word recognition and reading comprehension. All of the participants were included together (i.e., all three groups) in the hierarchical regression analysis. When age and articulation speed were controlled for, a CE composite (made up of both verbal and visuo-spatial complex spans) explained 45% of the variance in word recognition. Further, when articulation speed, age, and STM were controlled for, the CE composite contributed an additional 6% of variance to word recognition. The authors concluded that CE (and STM) contributed unique variance to word recognition performance.

It is important to note, however, that the skilled readers and LD-readers were entered into the regression analysis together making it difficult to differentiate CE's contribution to word recognition for each group. Additionally, the CE composite was made up of both verbal and visuo-spatial complex spans, therefore, the specific contribution of the verbal complex span could not be deciphered (i.e., because it was not reported in the study).

In summary, based on the small number of studies reviewed it appears that CE is involved in word recognition ability, but the exact nature of its role is not clear. Moreover, there is evidence to suggest that CE may play a greater role in word recognition ability for poor readers than for skilled readers. More studies, however, are needed to confirm this hypothesis before it can be concluded that CE is differentially related to word recognition in LD-readers versus skilled readers. Perhaps when multiple studies are conducted using well-defined samples and standardized complex-memory span measures a clearer understanding of CE's role in word recognition will be reached.

3.6 Is CE General or Specific in Relation to RD?

Although research has shown there is a link between CE and reading disabilities, the nature of the relationship has been a matter of debate. For instance, it is unclear whether central executive deficits in children with reading disabilities are domain-specific (i.e., in the verbal domain and/or related to phonological processing only) or domain-general (i.e., a general system not specific to the verbal domain). Related to this issue is whether CE makes a direct or unique contribution to reading disabilities (e.g., in reading comprehension) separate from the influence of verbal STM. If so, this would suggest that children with reading disabilities suffer from central executive processing deficits (e.g., monitoring/updating, inhibiting, and shifting) that are independent of their verbal STM (or phonologically related) deficits. In order to shed light on these questions, researchers have focused on the relationship between the central executive and reading comprehension ability.

Proponents of the domain-specific account (i.e., those that assert CE deficits are based in the verbal domain) suggest that verbal STM mediates the relationship between CE and reading comprehension ability (Crain, Shankweiler, Macaruso, & Bar-Shalom, 1990; Stanovich & Siegel, 1994). For example, it is hypothesized that inefficient phonological processing in VSTM leads to a "bottleneck" effect wherein less amounts of information (e.g., words) are transferred into the central executive for on-line extraction of meaning. Therefore, it is suggested that deficits in lower-level processing (such as in VSTM) lead to higher cognitive level CE processing deficits, which results in poor reading comprehension. According to the domain-specific perspective, verbal STM is the intermediary between CE and reading comprehension. Thus, based on this notion the central executive alone does not contribute unique variance to reading comprehension.

Supporters of the domain-general theory (i.e., those that claim CE is a general system not specific to the verbal domain) contend that even though VSTM and CE inherently share variance together (i.e., because CE regulates VSTM functioning), the central executive contributes unique variance to reading comprehension. Further, generalists suggest that the central executive is not entirely specific to the verbal domain. That is, central executive capacity may be made up of generalized attentional resources that are not exclusive to the verbal domain or reading comprehension. Domain-generalists interpret this to mean that children with reading disabilities have less attentional executive resources (or smaller CE capacity) than skilled readers to perform any cognitive task (not just reading related tasks) that requires the simultaneous storage and processing of information (De Jong, 1998; Siegel & Ryan, 1989; Turner & Engle, 1989). Therefore, according to generalists, poor readers may suffer from CE processing difficulties that are not specific to their reading comprehension deficits.

Evidence in support of CE as a domain-general system comes from an earlier study by Turner and Engle (1989) on typical college-age students. In the study, central executive capacity was measured using two different tasks. One was a complex mathematic computation task in which the subject had to read and verify a mathematical operation (e.g., '4/2–1=1?') (processing component) followed by a word that they had to memorize (storage component). The other was Daneman and Carpenter's (1980) complex reading span task (i.e., subjects read a sentence and remembered the last word). In both tasks the amount of processing increased (the number of operations or length of sentences) and central executive capacity was determined by the number of words accurately recalled.

Turner and Engle's findings showed that the mathematic computation span task correlated with reading comprehension performance as strongly as the reading span task. Additionally, the mathematic computation version accounted for the same amount of variance in reading comprehension, as did the reading span task. Therefore, the findings indicated that CE capacity predicted individual differences in reading comprehension regardless of the specific-domain or kind of processing (math or reading) embedded into the task. Since Turner and Engle's earlier study, subsequent studies have supported their findings (Engle, Nations, & Cantor, 1990; Engle, Cantor, & Carullo, 1992; La Pointe & Engle, 1990). Thus, the research in typical adult readers suggests that central executive capacity is a general resource independent of specific domains (i.e., math or reading).

Swanson and his colleagues extended Turner and Engle's (1989) findings further by assessing domain-general and domain-specific models of central executive processing in children with reading disabilities (Swanson, Howell, Ashbaker, & Lee, 1996, experiment 2; Swanson, 1999b; Swanson & Sachse-Lee, 2001; Swanson & Ashbaker, 2000). For instance, Swanson (1999b) assessed the role of the central executive in children with reading comprehension and word recognition deficits. The participants in the study consisted of children with reading disabilities (referred to as "LD readers" in the study, *n*=18, 11 years of age) who had both word recognition and reading comprehension deficits (i.e., a standard score below 90 on both word recognition and reading comprehension measures, and a full scale IQ score greater than 90). Matched age controls (CA) (*n*=18, 11 years of age) and reading-level matched younger peers (RL) (*n*=18, 11 years of age) were also included in the study. In order to determine whether CE made a unique contribution to reading comprehension, separate from domain-specific phonological processes (referred to as the "articulatory system" in the study), Swanson included a verbal STM measure (i.e., nonword repetition) and multiple phonological measures (phoneme deletion, digit naming, and phonological choice). The central executive was measured using both verbal and visual complex span tasks (e.g., sentence span, visual-spatial span, and counting span, see Swanson, 1999b for details). Two other constructs, long-term memory (LTM) and processing speed, were also included in the study. The long-term memory construct consisted of a composite score, which incorporated the following tasks: orthographic choice, semantic choice, and vocabulary. Processing speed was also a composite score, which included multiple timed phonological tasks, such as, phonemic deletion, digit naming, phonological choice, and pseudoword repetition. Swanson reasoned that to understand the relationship between CE and reading comprehension, other variables, which could potentially play a role, had to be included.

In a correlational analysis Swanson first tested whether the influence of CE on reading was domain-specific or domain-general. He hypothesized that if CE was a domain-general system, then both verbal and visual-spatial complex span tasks would be significantly associated with reading comprehension. Following, if CE was domain-specific, then only the verbal complex-memory span measure would significantly correlate with reading comprehension. The results indicated that regardless of the type of task (i.e., verbal or visual-spatial), all CE span measures correlated significantly with reading comprehension performance. This was still the case even when both the articulatory system (which, included VSTM) and the LTM composite measure were partialled from the analysis, suggesting that CE processes were directly associated with reading comprehension. These findings are similar to Turner & Engle's (1989) results and provide further support for the notion that a domain-general system underlies the CE processes involved in reading comprehension.

Next, through a series of hierarchical regression analyses Swanson assessed the relative contribution of CE to reading comprehension in the full sample. The analyses revealed that CE processes (a composite z-score of all of the CE tasks put together) accounted for 40% of the variance in reading comprehension when entered into the equation first. When the articulatory system (which included VSTM) was entered into the model after the central executive, CE's contribution went down to 8%. Next, when the LTM composite was added to the equation CE's contribution was reduced down to 6%. The fact that the central executive's contribution to reading comprehension was reduced as a result of adding in and the articulatory system and LTM into the model suggests that these variables have a certain amount of influence on the relationship between CE and reading comprehension.

Therefore, it appears that the relationship between CE and reading comprehension is partially mediated by phonologically based bottom-up processes (i.e., the articulatory system, which included VSTM). The results also indicate that CE makes a unique contribution to reading comprehension beyond articulatory and LTM composites. Thus, these findings support both a domain-specific and a domain-general account of CE. Swanson therefore, reasoned that the central executive "operates as a general executive system that shares resources with several processes (i.e., VSTM), as well as one that reflects some processes that are unique and not shared with other systems," (Swanson, 1999b, p. 27).

Lastly, Swanson examined whether LD readers and skilled readers differed in CE processes not specific to reading comprehension. If so, this would suggest that children with reading disabilities suffer from general CE deficits not related to their reading difficulties. In the analysis Swanson controlled for reading comprehension ability and found that skilled readers (i.e., CA-matched readers) performed better on CE measures compared to LD readers. Additionally, the results showed that significant differences in phonological processing speed remained between CA-matched and LD readers after reading comprehension performance was controlled for. Swanson interpreted these results to mean that children with reading disabilities experience central executive processing and phonological processing speed deficits that are not specific to their reading comprehension abilities. Therefore, according to Swanson poor readers have general central executive processing difficulties that are separate from their reading comprehension impairments. This finding supports the notion that CE may be a domain-general system (i.e., a general executive system that performs executive processes not specific to the verbal domain) to a certain extent in children with reading disabilities.

According to Swanson, general CE difficulties may reflect poor attentional executive capacity. That is, LD readers may have problems in coordinating lower-order processes (e.g., phonological codes in VSTM) and higher-order cognitive processes together (e.g., switching between two levels of processing or accessing information from both lower and higher-order skills). Therefore, Swanson suggests that children with dyslexia perhaps have deficits in coordinating/organizing information or processes (that are not specific to the verbal domain) within the central executive.

In summary, Swanson's (1999b) findings support the notion that CE is a domain-general system because both verbal and visual-spatial complex spans correlated significantly with reading comprehension performance. Secondly, Swanson showed that CE has a direct influence (beyond phonological processing, VSTM, and LTM) on individual differences in reading comprehension (for similar results, see Swanson & Ashbaker, 2000). Thirdly, the results also indicated that CE shares variance with other variables (e.g., VSTM and phonological processing) in its contribution to reading comprehension, therefore, it is not completely a domain-general system. Further, Swanson hypothesized children with reading disabilities experience CE deficits that go beyond their reading problems. He found that after controlling for reading comprehension ability statistically, significant CE differences remained between LD readers and CA-matched readers. Swanson inferred from these results that poor readers have domain-general central executive processing difficulties that are not specific to their reading impairments. Thus, based on Swanson's findings it appears that the nature of CE processes (in reading comprehension) is both domain-general and domain-specific in children with reading disabilities.

Although Swanson's (1999b) findings have been supported by other studies (e.g., Swanson & Ashbaker, 2000; Swanson & Sachse-Lee, 2001; Swanson, Zheng, & Jerman, 2009), some researchers argue that the domain-general account of CE should be interpreted with caution. For instance, critics such as Savage and colleagues (2007) assert that the studies supporting CE as a domain-general system have used inconsistent samples of children with reading disabilities. They argue that in most of the studies there has been no control for common co-occurring issues in reading disabilities such as attention, language, or visual-motor difficulties. Savage and colleagues hypothesize that these variables may actually be driving the findings that children with reading disabilities have domain-general CE deficits.

For instance, studies that have compared children with reading disabilities only (RD) to those with co-occurring Attention-Deficit/Hyperactivity Disorder (RD+ADHD) on memory measures have shown that there are differences between the two groups (e.g., Dewey, Kaplan, & Crawford, 1997; Roodenrys, Koloski, & Grainger, 2001). Specifically, children with RD demonstrate poor verbal STM and children with RD+ADHD (and ADHD only) have poor central executive functioning, suggesting that the ADHD drives the relationship with CE (for a detailed discussion see Savage et al., 2007).

In terms of language, there have been indications in the literature that poor readers with and without language difficulties have different memory deficits (e.g., Bishop & Snowling, 2004). For example, poor readers with general language impairments (i.e., in verbal comprehension) may experience CE deficits compared to children who have reading difficulties at the word reading level only. Another area of concern for Savage and colleagues (2007) is the difference in criteria used for IQ. For example, some studies have included children with reading disabilities that have IQ's of 80 and above (e.g., De Jong, 1998) while others have included children with IQ's of 85 or above (e.g., Swanson & Ashbaker, 2000; Swanson & Sachse-Lee, 2001). Sample differences in IQ limits may allow for other factors (e.g., language experience and/or background knowledge) separate from reading difficulties to confound the data.

Finally, Savage and colleagues suggest that there is a lack of reliability and construct validity among the complex span tasks used to index central executive functioning (for a review see Savage et al., 2007). Further, there is no standardization between the complex-memory span tasks used across studies. In the end, Savage and colleagues suggest that by including well-defined samples of children with reading disabilities and standardized complex-memory span measures, perhaps a clearer picture will emerge of the exact nature between CE and dyslexia.

In conclusion, multiple studies indicate that the central executive makes a unique contribution (independent of verbal STM and phonological processing) to reading disabilities (i.e., reading comprehension) (e.g., Swanson, 1999b; Swanson & Ashbaker, 2000; Swanson, Zheng, & Jerman, 2009). Also, CE operates separately as well as together with other processes (e.g., VSTM) when it comes to reading comprehension. The question of whether CE difficulties in children with reading disabilities are based in a domain-general system (e.g., executive processes that cut across verbal and visual-spatial domains) or a domain-specific system (e.g., executive processes around the verbal domain only), however, has yet to be fully resolved in the literature. This is because there has been evidence to support either side (e.g., for evidence of a general CE system see Swanson, 1999b, Swanson & Ashbaker, 2000; Swanson, Zheng, & Jerman, 2009 and for evidence of a domain-specific CE see Nation, Adams, Bowyer-Craine, & Snowling; 1999; Seigneuric, Ehrlich, Oakhill, & Yuill, 2000). In relation to this, some researchers (Savage et al., 2007) suggest that various confounds have influenced the indefinite findings (e.g., a lack of well-defined samples and a lack of construct validity of indices of CE). Thus, it appears that future studies are needed with well-defined samples and standardized CE measures before a clearer understanding of the central executive can be reached.

3.7 Do CE Deficits Cause or Contribute to Dyslexia?

Research has demonstrated that CE impairment is strongly associated with reading disabilities and reading comprehension deficits in particular. Further, studies have also shown that CE contributes independent variance to reading ability beyond verbal STM (e.g., Swanson & Ashbaker, 2000) in children with reading disabilities. Therefore, some researchers have suggested that CE deficits may play a 'causal' role in dyslexia, whereas others have claimed that CE impairment is merely a contributor to dyslexia (alongside other variables).

Researchers that support the causal position suggest that a smaller central executive capacity underlies poor reading acquisition. For example, Turner and Engle (1989) assert that a smaller CE capacity (not entirely specific to reading) leads to fewer resources available for maintaining information and comprehending (or processing) text, which results in poor reading comprehension. Another researcher (Siegel, 1993) posits that CE plays a critical role in acquiring word-decoding skills. For instance, just like in beginning readers, the process of decoding words (i.e., converting graphemes to phonemes, or letters to sounds) is slow and effortful for children with reading disabilities. This is because when decoding a word, a child must integrate multiple processes, such as, activating the verbal rules in LTM, decoding each segment in the word, and holding all of the phonemes in VSTM long enough to blend them together to form the word. Many of these processes may require the central executive. Therefore, word-decoding skills are posited to rely on central executive functioning. Studies presented in an earlier section (e.g., see CE and Word Recognition) lend some support to this hypothesis by showing that CE contributes significant variance to word recognition in LD-readers (e.g., Swanson & Ashbaker, 2000; Swanson & Alexander, 1997).

Similarly, another group of researchers suggest that inadequate CE capacity may ‘cause’ poor development of phonological awareness skills, which is a precursor to word-decoding ability and considered to be one of the main underlying causes of dyslexia (Tunmer & Hoover, 1992; Tunmer, Herriman, & Nesdale, 1988). The authors reason that phonological awareness tasks (e.g., phoneme deletion) rely on CE resources. For example, in a phoneme deletion task a word is presented verbally (e.g., “hat”) and then the participant is asked what the word would be when a certain phoneme (sound) is taken away (e.g., the sound of /h/; the resulting word would be “at”). This task requires that the spoken word be held in memory (i.e., the storage component) while the phoneme is deleted from the word and the remaining phonemes are re-blended together to form the new word (i.e., the processing component). Therefore, it is posited that phonological awareness tasks, such as phoneme deletion, include concurrent storage and processing components, which requires CE resources.

Evidence in support of a relationship between CE and phonological awareness comes from an earlier study by Leather and Henry (1994). Their study consisted of 7-year old typical readers and showed that complex-memory span tasks (CE measures) strongly correlated (.32 to .50) with phonological awareness tasks (e.g., phoneme blending, strip initial phoneme, and strip final phoneme). Leather and Henry interpreted the results to mean that CE and phonological awareness tasks share common features (i.e., concurrent storage and processing). A more recent study in typical readers ages 8-10, also found similar correlations between CE tasks and phonological awareness measures (e.g., .31 to .39), supporting the notion that CE capacity is linked to the ability to manipulate phonological codes (e.g., Georgiou, Das, & Hayward, 2008; see also Kirby, Begg, & Martinussen, 1996; Papadopoulos, 2001; Rohl & Pratt, 1995).

Although the studies reviewed here indicate that CE capacity is significantly linked to sublexical processing (i.e., phonological awareness), word level reading (i.e., word recognition) and connected-text level reading (i.e., reading comprehension), the evidence to date is not robust enough to conclude that CE exclusively causes dyslexia.

Swanson and his colleagues have suggested a more modest version to the causal position. For instance, in a recent meta-analysis of the research literature on memory and reading in children with and without reading disabilities, Swanson, Zheng, and Jerman (2009) concluded, "…our results converge with studies on individual differences, which suggest that a WM (i.e., CE) system plays a critical role in reading. However, the present study does not completely eliminate the possibility that processing efficiency at some language level drives this relationship," (p. 280). Therefore, Swanson and colleagues assert that CE is “critical” to reading ability, but that it does not necessarily cause reading disabilities (RD). This is because a lack of efficiency at any level of linguistic processing may partially constrain the relationship between CE and RD.

Moreover, in an earlier study Jong (1998) attempted to assess the ‘causal nature’ of CE and reading ability by comparing complex memory-span performance (CE) in younger reading-level matched children with LD-readers. This method assumes that reading levels are controlled for and therefore group differences in CE performance will reflect developmental issues (there are caveats to this interpretation as Jong noted; see Goswami & Bryant, 1989; Jackson & Butterfield, 1989). The results from the study showed that both groups performed similarly on the CE tasks, suggesting that their developmental pathways did not differ in the CE component of the verbal working memory system. Jong concluded that, “the fundamental deficit of reading disabled children is in the processing of phonological information, but this deficit is manifested most clearly in the dynamic manipulation of phonological codes, as required in measures of working memory capacity (CE)…” (p. 90). Therefore, CE plays a major role in reading disabilities, as Swanson and colleagues (2009) have suggested, however, its role may be secondary to phonological processing (as suggested by Jong, 1998) or perhaps possibly parallel to phonological processing.

Thus, taking into account the theoretical explanations of how CE may underlie reading disabilities, along with the empirical evidence that exists in the literature, it is reasonable to assume that CE is an important contributor to reading disabilities. It appears though, that there is no concrete evidence to date to support the notion that CE is the sole 'cause' of dyslexia.

3.8 Summary

Overall, the research suggests that children with reading disabilities experience central executive (CE) deficits (Siegel & Ryan, 1989; Swanson, 1999b; Swanson & Alexander, 1997). Additionally, studies indicate that CE is most notably related to reading comprehension ability (Gathercole, Brown & Pickering, 2003). In relation to this, although VSTM and CE are partially associated in the verbal working memory system, the literature suggests that CE contributes unique variance (separate from VSTM's influence) to reading comprehension performance (Swanson, 1999b).

While there is a strong link between CE and reading comprehension ability, it is unclear how precisely CE is involved. It is posited that CE plays a role in the construction of mental models of text (i.e., the "gist" or overall understanding of the text) by maintaining and processing incoming information.

One way researchers have tried to elucidate the underlying link between CE and reading comprehension has been to investigate whether CE mediates the relationship between higher-level comprehension skills (e.g., inference making and comprehension monitoring) and reading comprehension performance. One study demonstrated that a significant relationship exists between CE and higher-level comprehension skills. In subsequent analyses, however, the same study showed that CE did not exclusively mediate the association between higher-level comprehension skills and reading comprehension ability (Cain et al., 2004).

Therefore, although CE is related to higher-level comprehension skills, it remains ambiguous as to what specifically drives the relationship between CE and reading comprehension performance.

In the literature, there has been a long debate over whether CE is domain-specific (i.e., in the verbal domain) or domain-general (e.g., a general executive system) in reading comprehension. Together, the research suggests that CE is both specific and general in its contribution to reading comprehension, that is, it operates separately (performs executive processes independently), as well as together with VSTM in reading written text. Additionally, Swanson (1999b) posits that children with reading disabilities have general CE deficits that are not related to their impairments in reading. This is an interesting hypothesis that if correct, could have implications for the remediation of CE functioning in children with RD. Thus, it would be useful for future research studies to explore this notion.

Lastly, researchers have questioned whether CE ‘causes’ or contributes to dyslexia. According to the theoretical explanations put forth in the literature (e.g., that CE underlies the acquisition of phonological awareness and/or word-decoding skills), as well as the empirical evidence that exists to date, it appears that CE does not exclusively ‘cause’ reading disabilities. The central executive can be considered though, to be a major contributor to reading ability (e.g., specifically, reading comprehension and perhaps word recognition, as well as, phonological awareness). Moreover, it may be the case that CE is a core-underlying variable in reading disabilities that works in conjunction with and/or parallel to other core variables, such as, phonological awareness. Overall, our understanding of CE is still evolving and additional research is needed to fully conceptualize the construct CE and to make clear its role in reading disabilities.

CHAPTER FOUR

Fluency and the Double-Deficit Hypothesis

4.1 Fluency

The purpose of reading is to comprehend or extract meaning from written text. The ability to comprehend text involves the integration of multiple cognitive and linguistic processes at all levels of reading (e.g., the subword, word, and connected-text levels). In particular, reading comprehension depends on fluency (i.e., accuracy and speed at multiple levels).

Traditionally in the research literature fluency has been measured and defined at the word-level. This is because rapid (fluent) word reading is an integral component of reading comprehension. For instance, if word reading is automatic (i.e., accurate and quick), then a child is able to use their resources to engage in higher-level processing and to comprehend text. As opposed to dysfluent word reading, or slow and laborious word decoding, which results in a lack of resources for the comprehension of text.

Over the years, however, researchers have argued that fluency involves more than rapid word identification and that a broader, more comprehensive view of fluency is warranted. For instance, Norton and Wolf (2012) describe reading fluency as “a manner of reading in which all sublexical units, words, and connected text and all the perceptual, linguistic, and cognitive processes involved in each level are processed accurately and automatically so that sufficient time and resources can be allocated to comprehension and deeper thought,” (p. 9-3). This definition of reading fluency takes into account the “multi-component” nature (e.g., perceptual, linguistic, and cognitive) of fluent reading comprehension and recognizes that both accuracy and speed are important at every level of reading, including the subword level.

4.2 Naming Speed

An overwhelming number of studies have demonstrated that naming speed (subword fluency) is one of the key processes (i.e., alongside phonological processing) involved in reading. For example, research has shown that naming speed is correlated with and/or predicts many aspects of reading, including the accuracy and speed of pseudo-word reading (a phonologically based measure), word reading, and text-reading comprehension (e.g., Arnell, Joanisse, Klein, Busseri, & Tannock, 2009; Georgiou, Das, & Hayward, 2008; Kirby, Parrila, & Pfeiffer, 2003). In addition, naming speed performance can be used to distinguish young children at risk for reading failure (Badian, 1993; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004) and can differentiate children with dyslexia from typical readers (Denckla & Rudel, 1974, 1976a, 1976b). Moreover, there is research to suggest that in both alphabetic and non-alphabetic orthographies RAN may be one of the best predictors of reading fluency (e.g., Georgiou, Parrila, & Liao, 2008), indicating perhaps that it taps into some kind of universal mechanism(s). Lastly, naming speed consistently predicts later reading in typical and atypical readers (Lervag & Hulme, 2009). Thus, naming speed is a powerful construct in reading development and reading disabilities.

4.3 A Microcosm of Reading

Some researchers posit that naming speed is a strong factor in reading because it is a "microcosm" of reading itself (Wolf & Bowers, 1999). That is, naming speed is made up of many of the same underlying perceptual, cognitive, linguistic processes that are involved in reading (e.g., motor movements, visual processes, general processing speed, working memory, attention, inhibition, phonology, and orthography). Therefore, measures of naming speed such as, rapid automatic naming (RAN), "provide a unique window into the integrity and speed of the components required for fluent reading…" (Wolf et al., 2009, p. 85). Accordingly, naming speed captures the multi-component nature of reading fluency.

4.4 Measuring Naming Speed (RAN)

Naming speed is typically indexed by the rapid automatized naming (RAN) task (originally designed by Denckla, 1972; developed by Denckla & Rudel, 1974, 1976a, 1976b; further refined and standardized for publication by Wolf & Denckla, 2005). It is important to note, that the term "RAN" is often used interchangeably with "naming speed" in the reading literature and specifically refers to continuous sublexical naming speed. The RAN task requires a reader to quickly and continuously name a set of visually presented familiar stimuli at the sublexical level. The stimuli are repeated in a randomized order from left-to-right and there are 10 stimuli per row across 5 rows. Stimuli consist of either alphanumeric (e.g., letters or digits) or non-alphanumeric items (e.g., colors or objects). Subsequently, there are four versions of the RAN task: letters, digits, colors, and objects. Performance is based on the total time (in seconds) taken to name all of the stimuli (i.e., 50 items). Errors and self-corrections do not influence the performance score but are noted by the examiner for qualitative purposes.

A characteristic of the RAN task that is important to highlight is the continuous naming component. The method of rapidly naming stimuli *continuously* from left-to-right across rows and down the page mirrors the visual, motoric, executive processes, and synchrony involved in skilled reading. As opposed to discreet naming (e.g., present each letter separately and record the reading time for that one letter), which involves just decoding and not the additional processes associated with reading strings of letters continuously. Therefore, this may be one reason why rapid automatic naming is such a strong predictor of reading achievement and reading fluency. In conclusion, RAN strategically captures the continuous and automatic nature of reading.

4.5 What Underlies the RAN-Reading Relationship?

Although research has demonstrated that there is an association between RAN (naming speed) and reading ability, it remains less clear all that underlies the relationship. Multiple hypotheses have been put forth in the literature including, phonological access (i.e., phonology), visual processing, orthographic processing, automaticity, and/or global processing speed (for a brief review of all of the hypotheses, see Kirby, Georgiou, Martinussen, Parrila, Bowers, & Landerl, 2010). In particular, and relevant to this dissertation, some researchers have posited that the verbal working memory system (i.e., VSTM and CE) may be an important factor in RAN (Arnell, Joanisse, Klein, Busseri, & Tannock, 2009; Amtmann, Abbott, & Berninger, 2007).

For example, Amtmann and colleagues (2007) hypothesized that the phonological loop, the central executive, and executive processes (e.g., inhibition) are involved in rapid automatic naming (RAN) and rapid automatic switching (RAS) tasks (i.e., the rapid switching of reading letters and digits). Using a novel approach, they analyzed the performances on RAN/RAS tasks according to the time it took participants to name each row of symbols successively (i.e., row-by-row), as opposed to calculating the total time it took to name all five rows together, which is the typical way to determine naming speed performance. The authors conjectured that the first row of the RAN (and RAS) task taps more into phonological loop (or VSTM) functioning and performance on the subsequent rows adds "executive functions of working memory" (e.g., inhibition). This is because naming in the first row involves the automatic retrieval of phonological representations, the cross-code integration of phonological representations to orthographic name codes, and overt articulation, all of which include the phonological loop. Whereas naming in the subsequent rows, involves additional demanding processes: such as, the sustained mental effort over a period of time, the simultaneous activation of current name codes, and the inhibition of prior name codes from previous rows. Therefore, the authors suggested that performance on subsequent rows (i.e., rows 2-5) involves the central executive and other executive processes, such as inhibition. It is important to note that in the memory literature, inhibition is considered to be one of the main underlying mechanisms of the central executive (e.g., see Engle & Kane, 2004).

The authors investigated three hypotheses; however, only the third one will be discussed because of its relevance to the present study (for the other hypotheses and their corresponding results see Amtmann et al., 2006). The hypothesis dealt specifically with the role of the central executive and other executive processes in predicting RAN (and RAS) performance. Within this context, the third hypothesis stated that the central executive (to which the authors referred to as “phonological working memory”) and executive processes (e.g., inhibition and self-monitoring) would be related to individual differences in RAN (and RAS) intercept (i.e., number of seconds to read the first row) and trajectories (i.e., successive performance row-by-row) in children and adults with dyslexia.

Central executive functioning was indexed using the Numbers Reversed subtest of the Woodcock Johnson-Revised (WJ-R; Woodcock & Johnson, 1990), which is a common CE task (i.e., similar to the digits backward span from the WISC-IV). Inhibition was characterized by the Color-Word Form subtest and self-monitoring was indexed by the Verbal Fluency Letters subtest of the Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001). Also, for the third hypothesis the analysis included both children (mean age 11 years) and adults with dyslexia (parents of the children, mean age 45 years).

Following, the results for the RAN task are discussed and only relevant key findings from the RAS task are presented. The predictor variables (CE, inhibition, and self-monitoring) were entered into the growth mixture models for the RAN analysis one at a time, in addition to all at the same time. Subsequently, the results supported the third hypothesis and showed that inhibition and/or the central executive predicted initial naming (of the first row) and/or subsequent naming time (row-by-row) in children and adults with dyslexia.

Specifically, for the children with dyslexia none of the predictors were significantly associated with initial naming of the first row. In contrast, sustained naming time (row-by-row) was significantly predicted by the variable, inhibition, for children with dyslexia in the "slower" naming class (i.e., individuals who were slower on the first row and progressively slower over time). Briefly, for the RAS task, CE significantly accounted for sustained naming time in the "slower" and relatively "faster" (i.e., faster naming on the first row and row-by-row) naming groups of children with dyslexia.

For the adults with dyslexia, inhibition (for the faster naming group) and CE (for the slower naming group) significantly predicted initial naming time for the first row. Subsequently, the study did not report any results for RAN sustained naming time (row-by-row) in the adults. For RAS though, CE and inhibition significantly accounted for sustained naming time (in the faster group) in the adults with dyslexia.

Amtmann and colleagues (2007) concluded that both the central executive and other executive processes, such as inhibition, contribute to RAN/RAS performance or the automatic mapping of phonological codes onto orthographic codes over a sustained period of time. Thus, their findings suggest that naming speed ability (as indexed by RAN/RAS) is related to processes in the verbal working memory system (specifically, the central executive and inhibition).

Briefly, another study also examined the processes involved in RAN by using eye-tracking techniques and manipulating the stimuli in the RAN task (i.e., the phonological rime, articulation onset, and visual properties of the stimuli; for details see Jones, Obregon, Kelly, & Branigan, 2008). Overall, their findings indicated that both visual and phonological processes influence naming speed ability in good and poor readers. Further, they suggested that, "Phonological information affected dyslexic readers' processing times, and resulted in a delay to articulate articulation. It is also possible that limited working memory resources for maintaining multiple and similar phonological codes may be implicated," (Jones et al., 2008, p. 394). Therefore, the authors suggested that poor capacity for maintaining and processing multiple phonological codes in CE may contribute to delayed articulation and ultimately naming speed ability.

Based on the theoretical accounts and the empirical evidence available, there appears to be support for the notion that naming speed (as indexed by RAN) and the central executive are significantly related. One way to further explore this relationship would be to establish whether children characterized by naming speed (RAN) deficits specifically have impaired VSTM and/or CE functioning. Within the reading-memory literature there are no known studies (to the author's knowledge) that have directly assessed VSTM and CE performance in children explicitly identified with naming speed deficits. Further, relatively few studies have even examined the association between naming speed and the VWMS. One reason is because most of the research in reading and memory has focused on reading ability at the word and connected text-levels, rather than at the sublexical level, including naming speed.

This is an issue because studies suggest that up to 60% to 75% of poor readers and individuals with learning disabilities struggle with RAN or naming speed deficits (e.g., Katzir, Kim, Wolf, Morris, & Lovett, 2008; Waber, Forbes, Wolff, & Weiler, 2004). Also, efficient orthographic-phonological retrieval (naming speed) is considered to be one of the foundations for reading development and a significant predictor of later reading ability. In addition, the processes that underlie naming speed represent a major aspect of reading disabilities. Investigation into the relationship between the VWMS and naming speed ability is important because this area of research may lead to a more refined understanding of memory and reading, as well as additional evidence towards a memory-naming speed association.

4.6 The Double-Deficit Hypothesis

A framework that would be useful for exploring the verbal working memory systems of children with and without naming speed deficits is the double-deficit hypothesis (DDH). The DDH is based on the work of Bowers and Wolf (e.g., Bowers & Wolf, 1993; Wolf & Bowers, 1999), who showed that some children with dyslexia could be characterized by naming speed deficits (i.e., difficulty with the processes underlying the rapid recognition and retrieval of visually presented linguistic stimuli) separate from phonological awareness difficulties (i.e., difficulty with recognizing and manipulating the sounds that make up words). They argued that naming speed deficits (NSD) signified a separate core deficit in dyslexia and that a more differentiated view of reading failure (beyond the phonological processing core deficit) was needed. As a result, Wolf and Bowers (1999) developed the DDH and contended that most children with reading disabilities fall into three subtypes: those with phonological awareness deficits only (PD), naming speed deficits only (NSD), or both deficits known as double-deficits (DD). More recently, a fourth group of children that do not fall neatly within the DDH have been added, and are categorized under an unclassified reading disability (UcRD) subtype.

It is important to note that Wolf and Bowers did not assume that the DDH was the only explanation for reading disabilities or that it would explain all sources of reading failure. Instead, they proposed the DDH to challenge and advance the field of learning disabilities towards a more multi-component perspective of dyslexia.

Since the establishment of the double-deficit hypothesis, numerous studies across multiple writing systems have supported the notion that naming speed and phonological awareness represent two separate core deficits in reading disabilities and that children can have deficits in both (or double-deficits) (e.g., Badian, 1997; Kirby, Parrila, & Pfeiffer, 2003; Wolf & Bowers, 1999). This has challenged the reading disability field to include a more differentiated view of dyslexia that takes into account the complexity and heterogeneity of the disorder.

Under the DDH, children identified with phonological awareness deficits (PD) score at or below the 25th percentile on phonological awareness tasks, which consists of two sub-tests known as elision and blending. Elision involves the ability to manipulate the components of a word (e.g., what is "cat" without the /k/? "at"). Blending measures the ability to synthesize language sounds or phonemes (e.g., the student hears /k/ -/a/ -/t/ and has to say “cat”). Therefore, phonological awareness indexes a child’s ability to recognize the number, type, and order of phoneme sounds within a syllable (i.e., at the subword level). Children with phonological awareness deficits struggle with sublexical processing (i.e., Elision and Blending), lexical processing (i.e., accurately reading non-words, which is known as word attack), and reading comprehension (i.e., poor word reading accuracy results in poor reading comprehension). They do not, however, have difficulty with naming speed performance (i.e., fluency-related processes); that is, they can rapidly and continuously name letters (or digits).

Children characterized by naming speed deficits (NSD) score at or below the 25th percentile on rapid automatic naming (RAN) tasks. As described earlier, RAN tasks require a child to automatically access and retrieve verbal labels for visually presented familiar stimuli at the sublexical level (i.e., letters, digits, colors, and objects). Children with naming speed deficits experience difficulty in one or more of the underlying processes involved in fluency. Accordingly, they struggle with timed reading and fluency measures at the sublexical and lexical levels. In addition, they often have poor reading comprehension ability, perhaps because of a lack of word automaticity (or fluent word recognition), which results in little resources available for comprehension. Further, some research has shown that children with naming speed deficits have difficulty with word accuracy in connected text, which may seem unexpected because they are relatively unimpaired in phonological processing (Katzir, 2003). Katzir suggests that reading words within a reading comprehension context "adds" a serial (or continuous) processing demand that is not present when decoding single-words, which is free from comprehension processing. Therefore, the rapid and serial presentation of words in connected-text affects the word reading accuracy of a child with naming-speed deficits. Generally though, phonological awareness at the subword level and decoding at the word level are both intact in children with naming speed deficits. That is, they tend to not struggle with phonological processing (or accuracy).

Children identified with double-deficits (DD) have a combination of both phonological awareness and naming speed deficits. That is, they score at or below the 25th percentile on both phonological awareness tasks and RAN tasks. Reportedly, this group of children is considered to be the most severely reading impaired and the most difficult to remediate (Wolf & Bowers, 1999). This is because they struggle with both fluency-related processes and phonological processing (or accuracy) Therefore, the DD group performs poorly on all aspects of reading (i.e., fluency and accuracy at the subword, word, and connected-text levels).

Lastly, children characterized with unclassified reading disabilities (UcRD) score above the 25th percentile on both phonological awareness and naming speed tasks. Although they do not struggle with accuracy or fluency at the sublexical level, the UcRD group still experiences reading impairments.

Recent research (Ullman et al., 2009) suggests that they have fluency issues mainly at the connected-text level (i.e., in rate and accuracy).

4.7 Summary

Naming speed (or RAN) is considered to be a “microcosm” of reading itself (Wolf & Bowers, 1999) because it captures the multi-component nature of reading fluency and in particular, the synchrony of all of the underlying fluency-related processes involved in reading. In addition, naming speed is a core construct in both reading development and reading disabilities. Therefore, it is important to understand how naming speed is related to the verbal working memory system (VWMS).

One way to explore this relationship is to assess VSTM and CE functioning in children with and without naming speed deficits. A useful reading disability framework to use is the double-deficit hypothesis (DDH; Wolf & Bowers, 1999). Employing the DDH will provide a rich context for investigating the VWMS and naming speed because it will allow for comparisons between children with different sources of reading impairment. This includes children with phonological awareness deficits (PD), naming speed deficits (NSD), combined PD and NSD (i.e., double-deficits, DD), as well as children with no PD or NSD, that is, those with unclassified reading disabilities (UcRD).

CHAPTER FIVE

Present Study

The main goal of this study is to evaluate the verbal working memory system profiles (i.e., VSTM and CE) of children who fall into different subtypes of reading disability. Using the “double-deficit hypothesis” framework, children with naming speed deficits only (NSD), phonological deficits only (PD), or both (double-deficits, DD) will be assessed. In addition, a group of children that do not fall neatly within the DDH (unclassified reading disabilities, UcRD); with fluency issues largely in connected text only will also be examined.

5.1 Research Question and Hypotheses

Research Question: Do different subtypes of reading disability, as classified by the double-deficit hypothesis, have significantly different verbal working memory system (VSTM and/or CE) profiles?

Hypothesis 1: There is strong evidence in the literature supporting the notion that children with reading disabilities have VSTM and/or CE impairments. Therefore, it is hypothesized that the sample of children with reading disabilities in the present study will show VSTM and/or CE weaknesses (i.e., in the low average to lower end of average range <30th percentile) and/or deficits (i.e., >1 *SD* below the mean).

Hypothesis 2: There will be significant differences between reading disability subtypes (i.e., PD, NSD, DD, UcRD) on VSTM and CE measures.

Hypothesis 3: Children identified with naming speed deficits only (NSD) will have CE weaknesses or impairments. Naming speed ability (as indexed by

RAN total time) requires the coordination of multiple processes, including searching for orthographic symbols in long-term memory, retrieving correct phonological name codes, while also sustaining these mental processes over time. The coordination of these processes is hypothesized to place heavy demands on the central executive, which involves simultaneous storage and processing of information. Therefore, children characterized by naming speed deficits will have poor central executive functioning (CE). Given that verbal short-term memory and the central executive are partially correlated and that VSTM is hypothesized to be involved in the initial processes of naming (i.e., continuous naming of the first row on RAN tasks), it is postulated that the NSD group will show weaknesses in VSTM, but to a lesser degree than CE weaknesses.

Hypothesis 4: Children identified with phonological awareness deficits only (PD) will have weaknesses or impairments in VSTM. Some research has shown that phonological awareness and VSTM are associated. This is possible because both phonological awareness and VSTM rely heavily on phonological processing. Therefore, it is hypothesized that children characterized by phonological awareness deficits will have weaknesses or impairments in verbal short-term memory functioning (VSTM). Given that verbal short-term memory and the central executive are partially correlated and that CE has been hypothesized to be involved in phonological awareness tasks, it is postulated that the PD group will show weaknesses in CE, but to a lesser degree than VSTM weaknesses.

Hypothesis 5: Children with double-deficits (DD) will show greater impairment in VSTM and CE functioning, compared to children with single-deficits only. This is because the double-deficit hypothesis indicates that children with deficits in both naming speed and phonological awareness are among the most impaired poor readers. Also, if CE is strongly associated with NSD, and VSTM is strongly linked to PD, then the DD group would also have combined memory impairments (i.e., both VSTM and CE). Therefore, the DD group will show greater VSTM and CE impairments.

Hypothesis 6: Children with unclassified reading disabilities (i.e., those that do not have phonological awareness or naming speed deficits; UcRD) will have weaknesses in CE functioning, but not in VSTM ability. The unclassified reader group is characterized by fluency issues in connected-text (or in reading comprehension) and the research in the literature suggests that CE is significantly associated with reading comprehension ability. Therefore, it is hypothesized that the UcRD group will have CE weaknesses and to a much lesser extent VSTM weaknesses (since CE and VSTM share variance).

5.2 Methods

5.2.1 Participants

The data for the present study are from a previous large-scaled NICHD reading intervention study conducted from 2000-2004 (for details see Morris et al., 2010). Participants (*N*=448) in the intervention study were recruited from both public and private schools across three different sites, including Boston, Atlanta, and Toronto. Teachers referred students to the study if they showed difficulties in learning to read. The children had to meet the following inclusion criteria: (1) English was their primary language, (2) no hearing or vision problems, (3) no history of psychiatric illnesses or neurological impairments, (4) ages were between 6-4 and 8-6 at the time of initial testing, and (5) a composite Wechsler Intelligence Scale for Children, Third Edition (WISCI-III) IQ > 70 (Wechsler, 1991) or Kaufman Brief Intelligence Test (KBIT) score ≥75 (Kaufman & Kaufman, 1990).

Lastly, they had to meet criteria for a reading disability (RD), which was defined as low achievement and/or an ability-achievement discrepancy. A child was classified under low-achievement if they had an average standard score of ≤85 (i.e., at least 1 standard deviation below the mean) on multiple reading measures. Children met criteria for an ability-achievement discrepancy if they had one or more reading scores that were ≤1 standard errors of the estimate (SEM) below their predicted IQ score.

Reading scores (or achievement) were based on the following measures: (a) the mean standard score of three subtests; a broad index of global reading ability consisting of Word Identification and Word Attack from the Woodcock Reading Mastery Tests-Revised (WRMT-R; Woodcock, 1987) and Passage Comprehension from the Wide Range Achievement Test-3rd Edition (WRAT-3; Wilkinson, 1993); (b) the Basic Skills Cluster standard score; a broad measure of basic reading skills made up of Word Identification and Word Attack from the WRMT-R; (c) the Total Reading-Short Scale standard score; an estimate of global reading ability, which includes Word ID and Passage Comprehension from the WRMT-R.

Participants that met all of the criteria above were included in the larger study. For these participants, an extensive battery of tests (e.g., in reading, language, and memory) was given at multiple time points (e.g., pre-intervention, during intervention, and post-intervention) throughout the study. Additional descriptive information was also collected, including race and socio-economic status (SES).

5.2.2 Sample in Present Study

Based on the larger reading intervention study a sample of children with reading disabilities (*N*=134; males=54% and females=46%) was identified for the present study (for subsample characteristics see Table 1). Participants in the sample ranged from 7 to 9 years of age (Mean age=7.36) and were in grades 1-4 (Mean grade=2.20). Children under the discrepancy model and low achievement classification were both combined together in the present study to include more participants in the analyses. Accordingly, both behavioral and brain imaging studies indicate that there are no qualitative differences between the two groups in terms of reading impairment (e.g., Stuebing et al., 2002; Tanaka et al., 2011). Only participants with complete pre-intervention data for all of the dependent variables (i.e., VSTM and CE measures) and an average full scale IQ score (i.e., 80-120 on the Wechsler Abbreviated Scale of Intelligence, WASI; Wechsler, 1999) were included. Participants with borderline or superior full-scale IQs were excluded from the RD sample in order to limit variance attributed to low or high cognitive ability, as some research has suggested that the central executive (or working memory) is correlated with fluid intelligence (or inductive and deductive reasoning, which is indexed by performance subtests on the WASI) (e.g., Engle, Kane, & Tuholski, 1999; Kane, Hambrick, & Conway, 2005). Moreover, only pre-intervention data was used in the study because the purpose was to evaluate VSTM and CE functioning in children with RD separate from the effects of reading remediation. Socio-economic status was measured based on parental education and occupation using the Hollingshead SES index (Hollingshead, 1975). Subsequently, the SES index fell within the low to average range for the sample (*N*=99, *M*= 39.81, *SD*=12.3; note 35 participants were missing SES scores). The ethnicities in the sample represented demographics found in typical urban cities. There were 47.8% Caucasian, 41% African American, 4.5% Hispanic, 3% Asian, 3% "other," <1% unidentified participants.

The Social, Behavioral, and Educational Research Institutional Review Board (SBER/IRB) at Tufts University granted approval to use the data from the original NICHD study for the present study. All of the IRB requirements were followed for the dissertation.

5.2.3 Double-Deficit Hypothesis Subtypes

Children with reading disabilities were classified into four different subtypes, following criteria for the double-deficit hypothesis (DDH) as presented in the literature (Wolf & Bowers, 1999). Accordingly, children with phonological processing deficits only (PD) had a standard score ≤85 (or at least 1SD below age-normed expectations) on the Phonological Awareness Composite (PA), which consists of two subtests, Blending and Elision (from the CTOPP; Wagner, Torgesen, & Rashotte, 1999). Children classified with naming speed deficits only (NSD) had a standard score ≤85 on the Rapid Automatized Naming (RAN) Letter task (an index of naming speed) from unpublished norms for RAN (Biddle, 1996). Children with both phonological awareness and naming speed deficits (i.e., standard scores ≤85 on both PA and RAN-letter) were identified with double-deficits (DD). Finally, children who had standard scores >85 on both PA and RAN-letter were categorized under the unclassified reading disability group (UcRD).

A concerted effort was made to match the subtype groups across age, verbal ability (i.e., Verbal IQ), and gender. Subsequently, there were 33 participants in the phonological awareness deficit group (PD), 34 in the naming speed deficit group (NSD), 39 in the double-deficit group (DD), and 28 in the unclassified reading disability group (UcRD) for subtype characteristics see Table 2).

5.3 Measures

5.3.1 Subtype classification measures

<u>Phonological Awareness (PA)</u>: Phonological awareness is based on a composite standard score (*M*=100, *SD*=15) comprised of two subtests, Elision and Blending, from the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999). The Elision subtest measures a student's ability to manipulate the components of a word. For instance, the experimenter prompts the student to repeat a word then the experimenter asks them to delete a particular

syllable or phoneme from that word and finally say the newly formed word (e.g., What is "cat" without the /k/? "at"). The Blending subtest measures a student's ability to synthesize language sounds. For example, the student must listen to a series of orally presented sounds (i.e., phonemes or syllables) and combine them together to form a real word (e.g., the student hears /k/ -/a/ -/t/ and has to say "cat").

Rapid Automatic Naming – Letters (RAN-LE): The RAN-LE subtest measures the speeded integration of orthographic and phonological codes. Accordingly, the student must orally name a total of 50 letters randomly arrayed (in a 10 X 5 matrix) as accurately and quickly as possible (prepublication version of Wolf & Denckla, 2005). The standard score (*M*=100, *SD*=15) is based on the total amount of time (or latency) it takes to name all of the letters (unpublished norms from Biddle, 1996).

5.3.2 Verbal short-term memory (VSTM) measures

Phonemic level. Digits Forward Span (DFS): The digits forward span assesses the ability to encode and temporarily store information phonologically. It is a subtest of the Digit Span on the WISC-III (Wechsler, 1991). The student must repeat back sequences of single digits (e.g., '4-2-9') in the exact order they are presented by the experimenter. The set size ranges from three to nine digits. The number of digits recalled from the longest sequence correctly determines the raw score.

Non-word repetition (NWR): In addition to DFS, non-word repetition also assesses the ability to encode and temporarily store information phonologically and is considered to be a more sensitive measure of VSTM. NWR is a subtest of the CTOPP (Wagner et al., 1999). Students are required to repeat single to multi-syllable nonsense words (e.g., 'baf') as accurately as possible. The standard score (*M*=10, *SD*=3) is based on the highest number of correct trials.

Connected-text level. Sentence Repetition (SentR): Sentence repetition indexes the ability to encode and temporarily store connected-text. The SentR is a subtest on A Developmental NeuroPsychological Assessment (NEPSY; Korkman, Kirk & Kemp, 1998). The student is asked to repeat single sentences of increasing complexity and length immediately after they are presented. The standard score (*M*=100, *SD*=15) is based on the highest number of correct trials.

Story Recall (StoryR): Story Recall assesses the ability to encode and temporarily store meaningfully connected-text. StoryR is a subtest of the Woodcock-Johnson III (WJ-III; Woodcock, McGrew, & Mather, 2001). The student must listen to increasingly complex stories presented orally by the examiner. Immediately after listening to the story, the student must recall the meaningful parts of the story and as many details as possible. The standard score (*M*=100, *SD*=15) is based on the number of main events recalled as well as exact production of certain words or phrases. The order in which the events are recalled does not count towards the score.

5.3.3 Central executive (CE) measure

Digits Backward Span (DBS): The Digits Backward Span is a classic central executive measure that assesses the ability to simultaneously store and process verbal information. It is a subtest of the Digit Span on the WISC-III

(Wechsler, 1991). The experimenter presents increasing sequences of single digits and the student must repeat the reverse order of the sequences correctly (e.g., ‘4-8-5-2’ is presented and ‘2-5-8-4’ is the correct response). The set size ranges from two to nine digits. The number of digits recalled from the longest sequence correctly determines the raw score.

5.4 Results

5.4.1 Full Sample

Descriptive statistics of the dependent variables for the entire sample (*N*=134) are presented in Table 3. For the dependent measures that were in raw scores (i.e., digits forward span and digits backward span), z-scores were calculated based on the mean raw score of the total sample to compare to the normal distribution. Hypothesis 1 stated that the full sample would show weaknesses (below the 30th percentile) and/or deficits (i.e., <1 *SD* below the mean) in both VSTM and CE ability. The descriptive statistics supported this hypothesis. The full sample showed weaknesses (i.e., scored below the 30th percentile) on two of the verbal short-term memory measures. This included nonword repetition (*M*scaled score=7.28, *SD*=2.31, 18th percentile) and sentence repetition (*M*scaled score=8.09, *SD*=2.09, 25th percentile). As for the other verbal short-term memory measures, the sample scored in the average range for digits forward span and story recall (see Table 3). On the central executive measure, digits backward span, participants scored in the low average range (*M*z-score=-0.72, 23rd percentile) compared to the norm. Therefore, the current sample of children with reading disabilities showed weaknesses in verbal short-term memory and central executive functioning relative to age expected norms.

5.4.2 Double-Deficit Hypothesis Subtypes

Next, I examined whether verbal short-term memory and central executive functioning varied across subtypes of dyslexia. Descriptive statistics were calculated for each subtype and are included in Table 4. Subsequently, the normality assumption for running a MANOVA was not met. This is because some of the dependent variables were not normally distributed within each of the groups. Therefore, a Kruskal-Wallis non-parametric test was used to test whether there were differences between groups.

The independent variable (subtypes) consisted of four levels (i.e., phonological deficit, PD; naming speed deficit, NSD; double-deficit, DD; and unclassified reading disability, UcRD). There were five dependent variables that fell under two main categories: verbal short-term memory (i.e., nonword repetition, digits forward span, sentence repetition, and story recall) and central executive (i.e., digits backward span). The subtypes were matched on verbal IQ, age, and gender (see Table 2).

The Kruskal-Wallis test showed that there were no significant differences between the subtypes on VSTM and CE performance, except for on the story recall measure $H(3) = 16.55$, $p = .001$ (*Mean Ranks*: PD=51.68; NSD=71.04; DD=61.32; and UcRD=90.45) (see Table 4 for all results). Accordingly, post-hoc analysis (using the Mann-Whitney Test) for the story recall measure revealed that the UcRD group (M=109.79, SD=8.25) performed significantly better on the measure compared to PD (*M*= 98.30, *SD*=11.61) and DD groups (*M*=100.82, *SD*=12.97).

Therefore, the results from the between groups analysis did not support hypothesis 2, that is, children characterized by subtypes of reading deficits did not show significantly different VSTM and CE patterns (except for story recall). Hypothesis 3 was partially substantiated because children with naming speed deficits (NSD) showed weaknesses (scored in the low average range) in central executive functioning as predicted (*M*z-score=-0.81, 19th percentile). The NSD group, however, also showed comparable weaknesses in VSTM (non-word repetition, *M*scaled score=7.68, *SD*=2.13, 21st percentile), which was not originally predicted. Similarly, hypothesis 4 was partially supported in that children with phonological awareness deficits (PD) demonstrated weaknesses in VSTM measures (non-word repetition, *M*scaled score=6.91, *SD*=2.31, 14th percentile; sentence repetition, *M*scaled score=7.55, *SD*=1.84, 21st percentile) as predicted. The PD group, however, showed similar weaknesses in central executive functioning (*M*z-score=-0.80, 19th percentile), which was unexpected. Hypothesis 5 was not substantiated. Accordingly, children with double-deficits (DD) in both phonological awareness and naming speed did not demonstrate poorer VSTM and CE functioning compared to the other groups (see Table 4). Finally, hypothesis 6 was not supported because children with unclassified reading disabilities (UcRD, fluency issues in connected-text) showed weaknesses in verbal short-term memory functioning (nonword repetition 16th percentile and digits forward span 21st percentile), as opposed to central executive functioning (*M* z-score=-0.53, 30th percentile).

CHAPTER SIX

General Discussion

Most of the studies in the memory-reading literature have focused on children identified with deficits at the word reading or reading comprehension level. No studies have investigated the verbal working memory system (i.e., VSTM and CE) of children characterized by reading failure at the sublexical level, specifically naming speed deficits. Children with naming speed deficits experience difficulty with underlying fluency-related processes, which results in slow naming. The exact nature of naming speed deficits remains unclear and many different theories have been put forth in the literature (e.g., phonology, orthography, global processing speed, articulation etc), including VSTM and/or CE functioning.

Using the double-deficit hypothesis framework, the present study investigated the verbal working memory profiles (i.e., VSTM and CE) of children characterized with deficits at the sublexical level (e.g., NSD, PD, and DD) and those with no deficits at the sublexical level (i.e., unclassified reading disability). Thus, the research question in the current study explored whether children with naming speed deficits only (NSD), phonological deficits only (PD), double-deficits (DD), and unclassified reading deficits (UcRD) had different VSTM and CE profiles.

6.1 Full Sample Findings

The findings from the full sample analysis indicated that the children with various sources of reading disabilities had weaknesses[1] in the verbal working memory system (i.e., VSTM and CE). Accordingly, the poor readers scored in the low average (18th percentile) to lower end of average range (25th percentile) on two of the verbal short-term memory measures (i.e., nonword repetition and sentence recall respectively) and in the low average range (23rd percentile) on the central executive measure (i.e., the digits backward span). Therefore, the findings in the current study are consistent with the literature and demonstrate that both VSTM and CE weaknesses are present in children with reading disabilities (Swanson, Zheng, & Jerman, 2009).

Subsequently though, there were two verbal short-term memory measures that the full sample performed within the average range on. One of them was the digits forward span (DFS) from the WISC-III (Wechsler, 1991). It is important to note that the DFS mean z-score for the full sample (*M*=-0.53, ~30th percentile) was just at the cusp of the "lower end of average" performance level (<30th percentile). This implies that the participants experienced some difficulty with

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[1] In the present study, weaknesses were defined as scoring below the 30th percentile. In the working memory literature, a child must score 1*SD* below the mean (below 16th percentile) to have a deficit (Gathercole & Alloway, 2006). In the reading disabilities literature, however, a child is considered to be "reading impaired" if they score below the 30th percentile on basic reading skills (Moats & Tolman, 2009). In the current study a conservative stance was taken and the term "weakness" was used as opposed to "deficit" or "impairment."

the DFS task. One explanation for why the children with RD performed just within the average range on the digits forward span may be because DFS is not as sensitive of a measure as other VSTM measures, such as, nonword repetition. For instance, it has been suggested that the DFS relies partly on long-term memory (LTM) because digits (i.e., single digits 1-9) are familiar verbal items that children learn and become automatic at a very young age. Therefore, remembering sequences of single digits (e.g., 4-8-2-5) is an easier task for children than remembering nonwords (e.g., 'oganaduwa'), for which there is no background knowledge or long-term memory representations. Accordingly, the current sample performed more poorly on the nonword repetition measure (e.g., 18^{th} percentile, low average range) than the DFS subtest (e.g., ~30^{th} percentile, average range), providing support for this explanation.

As for the second VSTM measure, story recall from the WJ-III (Woodcock et al., 2001), the sample performed solidly within the average range scoring in the 58^{th} percentile. The measure required children to listen to a story presented auditorally and then to immediately retell the meaningful parts as well as details of the story to the experimenter. The score was based on the number of main events recalled and exact production of certain words or phrases. One possible reason why children with RD did not have difficulty with this task may be because the verbal information was presented within a context, that is, within a meaningful story structured around a predictable pattern (i.e., a beginning, middle, and end). These two elements, meaning and structure, provide a scaffold for remembering information more readily.

The story recall findings in the present study are consistent with results from Kibby and Cohen (2008). In their study, children with RD performed comparably to controls on a story memory task. The authors suggested that the poor readers were unimpaired on the story memory task because they had an intact semantic short-term memory (STM). In the memory field, researchers have suggested that the retention of verbal information is supported not only by phonological STM, but also by semantic STM (Haarmann & Usher, 2001; Hanten & Martin, 2000; Martin & Freedman, 2001). The construct, semantic memory, has traditionally been classified under the declarative division of long-term memory (LTM). Declarative memory refers to memory for facts, knowledge, and events. Declarative memory is further sub-divided into episodic and semantic memory. Semantic LTM is posited to store facts, meanings (e.g., of words), concepts and knowledge about the external world.

Research by Haarmann and Usher (2001), however, has suggested that a short-term memory semantic store also exists, in addition to semantic LTM. For instance, they were able to demonstrate that there were semantic effects in immediate recall (STM) that could not be accounted for by semantic LTM. Moreover, functional neuroimaging studies have shown that there is a specific area of the brain (i.e., the dorso-lateral prefrontal cortex) that significantly activates only for semantic memory tasks compared to phonological recall tasks (Crosson et al., 1999; Gabrieli, Poldrack, & Desmond, 1998).

Therefore, based on the above findings, it is possible that a semantic STM component exists. If this is the case, then it may be that children with reading disabilities remember meaningful verbal information (e.g., in stories) because they have intact semantic short-term memory stores (as suggested by Kibby & Cohen, 2008). Additionally, it could be that poor readers remember verbal information in stories because it is presented in a meaningful and predictable context, which partially depends on semantic long-term memory (i.e., background knowledge for the patterns in stories).

Subsequently, both of these concepts (i.e., semantic STM and semantic LTM) may be useful for reading remediation. For instance, perhaps an additional way to help children with reading disabilities may be to encourage semantic encoding and storage of verbal information (i.e., utilize their semantic STM). Another idea could be to teach new reading concepts in meaningful contexts (such as stories) and to build on a child's current background knowledge (i.e., use their semantic LTM). One reading intervention program that utilizes these concepts is RAVE-O (Retrieval, Automaticity, Vocabulary, Engagement with Language, Orthography). The RAVE-O program effectively integrates semantic encoding of material and also builds on background knowledge (LTM) with the children. Both of these approaches are implemented throughout the program and at every level of reading (i.e., from the letter to the connected-text level) (for details, see Wolf & Katzir-Cohen, 2001).

More research is needed in other samples of children with reading disabilities, however, to verify that they are in fact unimpaired on story recall measures. Further, additional research is necessary to confirm the existence of semantic STM and to understand how it functions in poor readers.

6.2 DDH Subtype Findings

The present study is the first one (to the author's knowledge) to investigate VSTM and CE functioning among children with reading disabilities characterized by reading failure at the sublexical (subword) level, particularly those with naming speed deficits. Contrary to the prediction of hypothesis 2 (i.e., the subtypes would have different VWMS profiles), there were no significant differences between the subtypes. That is, children with phonological awareness deficits (PD), naming speed deficits (NSD), double-deficits (DD), and unclassified reading deficits (UcRD) all had similar verbal working memory system profiles (except for on the story recall task, which will be discussed later).

Each of the groups showed "weaknesses" in VSTM and CE functioning, which means that they scored below the 30^{th} percentile. Memory researchers though define memory impairment as occurring more than 1*SD* below the mean or less than the 16^{th} percentile (see Gathercole & Alloway, 2006). Therefore, in order to determine the extent to which each group was impaired in VSTM and CE functioning a post-study analysis was performed. The measures used in the analysis consisted of the nonword repetition task for VSTM (it is considered to be a more sensitive measure of VSTM) and the digits backward span to index CE functioning. The results showed that almost a third to a half of the participants in each group had VSTM impairments (i.e., PD: 52%, NSD: 32%, DD: 44%, and UcRD: 43%). For the central executive measure, a smaller percentage of participants in each group had CE impairments (e.g., PD: 15%, NSD: 12%, DD: 13%, and UcRD: 11%). Accordingly, the post-study analysis suggests that children with reading disabilities (characterized largely by sublexical deficits) experience marked impairments in both VSTM and CE functioning.

It is interesting to note that in the present sample a higher percentage of children with RD had VSTM impairments than CE impairments. Some studies have failed to find CE impairments in poor readers (e.g., Van der Sluis, van der Leij, & De Jong, 2005), which may suggest that not all samples of children with RD have severe CE impairments. It could also be, however, that the task in the present study, digits backwards span (DBS), was not sensitive enough to capture simultaneous storage and processing (e.g., Baddeley, 1990; Gathercole & Baddeley, 1993). For example, other studies have used complex memory span tasks (see Chapter 3) to investigate CE functioning in RD samples because it is a more challenging measure, which taps into CE processing. In the future, a meta-analysis of the studies that have employed digits backward span and/or complex memory span tasks in children with RD and found CE impairments would help to clarify this issue.

NSD and PD Groups

Specifically, it is interesting that children with naming speed deficits only (NSD) and children with phonological awareness deficits only (PD) both had similar VSTM and CE profiles. It was predicted that the NSD group would have significant weaknesses in their CE functioning (compared to the PD group) because naming speed ability (i.e., RAN performance) is posited to depend on the coordination of multiple processes, including searching for orthographic symbols in long-term memory, retrieving correct phonological name codes, while also sustaining these mental processes over time. In contrast, the PD group was predicted to show more weaknesses in VSTM functioning (compared to the NSD group) because phonological awareness ability relies heavily on phonological encoding and storage. Both groups, however, showed similar VSTM and CE functioning. Although there were no significant differences between NSD and PD scores, on closer observation there was a trend toward the PD group scoring lower on each of the VSTM measures than the NSD group. This could indicate that the PD group struggles slightly more with VSTM functioning than the NSD group, providing some support for the PD-related hypothesis. Additional research confirming this pattern though is needed in other samples before it can be concluded that children with phonological deficits have weaker VSTM functioning than children with naming speed deficits.

It was also hypothesized that within the NSD group, their CE functioning would be more impaired than their VSTM functioning and vice-versa for the PD group (i.e., VSTM more impaired than CE). Since there were multiple VSTM tasks (e.g., digits forward span, non-word repetition, sentence repetition, and story recall), I selected one measure to represent VSTM functioning. I chose nonword repetition because it is considered to be the most sensitive index of VSTM. Subsequently, for the NSD group VSTM performance was at the 22nd percentile and CE performance was at the 19th percentile. Similarly, for the PD group VSTM performance was at the 14th percentile and CE performance was at the 19th percentile. Thus, it appears that within the NSD and the PD groups, VSTM and CE functioning were impaired to a similar degree.

DD Group

As for the DD group, that is, children with combined impairments in phonological awareness and naming speed, they performed comparatively similar to the single-deficit groups on most of the VSTM measures (except for story recall) and the CE task. This was unexpected, because the DD group is considered to be the most severely reading impaired subtype. Therefore, it was hypothesized that they would also be more impaired in VSTM and CE functioning (compared to the other groups). Since the DD group did not perform poorer on the VSTM and CE tasks, this suggests that combined reading impairments are not accompanied by more inferior VWMS functioning than a single-deficit. This is useful information because it means that children with combined reading deficits do not have more severe memory issues than single-deficit groups: therefore, the same memory intervention support can be used for children with combined deficits or single-deficits.

UcRD Group

As discussed earlier in this chapter, the full sample of children with reading disabilities scored in the average range on the story recall measure, that is, the participants were unimpaired on this measure. In the group analysis, however, there were significant differences between the UcRD group and the PD/DD groups (see Table 4). Accordingly, the post-hoc analysis revealed that the UcRD subtype (73^{rd} percentile) performed significantly better than the PD and DD subtypes (45^{th} percentile and 50^{th} percentile respectively), but not the NSD group (62^{nd} percentile). The UcRD group is mostly characterized by rate and accuracy difficulties at the connected-text level, with intact lower-level processes (i.e., phonological awareness, naming speed, and word decoding). Further, in a recent study they significantly outperformed the other DDH subtypes on language comprehension (Ullman et al., 2009). Therefore, it could be that the UcRD group performed better on the story recall task because they have higher language comprehension skills. That is, they were able to use their language comprehension skills to comprehend and retain the story information better than the other groups. Interestingly, the PD and DD groups performed the lowest on the story recall task, and the NSD group did not significantly differ from any of the groups. This may indicate that the story recall measure taps into phonological processing, which could be why the PD and DD groups (i.e., those with phonological awareness deficits) scored lower than the other subtypes and the NSD group was not as affected.

In summary, the results from the full sample analysis were consistent with previous studies in demonstrating that children with reading disabilities have weaknesses in their verbal working memory systems (i.e., VSTM and CE functioning). Findings from the subgroup analysis indicated that children with naming speed deficits have weaknesses (and actual impairments for some) in both VSTM and CE functioning. This suggests that a relationship exists between naming speed skills and memory. Further, children with sublexical deficits (the PD and DD groups) and without (the UcRD group) displayed weaknesses (and impairments) in their verbal working memory systems.

6.3 Limitations

There are limitations to the present study that should be taken into account by the reader. For instance, the age-range of the sample (i.e., 7-9, mean age: 7.36) was restrictive and did not allow for developmental trajectories of the memory-reading relationship, which would be informative. Further, only one central executive measure (i.e., digits backward) was included in the study. It would have been helpful to include a complex-memory task (e.g., reading span, Daneman & Carpenter, 1980), which is more demanding than the digits backward span task. Also, the sample size was somewhat small for group comparisons (smallest group n=28, largest group n=39). Therefore, the results should be replicated with a larger sample. Methodologically, not all of the dependent variables were normally distributed across each of the groups so non-parametric tests had to be employed. Hence, future studies should use normally distributed data to confirm the results from the present study. Additionally, the children in this study were not screened for other common co-occurring learning difficulties, such as attention deficit hyperactivity disorder (ADHD). Although the literature is mixed, researchers suggest that children with co-morbid issues (i.e., ADHD/dyslexia) experience CE difficulties and children with dyslexia only have VSTM problems (see Savage et al., 2007). Finally, although all of the measures in the current study were standardized and normed, a control group of typically developing children would have been useful for comparison.

6.4 Implications

6.4.1 Theoretical

The findings from the present study have important implications for the theory of dyslexia. Accordingly, VSTM and CE functioning were poor in each of the DDH subtypes, including two core underlying deficits in reading disabilities, that is, naming speed (fluency subprocesses) and phonological awareness (accuracy subprocesses). This suggests that the verbal working memory system (i.e., VSTM and CE) is significantly associated with reading deficits at the sublexical (or subprocessing) level. First, this establishes that children with naming speed deficits have VSTM and CE difficulties. Second, this confirms that children with different sublexical reading deficits (i.e., NSD, PD, and DD) have poor VSTM and CE functioning, similar to children with word level and/or connected-text level reading disabilities. Thus, together the findings from this study and the evidence assembled in the memory-reading literature indicate that VSTM and CE deficits are significantly involved at all levels of reading failure (i.e., the sublexical, word, and connected-text levels).

Overall though, the learning disability field does not consider VSTM and/or CE to be “core” underlying deficits in dyslexia, like phonological awareness and naming speed, because many of the studies have been mixed and inconclusive. This is due to the numerous inconsistencies that plague the memory-reading field (see Chapter 3, Savage et al., 2007). Therefore, it may be that the complex, indefinite findings has masked the fact that VSTM and CE are key (or “core”) components in reading disabilities.

Based on the findings from this study, and the literature, it is clear that the verbal working memory system is a common thread across all levels of reading disabilities. This suggests that VSTM and CE are significant contributors that with other core components manifest a reading deficit. Thus, this should be reflected in a multi-componential theoretical account of dyslexia.

6.4.2 Assessment

Reading is a complex skill that requires multiple underlying components (e.g., phonology, naming speed, orthography, etc.). Therefore, it is important to assess each one to determine the specific area(s) of deficit. Once the deficient skill or skills are identified, then an appropriate intervention approach (or program) can be ascertained for a child.

In the assessment of reading disabilities, VSTM and CE have been (for the most part) categorized under the index of general intelligence (IQ) and have not been included as one of the important underlying components in RD. Although there is sufficient evidence to suggest that the verbal working memory system is a significant factor in reading disabilities, it is not typically examined outside of IQ tests. Further, the memory subtests commonly included in IQ tests consist of digits forward span (DFS; the recall of digits in the same order as presented) and digits backward span (DBS; the recall of digits in the reverse order), both of which are considered to be among the less sensitive measures of the verbal working memory system. Therefore, if a child has a mild to moderate problem with the verbal working memory system, it will most likely not be reflected in their "digit span" score (i.e., a composite of DFS and DBS on the

Wechsler scales). Moreover, the raw scores for each task, DFS and DBS, cannot be converted into standard scores independently, because the raw scores must be combined into a composite score to obtain a standard score. Therefore, one cannot easily gauge a child's performance (relative to the norm) on each test.

One reading measure that does include indices of verbal short-term memory is the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999). There are two tasks, the "memory for digits" and "nonword repetition." The memory for digits task is similar to the digits forward span task used in IQ tests (though the digits are presented faster, 2 digits per second). The nonword repetition task is considered to be one of the more sensitive measures of verbal short-term memory and requires a child to repeat nonwords of increasing lengths. Although the CTOPP includes two different measures of verbal short-term memory, it does not include a central executive task. Thus, generally the assessments in reading disabilities do not prioritize the evaluation of VSTM *and* CE.

Accordingly, there is a major disconnection between the findings in the memory-reading literature and overall assessment practice. Even though the research indicates that most children with reading disabilities have weaknesses or impairments in their verbal working memory systems; they are not assessed thoroughly for VSTM and/or CE difficulties. This is an issue because research has shown that memory problems in children with reading disabilities do not subside and instead persist into adulthood (e.g., Siegel, 1994; Swanson & Sachse-Lee, 2001).

Moreover, the central executive deficits in children with dyslexia may affect more than reading. For example, studies show that children with poor CE functioning are at greater risk for lower academic achievement (e.g., Cowan & Alloway, 2008). Subsequently, they have trouble with remembering instructions, maintaining the details of a task, and knowing what to do next when a task involves multiple steps (Gathercole & Alloway, 2008). Overall, this affects a child's capacity to learn. The research has shown that children with reading disabilities also have CE impairments (e.g., Swanson, Zheng, & Jerman, 2009). Therefore, a child with a reading disability and a CE impairment (i.e., below the 16^{th} percentile) may struggle with processes general to learning, which are separate from their reading issues (e.g., Swanson, 1999b). Thus, for multiple reasons it is important to examine the VSTM and CE profiles of children with dyslexia and to include comprehensive measures of the verbal working memory system in assessments (e.g., the Automated Working Memory Assessment developed by Alloway, 2007).

6.4.3 Intervention

Given that the memory-reading research (and the findings in the present study) shows that children with various sources of reading disability (i.e., at the sublexical, word, and connected-text levels) have VSTM and/or CE difficulties, it is useful to consider this in reference to interventions. Studies indicate that there is a relationship between deficits in the verbal working memory system and reading failure; however, it remains unclear as to the exact nature of their association. That is, it may be the case that poor VSTM and CE functioning contribute to (or even underlie) reading disabilities, or it could be that difficulties in the core components of reading lead to inefficient VSTM and CE processing (or deficits). Theoretically improving the verbal working memory system may help to remediate reading more effectively; alternatively, improving the processes underlying reading may lead to better VSTM and CE functioning.

Although no published research on these topics was found, there is one group of researchers in the Netherlands who are currently studying this (Drs. Braams and Walda at Raboud University). These researchers are evaluating whether working memory training (using the Cogmed program; see Klinberg et al., 2005) will increase the efficiency of reading remediation in children with dyslexia. Thus, the future findings from this study may shed light on the nature between memory and reading impairments and lead to more effective ways to treat reading disabilities.

Over the past decade, research has shown that memory is not a static entity, which cannot be changed. Instead multiple studies now demonstrate that with systematic cognitive training (using computerized Cogmed program, 25 sessions, 45 minutes per session), working memory (CE) capacity can be increased (e.g., Klingberg, 2010; Klingberg, Forssberg, & Westerberg, 2002; Mezzacappa, & Buckner, 2010). There are caveats to this approach though, which are important to note. For instance, it is presently not substantiated in the research literature whether gains made from ‘systematic cognitive training’ transfer or generalize to other un-trained memory tasks (e.g., memorizing information for a test) or contexts (e.g., the school environment). Also, another question concerns whether 'gains' from cognitive training last after training (or practice) has finished? That is, if memory capacity is increased, does it remain increased indefinitely? Finally, there are no published studies to date that have specifically assessed memory cognitive training in children with dyslexia. Thus, more studies are needed to evaluate the effectiveness of cognitive training programs (e.g., Cogmed).

Other ways to assist memory functioning in children with dyslexia involve the use of various strategies. Some of these include chunking (i.e., taking single units of information and grouping them into larger units); clustering (i.e., organizing items into categories); mnemonics (i.e., organizing information idiosyncratically); coding (i.e., using different methods to present information); using cues to facilitate recall; breaking complex instructions into smaller steps; and practicing rehearsal of information to keep things in VSTM. Therefore, there are multiple ways (or strategies) that the memory weaknesses in children with reading disabilities can be compensated.

Finally, the findings on story recall in the present study (where all children with RD performed in the average range) and research in the literature strongly indicate that connecting information to meaning (e.g., a context) and background knowledge (i.e., semantic LTM) is important for retaining and learning new material. For instance, the RAVE-O reading intervention program uses multiple methods for tapping into, and building upon, 'meaning' for struggling readers. One way the program does this is to introduce multiple meanings to *core words* in various contexts (e.g., a *core word* might be "bat," which can have multiple meanings, such as, a baseball ‘bat’ or a mammal flying ‘bat’). In the RAVE-O program, children learn multiple meanings by creating ‘word webs’ (or semantic associations) for each core word (e.g., a ‘bat’ may be associated with a baseball, a stadium, a game etc.), which then builds on their background knowledge (or semantic LTM). Next, the core words are integrated into short stories. This presents the core words in a meaningful context, which aids the children in encoding and retrieving the multiple meanings. In addition, ‘image cards’ are used to pictorially present the multiple definitions (e.g., for the core word ‘bat,’ the image cards would include a picture of a baseball bat and a picture of a mammal bat). This provides visual images or ‘cues’ for the core words, which the children can also use to retain (and retrieve) the multiple meanings. All of these methods, in addition to many others in the RAVE-O program (see Wolf & Katzir-Cohen, 2001), help to build fluency or automaticity in reading. Therefore, programs such as RAVE-O demonstrate that building upon meaning and integrating it at multiple levels is important for memory and effective in remediating reading disabilities.

6.5 Future Research Directions

In the memory-reading literature there are still a number of questions that remain. For example, although the present study indicates that VSTM and CE are associated with naming speed deficits, it is not clear whether they directly contribute variance to RAN performance. This would be important to investigate because the verbal working memory system is hypothesized to play a role in rapid automatic naming and there have been a limited number of studies that have examined this. Moreover, it would be useful to assess the relationships among VSTM, CE, and rapid automatic switching (RAS) tasks. The RAS tasks are similar to rapid automatic naming tasks; however, they involve additional processing and therefore, are more challenging. The RAS tasks require an individual to name alternating stimuli rapidly and continuously (e.g., letters and numbers or letters, numbers, and colors). Rapid automatic switching tasks tap into underlying fluency-related processes (similar to RAN tasks), as well as additional executive processes, such as, switching and inhibition (Norton & Wolf, 2012). Therefore, given that RAS tasks involve additional executive processes (i.e., switching and inhibition); it is possible that the central executive is important for RAS performance. Thus, it would be useful to explore this in future studies.

Another question is whether VSTM is more important in pre-literacy and early reading development than later development? That is, does VSTM play more of a role in the acquisition of basic reading skills (e.g., phonological awareness, naming speed etc.) compared to later reading development (e.g., reading comprehension)?

Lastly, very few studies have systematically investigated the role of CE in sublexical processes. Most of the research has focused on the relationship between CE and connected-text level processes (i.e., reading comprehension). The findings from the present study suggest that a relationship exists between CE and sublexical processes (e.g., naming speed and phonological awareness). Therefore, given that it appears there is a relationship, future studies should assess how much CE predicts naming speed and phonological awareness abilities. If CE does contribute variance to sublexical processes, then this would provide more support for the notion that CE (and VSTM) should be integrated into the theory, diagnosis, and assessment of dyslexia.

6.6 Conclusion

Overall, the findings in this dissertation add to the existing memory-reading literature by establishing that children with sublexical core deficits have VSTM and CE weaknesses (and impairments). Also, it is a new base of evidence for the involvement of the verbal working memory system at all levels of reading disability (i.e., sublexical, word, and connected-text levels). This indicates that VSTM and CE are important factors in reading failure and therefore, must not be ignored. Thus, the theory, diagnosis, and remediation of reading disabilities should expand to include the verbal working memory system. Finally, this dissertation supports the notion that a multi-component model of dyslexia is needed to account for the multiple pathways to reading failure.

Table 1
Full Sample Characteristics

Variable	*M*	*SD*	Range
Age	7.36	0.65	7-9
Full Scale IQ	94.29	8.41	80-117
Verbal IQ	96.10	8.28	80-116
Performance IQ	93.81	10.42	70-126

N=134

Table 2

Subtype Characteristics Across Variables

	NSD n=34		PD n=33		DD n=39		UcRD n=28	
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	SD
Age	7.29	0.52	7.55	0.79	7.38	0.67	7.18	0.55
Gender	F=12, M=22		F=17, M=16		F=18, M=21		F=15, M=13	
Full Scale IQ	95.50	8.79	90.94	7.87	92.36	7.18	99.46	7.69
Verbal IQ	96.29	8.17	95.27	8.58	94.54	8.47	99.00	7.41
Performance IQ	95.91	11.31	88.79	8.45	91.77	8.36	100.00	10.64
RAN-Letters	62.59	22.72	96.06	8.36	65.41	17.45	96.64	8.18
Phonological Awareness	91.35	3.37	79.82	5.47	79.77	6.37	95.39	8.50

Note: All variables are in standard scores except for Gender, which is in count form. NSD=naming speed deficit, PD=phonological deficit, DD=double-deficit, and UcRD=unclassified reading disability. IQ is based on the WASI, RAN-Letters is based on the RAN subtest, and Phonological Awareness is a composite score based on the CTOPP.

Table 3

Full Sample Descriptive Statistics of the Dependent Measures

Variable	*M*	*SD*	Range	Performance Level
VSTM				
Phonological Level				
Digits Forward Span	4.43 z = -0.53	1.09	2-7	Average
Non-Word Repetition	7.28	2.31	2-14	Low Average
Connected Text Level				
Sentence Repetition	8.09	2.09	2-14	Lower end of Average
Story Recall	103.06	11.57	61-128	Average
CE				
Digits Backward Span	2.40 z = -0.72	0.87	0-4	Low Average

Note: Digits Forward and Digits Backward Spans are presented in raw scores with equivalent z-scores, Nonword Repetition and Sentence Repetition are in scaled scores, and Story Recall is in a standard score. VSTM=verbal short-term memory, CE=central executive. Performance level: LA=low average (at or below 25^{th} percentile); A_low=lower end of average (26-29^{th} percentile); A=average (30-72^{nd} percentile); and A_higher=higher end of average (73-76^{th} percentile).

Table 4

Double-Deficit Hypothesis Subtype Analysis of Verbal Short-Term Memory and Central Executive Performance

	NSD *n*=34		PD *n*=33		DD *n*=39		UcRD *n*=28			
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	SD	Significance	Differences
VSTM										
Phonological Level										
Digits Forward Span	4.71 z=-0.26 (A)	1.09	4.45 z=-0.50 (A)	1.00	4.36 z=-0.59 (A)	1.09	4.18 z=-0.76 (LA)	1.16	H(3)=3.98, p=.26	NSD=PD=DD=UcRD
Non-Word Repetition	7.68 (LA)	2.13	6.91 (LA)	2.31	7.31 (LA)	2.75	7.18 (LA)	1.81	H(3)=1.42, p=.70	NSD=PD=DD=UcRD
Connected Text Level										
Sentence Repetition	8.35 (A_low)	2.42	7.55 (LA)	1.84	8.23 (A_low)	2.06	8.21 (A_low)	1.99	H(3)=1.34, p=.72	NSD=PD=DD=UcRD
Story Recall	104.71 (A)	9.45	98.30 (A)	11.61	100.82 (A)	12.97	109.79 (A_high)	8.25	H(3)=16.55, p=.001	*UcRD > (PD=DD) NSD=UcRD; NSD=PD=DD
CE										
Digits Backward Span	2.32 z=-0.81 (LA)	0.81	2.33 z=-0.80 (LA)	0.89	2.41 z=-0.71 (LA)	0.91	2.57 z=-0.53 (A)	0.88	H(3)=1.39, p=.71	NSD=PD=DD=UcRD

Note: NSD=naming speed deficit; PD=phonological deficit; DD=double deficit; and UcRD=unclassified reading disability. VSTM=verbal short-term memory and CE=central executive. Digits Forward and Digits Backward Spans are presented in raw scores with equivalent z-scores, Nonword Repetition and Sentence Repetition are in scaled scores, and Story Recall is in a standard score. Performance level: LA=low average (at or below 25th percentile); A_low=lower end of average (26-29th percentile); A=average (30-72nd percentile); and A_higher=higher end of average (73-76th percentile). For Story Recall, the Mann-Whitney Test analyses is significant at *$p<.001$.

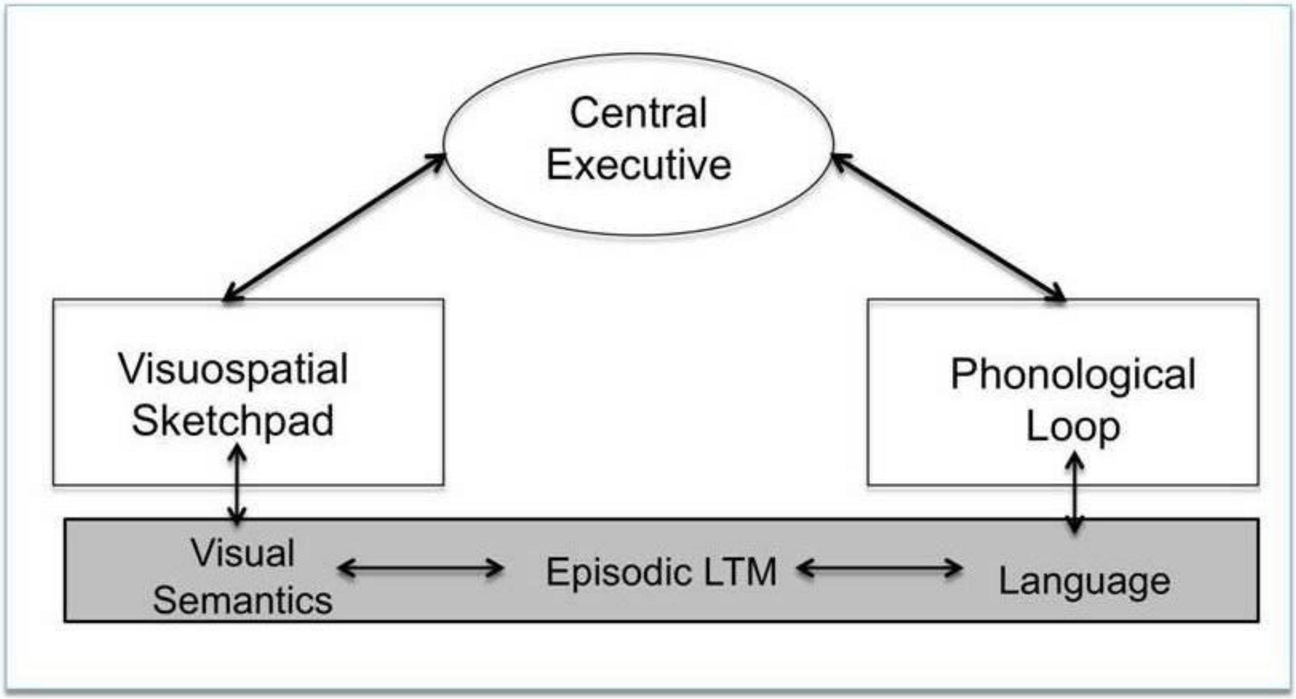

Figure 1. The multi-component working memory model. Baddeley and Hitch's (1974) model (Baddeley, 2000, p. 421).

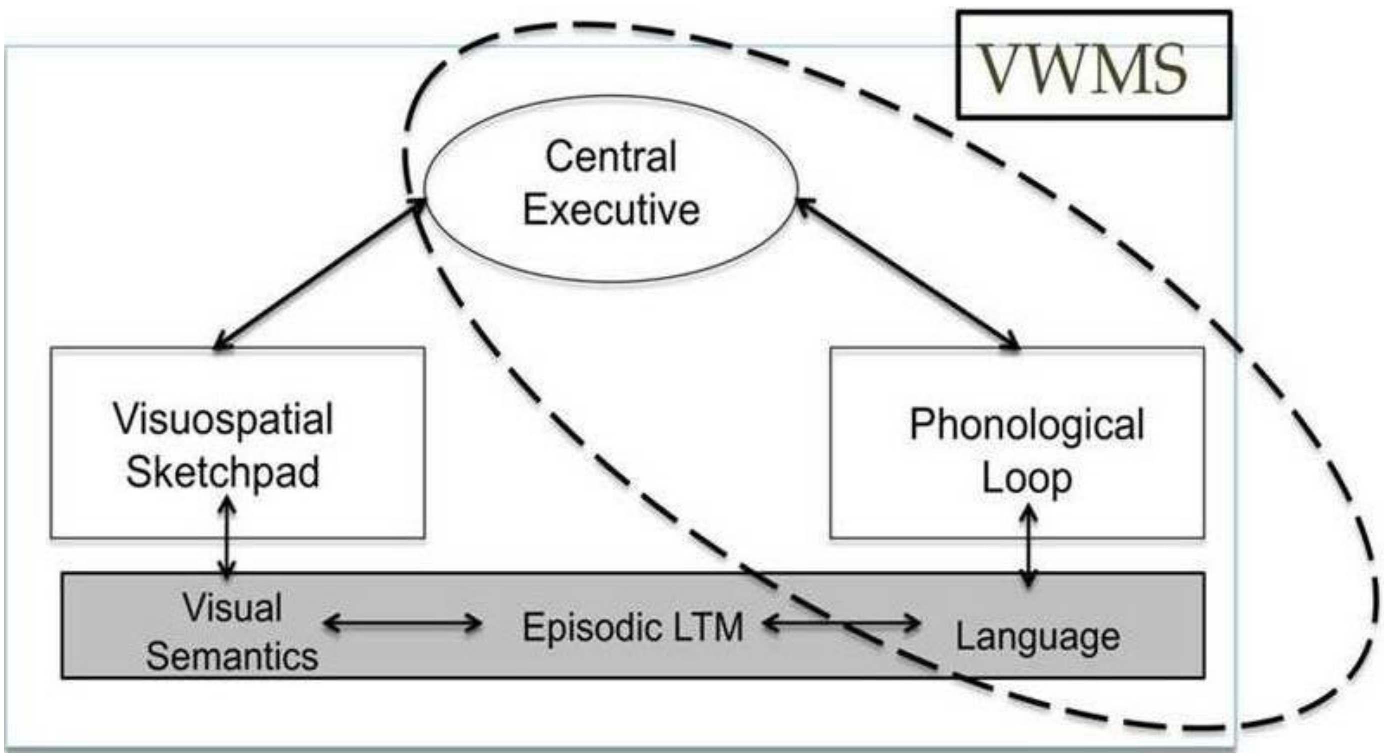

Figure 2. The verbal working memory system (VWMS). The present dissertation will focus on the verbal working memory system (VWMS), which includes verbal short-term memory (VSTM; the phonological loop) and the central executive (CE).

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