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INTRODUCTION

ABSTRACT: We review research showing that working memory (WM) deficits are fundamental problems of children and adults with learning disabilities (LD). Depending on the academic task, age, type of disability, and processing demands, these deficits manifest themselves as a domain-specific constraint (i.e., the inefficient accessing of phonological representations) and/or a domain general constraint (i.e., capacity limitations in controlled attentional processing). Further, these general and specific WM constraints can operate independently of one another in predicting performance in some academic domains (e.g., word problem solving). We argue that in the domain of reading and/or math, individuals with LD have smaller general working-memory capacity than their normal achieving counterparts and this capacity deficit is not entirely specific to their academic disability (i.e., reading or math). We generally conclude that individuals with LD (primarily those with reading disabilities) suffer WM deficits related to the phonological loop, a component of WM that specializes in the retention of speech-based information and this system is of service in complex cognition, such as reading comprehension, problem solving, and writing. However, this simple subsystem for individuals with LD is not the only deficit in WM that is deeply rooted in difficulties in complex cognition (e.g., reading comprehension). We find that in situations that place high demands on processing, individuals with LD have deficits related to controlled attentional processes (e.g., maintaining task relevant information in the face of distraction or interference) when compared to their chronological aged-matched counterparts.

The purpose of this target article is to propose an empirical foundation for the view that a learning disability (LD) reflects a fundamental deficit in working memory. We find, as do others, that children and adults with LD experience considerable difficulty on working memory (WM) tasks (e.g., Bull, Johnston, & Roy, 1999; Chiappe, Hasher, & Siegel, 1999; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; de Jong, 1998; Passolunghi, Cornoldi, & De Liberto, 1999; Siegel & Ryan, 1989; Swanson, Ashbaker, & Sachse-Lee, 1996). We argue that these deficits, depending on task demands, manifest themselves as a domain-specific constraint (i.e., the inefficient accessing of phonological representations) or a domain general constraint (i.e., capacity limitations in controlled attentional processing). How these two constraints operate independently and potentially interact will be discussed. We do not argue that WM deficits underlie the vast array of problems experienced by individuals with LD in the experimental literature. We do argue, however, that such deficits are a corollary to their difficulties on a number of cognitive tasks. We review evidence that suggests that deficiencies in WM are critically related to poor performance in a number of academic domains, such as reading, mathematics, and writing. Before discussing research linking WM to LD, we provide our definition of LD and the theoretical framework for the construct of WM. We also consider four caveats that must be taken into consideration when generalizing findings from the literature.

Definition of LD

The concept of learning disabilities rests on two assumptions:

a. academic difficulties are not due to inadequate opportunity to learn, general intelligence, physical or emotional disorders, but to basic disorders in specific psychological processes, and

b. these specific processing deficits are a reflection of neurological, constitutional, and/or biological factors.

Although these assumptions may seem straightforward, there is some disagreement in how they should be operationalized (see Morrison & Siegel, 1991, for a review). In our studies, we define LD samples by their primary academic difficulties in reading and mathematics and then attempt to isolate problems in psychological processes. We operationally defined learning disabilities as those children and adults who have general IQ scores on standardized tests above 80 and who have reading scores and/or math scores below the 25th percentile on a standardized reading/and or mathematics achievement measure. In some studies, our criterion for defining low achievement is much lower than a cut-off score below the 25th percentile (< 8 percentile) and general IQ is higher (> 85). In general, the majority of the studies we will cite use LD samples with primary deficits in reading, particularly word recognition accuracy. However, we recognize that reading problems are strongly correlated with other problems, such as mathematics. Thus, LD samples with reading problems may suffer problems in other academic domains that share a common resource (e.g., language). As Siegel and Ryan (1989) stated

> it is difficult to find RD children who do not also have problems with arithmetic, particularly when calculation is involved, because of the required reading of numbers and symbols in the tasks (p. 975).

An IQ-achievement test score discrepancy is not used in our most recent studies because of serious problems with this type of definition of LD (e.g., Siegel, 1988; 1989; 1992). We recognize that our definition is restrictive, but is consistent with several ongoing research programs (e.g., NICHD funded studies in the field of LD within the last 10 years).

Working Memory Framework

Research in cognitive psychology has provided several studies on the division between long term memory (LTM), in which memory for procedures, declarative information, and autobiographical events is maintained for years, and short-term memory (STM), in which information is maintained for a very short period of time (Atkinson & Shiffrin, 1971). Baddeley and his researchers introduced a concept of “working memory,” in which STM was seen as a limited capacity system for storing and manipulating information (Baddeley & Hitch, 1974). Currently, STM and WM are seen as distinct operations (Engle, Kane, & Tuholski, 1999a). Working memory is referred to as a processing resource of limited capacity involved in the preservation of information while simultaneously processing the same or other information (e.g., Baddeley & Logie, 1999; Engle et al., 1999a; Just & Carpenter, 1992), whereas STM is typically used to describe situations in which small amounts of material are held passively (i.e., minimal resources from LTM are activated to interpret the task, such as digit or word span tasks) and then reproduced in a sequential or untransformed fashion (i.e., the participant is asked to reproduce the sequence of items in the order they were presented)—see, for example, Daneman & Carpenter (1980) and Klapp, Marshburn, & Lester (1983); also see Gathercole (1998) for a comprehensive review of the developmental literature on WM and STM. Everyday examples of WM tasks might include holding a person's address in mind while listening to instructions about how to get there, or perhaps listening to a series of events in a story while trying to understand what the story means. Everyday examples of STM tasks might include recalling in order a series of digits, such as a telephone number, immediately after their presentation.

The research reported within this article is consistent with a tripartite view of WM by Baddeley (e.g., Baddeley, 1986; Baddeley & Logie, 1999). This view characterizes WM as comprising a central executive controlling system that interacts with a set of two subsidiary storage systems: the speech-based phonological loop and the visual-spatial sketch pad. The phonological loop is responsible for the temporary storage of verbal information; items are held within a phonological store of limited duration, and the items are maintained within a store through the process of subvocal articulation. The visual-spatial sketch pad is responsible for the storage of visual-spatial information over brief periods and plays a key role in the generation and manipulation of mental images. The central executive is involved in the control and regulation of the WM system. According to Baddeley and Logie (1999), it coordinates the two subordinate systems, focusing and switching attention, and activating representations within LTM. The central executive is thought to play an important role in “controlled attention,” which coincides with Norman and Shallice's (1986; Shallice, 1988) Supervisory Attentional System (SAS) model. Although the WM model used by the present authors is consonant with Baddeley's tripartite struyture, our research also incorporates the notion that there is a mental work space that has limited resources. This assumption is also consistent with the Daneman and Carpenter's model (1980; also see Carpenter, Miyake & Just, 1994; Just & Carpenter, 1992), which views WM as reflecting a combination of processing and storage. This combined processing and storage is under the influence of a central executive system that can operate distinct from the two subordinate systems.

There are correlates in the neuropsychological literature that complement the tripartite structure, suggesting that some functional independence exists among the systems (e.g., Jonides, 2000;Parkin, Yeomans, & Bindschaedler, 1994; Ruchkin, Berndt, Johnson, Grafman, Rotter, & Canoune, 1999; Salway & Logie, 1995; Smith & Jonides, 1997). Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies suggest separate neural circuitry for the storage and rehearsal components of both the phonological and the visual-spatial system, with phonological system activity mainly located in the left hemisphere and visual-spatial system activity located primarily in the right hemisphere (Smith & Jonides, 1997). Executive control processes, on the other hand, are associated primarily with the prefrontal cortex (e.g., Awh, Smith, & Jonides, 1995; Reichle, Carpenter, & Just, 2000; Schretlen, Pearlson, Anthony, Aylwar, Augustine, Davis, & Barta, 2000; Smith & Jonides, 1999). Baddeley and Logie (1999) review evidence that the left parietal lobes are associated with verbal WM tasks (i.e., phonological loop), while the right posterior parietal lobe may be one of several locations related to visual-spatial WM activity. They also suggest that most of the executive functions are linked to the frontal lobes, although it is possible that many other tasks related to central executive processing involve other areas of the brain as well. Neuropsychological evidence also suggests that children with LD experience difficulties related to these structures (e.g., Bull et al., 1999; Crosson, 1999). Based on the type of task, of course, studies suggest that children with LD have processing difficulties related to regions of the frontal lobe (e.g., Lazar & Yitzchak, 1998), left parietal lobe (e.g., Pugh et al., 2000; Shaywitz et al., 1998), as well as problems related to the interhemispheric transfer and coordination of information across the corpus callosum (Obrzut, Hynd, Obrzut, & Pirozzolo, 1981; Swanson & Obrzut, 1985). Clearly, the biological correlates of the various subcomponents in WM in LD samples is just beginning to be identified with advances in technology.

Caveats

There are some potential caveats in interpreting findings from the literature that qualify the conclusions that can be drawn. First, there are different views as to the source of individual differences in the general WM literature (see Miyake & Shah, 1999, for a review). Engle's (Engle et al. 1999a; Engle, Tuholski, Laughlin, & Conway, 1999b) model, for example, places emphasis on limitations related to controlled attention and activating relevant LTM traces above a critical threshold. Baddeley (Baddeley & Logie, 1999), on the other hand, suggests that individual differences may be related to one of the specialized functions of the phonological loop or the visual-spatial sketch pad. These constraints might be further fractionalized (for example, the capacity for rehearsal). Other models see WM as the activated portion of LTM and individual differences reflect the extent to which processing is supported by strategies and prior knowledge (Ericsson & Kintch, 1995). Although we have drawn from findings of Baddeley, Daneman, Carpenter and others (i.e., Engle and colleagues' model plays a major role in Swanson's studies), in placing our results in context, other models must be considered (e.g., Ericsson & Kintsch, 1995).

Second, more research has been done on some components of WM than others. The majority of work has focused on the phonological aspects of WM, particularly as it applies to reading (e.g., Gathercole, 1998; Gathercole & Baddeley, 1993). In fact, some studies suggest learning disabilities in the area of reading are isolated to a specific deficit in phonological WM (phonological processes such as phonemic awareness) and that deficits in activities of the executive system (whether they are specific to certain activities or cut across all executive activities) are manifestations of problems in the phonological system (e.g., Crain, Shankweiler, Macaruso, & Bar-Shalom, 1990; Shankweiler & Crain, 1986). However, recent efforts have been made to determine how domain general factors, as well as the domain specific factors, contribute to constraints in WM performance across various tasks (Engle et al., 1999a). For example, sustained attention, a component of the executive system, can act as a unitary and domain free system under some conditions (high interference). Thus, performance on an array of tasks reflecting different encoding and representations (e.g., verbal and visual-spatial) may drawn on this unitary system. However, tasks that draw primarily on specialized knowledge may be moderated by a domain specific system that draws few resources from a general system. This view is akin to a hierarchical structure of intelligence (Carroll, 1993) in which there is a general domain free factor that overarches several subordinate systems. Under some conditions, a general system accounts for intelligent performance, whereas at other times there is variance related to performance beyond what a general factor explains.

Third, limitations in methodology obscure our interpretations as to whether WM deficits are general or domain-specific. Unfortunately, there are problems with previous studies that have relied exclusively on single measures of WM. In some studies, domain specific deficits in samples with LD were merely an artifact of a single task (see Salthouse, 1990; Swanson, 1992, for discussion of this issue). Because isolated WM measures provide information about the unique variance of tasks, there is a problem when studies rely exclusively on a single measure of verbal or visual-spatial WM operations. Given that there are poor intercorrelations between WM measures (see Salthouse, 1990, for review), one may argue that generalizing from previous studies is difficult because some of these tasks reflect unstable operations. For example, previous research on aging has reported weak intercorrelations (correlations about .14 to .34) between WM measures reporting to measure the same or related WM processes (Salthouse, 1990). Thus, persons who score high on one type of verbal (or visual-spatial) WM measure do not necessarily score high on a similar type of verbal WM (or visual-spatial) measure, suggesting that individual differences in the relationship between WM and a specific academic domain (e.g., reading) may reflect a number of factors other than WM operations. These factors may be related to isolated task specific variance such as vocabulary, syntax, auditory discrimination, imagery. visual rehearsal, processing speed, and/or prior knowledge to list a few possibilities. Thus, it is necessary to use several measures of WM that reflect an array of situations when one assesses WM (Swanson, 1992). Swanson (1992; 1995) developed a battery of measures of WM that reflected an array of retrieval situations. He reasoned that with multiple indicators, in comparison to single measures, one would be able to provide a more reliable and generalizable indicator of individual differences in WM and achievement.

In addition, many of the WM measures we reviewed lack basic information on psychometric aspects. Very seldom is the reliability and validity of the measures reported. One exception is the aforementioned WM battery developed by Swanson (1992), which parallels very closely the construction of Daneman and Carpenter's WM measure. Reliability and validity data have been reported (Swanson, 1992; 1996) as well as standardized across a broad age range (Swanson, 1995). Additional measures are being developed along this line (e.g., Gathercole & Pickering, 2000).

Finally, we draw heavily from our own research on LD. This focus was done for several reasons, and the most obvious one is that we are most familiar with this research. Another reason is that our work focuses on the important components of WM as they relate across a broad array of academic outcomes. We also attempt to integrate the findings of two independent research programs that have isolated specific deficits in the phonological system (e.g., Siegel, 1993; 1994) and executive system (e.g., Swanson, 1999a; Swanson et al., 1996). Several other excellent research programs (e.g., Bull & Johnston, 1999; de Jong, 1998; McLean & Hitch, 1999; Oakhill & Kyle, 2000; Passolunghi, et al., 1999) have implicated WM problems in the phonological and executive system in LD samples. We cite this research where appropriate.

Given these caveats, we will now briefly review the psychological literature linking LD to components of WM.

THE PHONOLOGICAL SYSTEM

In Baddeley's model (1986), the articulatory or phonological loop is specialized for the retention of verbal information over short periods of time. It is composed of both a phonological store, which holds information in phonological form, and a rehearsal process, which serves to maintain representations in the phonological store (see Baddeley, Gathercole, & Papagano, 1998, Burgess & Hitch, 1992, for an extensive review). This relatively simple model has accommodated a number of experimental studies of normal adults, children, and neuropsychological patients (see Gathercole & Baddeley, 1993, for review). In addition, there are a substantial number of studies that support the notion that children with LD experience deficits in processes related to the phonological loop (e.g., see Siegel, 1993, for a review of studies showing deficits in LD readers related to phonological representations; then see Swanson, Cooney, & O'Shaughnessy, 1998, for a synthesis of studies showing deficits in verbal rehearsal), and therefore the relevant research will be only summarized here.

Several studies suggest that the phonological loop deficit may lie at the root of word learning problems in children with LD (e.g., see Siegel, 1993, for review). That is, LD readers' poor word recognition is related to the utilization and/or operation of their articulatory loop (see Hulme & Snowling, 1992; for a comprehensive review). For example, LD readers are less able to generate pronunciations for unfamiliar or nonsense words than skilled readers (Gathercole & Baddeley, 1989), suggesting a deficient utilization or operytion of the phonological recoding function of the articulatory control process. The strongest support for this assumption comes from the research on dyslexia. Dyslexia is viewed as a specific developmental disorder for which a modular impairment in phoneme-grapheme system knowledge, or a phonological deficit, has been postulated (Stanovich, 1990). The manifestations of this phonological deficit are poor acquisition of reading (Siegel, 1993), poor performance on phonological awareness tasks (Bradley &

Bryant, 1978), slow naming speed (Denckla & Rudel, 1976), and impaired verbal STM (Nelson & Warrington, 1980). The current research suggests that this deficit (a) predates the acquisition of literacy (Scarborough, 1990), is independent of IQ (Siegel, 1988; 1992), and persists over time (Bruck, 1990; 1992). Further, there is some universality to this deficit regardless of language (Landerel, Wimmer, & Frith, 1997), and there is a neurological basis found in the speech processing areas of the brain (Paulesu, Frith, Snowling, Gallagher, Morton, Frackowiak, & Frith, 1996). There are, of course, arguments that phonological processing deficits reflect more general deficits, such as auditory-temporal order (Tallal & Piercy, 1975, then see Studdert-Kennedy, Mody, & Brady, 2000), but these arguments are beyond the scope of this article.

In general, difficulty in forming and accessing phonological representations impairs the ability to learn new words in individuals with LD. Interestingly, this phonological impairment does not appear to have broad effects on general ability apart from the developmental consequences on language-related functions (see Hohen & Stevenson, 1999). One of those language functions alluded to in the literature is verbal memory (e.g., Gathercole, 1998). Thus, for example, verbal IQ, as measured on a Wechsler scale, may be lower than performance IQ, but most of those dips are related on such tasks as digit span or perhaps the arithmetic subtest. Both tasks are assumed to act as a measure of verbal STM memory (however, poor number facts learning may also play a role on the arithmetic task). Before reviewing the evidence on verbal memory, the overlap as well as the distinctions between verbal STM and verbal WM must be addressed.

Verbal STM vs. Verbal WM

Clearly, there is some confusion in the literature in LD about whether phonological deficits in verbal STM are synonymous with deficits in verbal WM. Most of studies that compare skilled and LD readers' performance assume that verbal STM measures capture a subset of WM performance, the use and/or operation of the phonological loop (see Gathercole, 1998; Gathercole & Baddeley, 1993, for a comprehensive review). Some authors have even suggested that the phonological loop may be referred to as verbal STM (e.g., Baddeley, 1986; Brown & Hulme, 1992; Dempster, 1985), because it involves two major components discussed in the STM literature: a speech-based phonological input store and a rehearsal process (see Baddeley, 1986, for review). For example, Crain and Shankweiler (1990) stated,

> Along with other researchers, we envision the verbal working memory system as having two parts… First, there is a storage buffer, where rehearsal of phonetically coded information takes place. This buffer has the properties commonly attributed to STM: It can hold linguistic input briefly… The second component of working memory is a coytrol mechanism, whose primary task is to relay results of lower-level analysis of linguistic input upward through the system.(p. 542).

The majority of research to date clearly suggests that children with LD rehearse less and perform more poorly on tasks requiring the short-term retention of order information than non learning disabled (NLD) children (e.g., see O'Shaughnessy & Swanson, 1999; Swanson, Cooney, & O'Shaughnessy, 1998; for a comprehensive review of the STM literature), suggesting inefficient utilization of the phonological rehearsal process (Henry & Millar, 1993). Further, because children with LD have smaller digit spans than non learning disabled children, it is assumed they have basic inefficiencies in the storage of phonological input. In addition, several studies also suggest that the phonological system, via the phonological loop (i.e., phonological store; subvocal rehearsal), influences the reader's verbatim memory capacity, which in turn supports comprehension (e.g., Perfetti, 1985). For example, McCutchen, Bell, France, and Peffetti's (1991) model of reading suggested that phonological codes are made available during word recognition and are used to retain information in WM. Automatic activation of phonological codes is assumed to increase the likelihood that those codes are available in WM which in turn frees resources for other reading processes (e.g., comprehension). These assumptions are consistent with many bottom-up models of reading that view the primary task of executive processing as one of relaying the results of lower-level linguistic analyses upward through the language system (e.g., Shankweiler & Crain, 1986). Phonologically analyzed information at the "word-level" is then transferred to WM storage, whereby it is moved (thus freeing storage for the next chunk of phonological information) upward through the processing system to promote on-line extraction of meaning.

In contrast to the assumption that STM is a subset of WM, others argue that STM and WM are distinct operations (e.g., Daneman & Carpenter, 1980; Cantor, Engle, & Hamilton, 1991; Cowan, 1995; Engle et al., 1999b; Swanson, 1996). Along with these authors, we argue that WM tasks require the active monitoring of events. Monitoring of events within memory is to be distinguished from simple attention to stimuli held in STM. There are many mnemonic situations in which a stimulus in memory is attended to and the other stimuli exist as a background—that is, they are not the center of current awareness. These situations, in our opinion, do not challenge monitoring. Monitoring within WM implies attention to the stimulus that is currently under consideration together with active consideration (i.e., attention) of several other stimuli whose current status is essential for the decision to be made.

A study by Swanson and Ashbaker (2000) directly addressed this issue by testing whether verbal STM and WM reflect independent operations. LD and skilled readers and younger reading level matched children were administered a battery of tests to assess executive and phonological processing. Measures of the executive system were modeled after Daneman and Carpenter's (1980) WM tasks (i.e., tasks demanding the coordination of both processing and storage), whereas measures of the phonological system included those that related to articulation speed and verbal STM. For example, in one of the four executive processing tasks (Listening Sentence Span, Auditory Digit Sequence, Visual-Spatial Matrix, Mapping & Directions) administered, the Listening Sentence Span task consisted of 17 unrelated declarative sentences, seven to ten words in length. The sentences were arranged into sets of two, three, four, or five, with two sets at each level. An example of the sentences at the three-sentence level included:

1. We waited in line for a ticket.

2. Sally thinks we should give the bird its food.
3. My mother said she would write a letter.

After the presentation of sentences in a set, children were asked a question ("Where did we wait?") and then asked to recall the last words in each sentence.

A Digit and Word Span task assessed verbal STM. These tasks included presenting digits (e.g., 1, 8, 5) or words (e.g., red, car, boy) in sets of increasing length and participants were asked to recall the digits or words in exact order. Verbal STM (word and digit span tasks) and articulation speed tasks were considered to be a derivative and/or share a substrate of processes related to the phonological system (Baddeley, Lewis, & Vallar, 1984; Brown & Hulme, 1992). This is because a significant linear relationship between articulation rate and verbal memory span has been found in many experimental situations (e.g., Brown & Hulme, 1992), whether the differences in articulation rate were due to developmental increases in children (Hulme, Thomson, Muir, & Lawrence, 1984), reading ability (McDougall, Hulme, Ellis, & Monk, 1994), and/or with pseudowords and familiar words (Hulme, Maughan, & Brown, 1991). Further, articulation rates have been interpreted as a measure of how quickly words can be encoded and rehearsed within the phonological loop (McDougall et al., 1994). In short, the model assumes that subjects who are fast articulators can maintain more items than subjects who are slow articulators.

The Swanson and Ashbaker (2000) study yielded two important results. First, although the LD reading group was inferior to skilled readers in WM, verbal STM, and articulation speed, the differences in verbal STM and WM had little connection with articulation speed. Reading-related differences on WM and STM measures were sustained when articulation speed was partialed from the analysis. Moreover, these reading group differences were pervasive across verbal and visual-spatial WM tasks, even when verbal STM was partialed out, suggesting that reading group differences are domain general. Second, WM tasks and verbal STM tasks contributed unique or independent variance to word recognition and reading comprehension beyond articulation speed. These results were consistent with those of Daneman and Carpenter (1980) and others (e.g., Engle et al., 1999b), who have argued that verbal STM tasks and WM tasks are inherently different, and while phonological coding might be important to recall in STM, it may not be a critical factor in WM tasks.

The above findings from Swanson and Ashbaker's study are consistent with early work on LD samples (Swanson, 1994; Swanson & Berninger, 1995). In a 1994 study, Swanson tested whether STM and WM contributed unique variance to academic achievement in children and adults with learning disabilities. In this study, Swanson found that STM and WM tasks loaded on different factors. Further, these two factors both contributed independent (i.e., unique) variance to reading and mathematics performance. A study by Swanson and Berninger (1995) tested whether STM and WM accounted for different cognitive pryfiles in LD readers. The rationale behind testing the independence of these two measures was that WM was seen as drawing resources from LTM (e.g., Cantor & Engle, 1993), whereas verbal STM memory was seen as a system that can operate independently of LTM (e.g., Dempster, 1985). Further, the phonological processes that are directly associated with reading recognition were seen as modular (Stanovich, 1990), and therefore were assumed to operate independently of a central system. To test this notion, Swanson and Berninger used a double dissociation design to compare children deficient in reading comprehension (based on scores from the Passage Comprehension subtest of the Woodcock Reading Mastery Test) and/or recognition (based on scores from the Word Identification subtest of the Woodcock Reading Mastery Test) on WM and phonological STM measures. Thus, participants were divided into four ability groups: High comprehension/High Word Recognition, Low Comprehension/High Word Recognition, High Comprehension/ Low Word Recognition, and Low Comprehension/Low Word Recognition. The results were straightforward: WM measures were related primarily to reading comprehension, whereas phonological STM measures were related primarily to reading recognition. Most critically, because no significant interaction emerged, the results further suggested that the comorbid group (i.e., children low in both comprehension and word recognition) had combined memory deficits. That is, WM deficits were reflective of the poor comprehension-only group and STM deficits were reflective of the poor recognition-only group.

Stanovich and Siegel (1994) also show that LD readers (as well as poor readers) suffer deficits in both verbal WM and verbal STM even after reading ability is controlled. In their study, Stanovich and Siegel amalgamated a sample that consisted of over 1500 children from ages 7 to 16 years. Children were classified into poor readers who also had low IQs, poor readers who had average IQs, and those children who had average scores in IQ and reading. They compared these groups on various processing measures when reading scores were entered first into a regression model. The processing variables of interest were performance on STM rhyming and non-rhyming tasks and WM tasks that included words or numbers. The STM tasks included letter spans that rhymed (B,C, D, G, P, T, V) and did not rhyme (H, K, L, Q, R, S, W). The verbal WM task (WM-sentences) included orally presenting sentences of increasing set size that required children to supply missing words (People go see monkeys in a -----) and then asking them to recall those supplied words. The number WM task (WM-counting) required children to count yellow dots from a series of blue and yellow dots arranged in irregular patterns. The patterns were on cards and the number of cards in each set increased in number. For each set, the child was to recall the count of yellow dots for each card after all cards had been presented. When LD readers (those children with a discrepancy between IQ and reading) and poor readers (those children whose IQ matched their low reading level) were compared to skilled readers, a significant advantage was found in favor of skilled readers' recall on the verbal WM task that included words and the STM tasks that included rhyming words. No differences in recall were found between the two poor reading groups. Swanson (1999b) extended this finding by showing that skilled readers performed better on WM tasks than LD readers, even when the influence of reading comprehension was removed. He also found in a separate sample (Swanson, Mink, & Bocian, 1999) that when entering intelligence and reading (word recognition) first in the equation in the prediction of verbal WM performance, chiydren with reading disabilities but without hyperactivity performed significantly poorer on a verbal WM tasks than those children who were slow learners or were comorbid (reading problems combined with ADHD).

Further support that LD readers suffer problems in both verbal STM and verbal WM is found in a life span study of Siegel (1994). Her study included some 1200 individuals, ages 6 to 49. These individuals were presented tasks related to word recognition, pseudo word decoding, reading comprehension, and WM, as well as a STM task requiring the recall of rhyming and nonrhyming letters. The results showed that there was a gradual growth in WM skills from age 6 to 19 with a gradual decline after adolescence. On the memory tasks, across most age levels, individuals with reading disabilities performed at a significantly lower level than individuals with normal reading skills. Thus, LD readers experienced deficits on WM and verbal STM tasks across childhood, adolescence, and adulthood.

What can we conclude from the above studies? We think there are three important observations to be made.

1. Verbal WM can operate independently of verbal STM. The implication of this finding is that LD students' poor WM may co-occur with weak STM, but these WM problems also maintain some independence from the development of STM (Swanson, 1994; Swanson & Ashbaker, 2000; also see Engle et al., 1999a).
2. Although skills associated with phonological processes (i.e., articulation speed and STM) are important to individual differences in reading, they are no more important than verbal and visual-spatial WM. Our regression analysis has found that articulation speed, STM, and WM substantially reduced reading group variance in reading recognition and comprehension, but no one process was more important than another in this reduction (Swanson & Ashbaker, 2000).
3. Articulation rates do not explain all of the variance in memory performance between skilled and LD readers (Swanson & Ashbaker, 2000). Our results do confirm, however, that robust reading group differences emerge on articulation speed measures. However, it appears that articulation rates and memory processes can develop independently of each other.

Given the above findings, what is the relationship between WM and STM in children with LD? An earlier study by Cantor et al. (1991) may clarify this relationship. Their study assessed the relationship between complex span measures of WM, measures of STM, and comprehension as measured by the verbal SAT (Scholastic Aptitude Test). Their results showed that two distinct factors, STM and WM, contributed significant variance to comprehension. In a follow-up study, Engle et al. (1992) argued that STM was important to comprehension when it involved surface coding (e.g., the recall of words in a phrase, or literal comprehension), whereas WM was important in comprehending the gist and complexities of reading comprehension. This interpretation is consistent with some of our findings. That is, although the WM measures in our studies (Swanson, 1994; Swanson, 1999b; Swanson & Berninger, 1995) were more highly related to comprehension than STM, some meaningful correlations emerged between STM and comprehension (coeffycients ranging from .30 to .40—see Table 2 of Swanson & Ashbaker, 2000). Further, standardized reading comprehension passages in our studies were composed of questions that vary from literal to inferential, thereby capturing surface coding as well as more complex comprehension.

Although a distinction can be made between the contributions of STM and WM to reading, we recognize from current models of WM and expert knowledge (Ericsson & Kintsch, 1995) that the distinctions between STM and WM are obscured because both systems can draw from a LTM source. Thus, the relationship between WM and LTM, as well as STM and LTM, must also be clarified. Parallel to Anderson, Reder, and Lebiere (1996) and Ericsson & Kintsch (1995), we assume that WM consists of temporary or permanent knowledge units in LTM that are currently active. On the other hand, STM is information maintained at a surface level that does not consciously rely on permanent knowledge structures for its operation (e.g., Engle et al., 1992). This independence of STM from LTM processing has been established in the literature for some time (e.g., Geiselman, Woodward, & Beatty, 1982). However, it is reasonable to assume that if verbal STM tasks are designed to share components of WM, then STM would correlate with LTM. Thus, in our studies it is reasonable to assume that WM and STM can share some common variance with LTM. However, the majority of our studies show unique variance between the systems in predicting reading.

Summary

There is evidence that participants with LD suffer deficits in the phonological system. A substrate of this system may contribute to problems in verbal WM that are independent of problems in verbal STM. In addition, these problems in verbal WM are not removed by partialing out the influence of verbal articulation speed, reading comprehension, or IQ scores. We now turn our attention to the visual-spatial component of WM.

VISUAL-SPATIAL SKETCH PAD

The visual-spatial sketch pad is specialized for the processing and storage of visual material, spatial material, or both, and for linguistic information that can be recoded into imaginal forms (see Baddeley, 1986, for a review). Measures of visual-spatial WM have primarily focused on memory for visual patterns (e.g., Logie, 1986). A major study by Gathercole and Pickering (2000) found that visual-spatial WM abilities, as well as measures of central executive processing, were associated with attainment levels on a national curriculum for children aged 6 to 7 years. Children who showed marked deficits in curriculum attainment also showed marked deficits in visual-spatial WM. Thus, there is a strong relationship between visual-spatial WM and academic performance in the younger grades. However, the literature linking LD to visual-spatial memory deficits is mixed. For example, several studies in the STM literature suggest that learning-disabled children's visual STM is intact (see Jorm, 1983; Swanson et al., 1998, for a comprehensive review). When visual-spatial WM (combined storage and processing demands) performance is considered, however, some studies find that visual-spatial WM in students with LD is intact when compared with their same age counterparts (e.g., Swanson et al., 1996, Exp. 1), whereas others suggest problems in various visual-spatial tasks (Swanson et al., 1996, Exp.2). Most studies suggest, however, that depending on the type of academic disability, greater problems in performance are more likely to occur on verbal than visual-spatial WM tasks.

The majority of studies assessing the importance of visual-spatial WM either

a. partial out the influence of verbal aptitude between LD and NLD children on visual-spatial WM measures or

b. compare children subgrouped by difficulties in reading and mathematics with average achievers.

In an example of the first case, Swanson, Bocian, and Mink (1999) found, via a regression analysis that partialed out the influence of verbal IQ, that a reading-disabled groups were inferior in performance to slow learners (garden variety poor readers) on visual-spatial and verbal WM measures. That is, although children with a specific reading disability have a greater deficit on the verbal WM task than the visual-spatial WM task, performance on both types of tasks was inferior to other poor learning groups when controls are made of verbal IQ.

In an example of the second, Siegel and Ryan (1989) compared the WM of normal achieving and subtypes of learning-disabled children. Children were presented the WM sentences and the WM counting task, as discussed earlier for the Stanovich and Siegel (1994) study. This latter task was considered to involve fewer verbal demands than the sentence span task. They found that children with learning disabilities, primarily in arithmetic, had lower scores on a WM task that involved counting, whereas a subgroup of learning-disabled children with difficulties primarily in reading had problems on both the sentence and counting WM tasks. Both of these groups with learning disabilities, however, were inferior in their WM for numbers and words than a attention-deficit disorder group and a normal achieving group. The important finding was that there was performance differentiation on the WM measures related to subtype. This differentiation was related to the type of verbal material rather than to a differentiation between visual-spatial and verbal WM. That is, individuals poor in arithmetic are asked to manipulate digits in memory, which in turn accounts for their deficiency on specific low verbal tasks (also see Hitch & McAuley, 1991).

It may not be the case, however that differentiation occurs between reading and math subgroups when visual-spatial WM measures are used (Swanson, 1993c; then see Fletcher, 1985). For example, Swanson (1993d) found that 10-year old children with LD who suffered either math problems or reading problems could not be clearly differentiated on performance for verbal or visual-spatial WM measures. His study included six tasks that assessed verbal WM (Rhyming, Story Retelling, Auditory Digit Sequence, Phrase Sequencing, Semantic Association, Semantic Categorization) and five tasks (Visual Matrix, Picture Sequence, Mapping & Directions, Spatial Organization, Nonverbal Sequencing) that assessed visual-spatial WM. Consistent with Daneman and Carpenter's (1980) format, all tasks required the maintenance of some information during the procesying of other information. The processing of information was assessed by asking children a comprehension question about to-be-remembered material, whereas storage was assessed by accuracy of item retrieval. The comprehension question generally required a simple recognition of new and old information. Swanson found on these task that arithmetic disabled children's performance was as low as LD readers across verbal and visual-spatial WM tasks.

In a later study, Swanson et al. (1996) tested whether there may be potential performance advantages for LD readers on visual-spatial WM tasks relative to verbal WM tasks and if these advantages may be related to processing demands. Reading disabled and chronologically aged-matched and reading level (RL) matched students were compared on verbal and visual-spatial WM measures under three different conditions: initial (conditions in which there are no cues or probes to help them recall information), gain (conditions in which cues are used to help them recall previously forgotten information in the initial condition), and maintenance (conditions in which one represents the gain condition, but this time without help). A rationale for these conditions is necessary before proceeding to the results. The logic for the conditions is as follows (also see Swanson, 1992; (Swanson, 1999a): The initial condition reflects the baseline of each participant's self-initiated processes to access information. There is substantial evidence that performance differences between LD readers and skilled readers increase as demands for resources (i.e., number of items to be stored) increase under such conditions (de Jong, 1998; Siegel, 1994; Swanson, 1992). The gain condition is designed to enhance item accessibility of stored items by tailoring cues to help participants reinstate memory traces or to retrieve forgotten items from the initial or baseline conditions. Previous studies have shown that such conditions significantly improve performance over baseline conditions across a large age range with average achievers (e.g., Swanson, 1999a), and children with reading deficits (e.g., Swanson, 1993d; Swanson et al., 1996).

Some studies have shown that the gain conditions improved span scores by as much as 1 to 2 standard deviations from the baseline conditions (Swanson, 1992; 1993; 2000). Improvements in performance are related to processing efficiency. Processing efficiency improves because cuing procedures reduce the number of inefficient strategies for accessing (retrieving) previously presented information. As with almost any experimental technique, however, objections can be raised about how the results of the manipulations can be best interpreted. One reservation in arguing that differences between reading groups are due to enhanced processing efficiency (i.e., improved access to previously forgotten items) is that the manipulations between the initial and gain condition are limited to individual differences in a participant's ability to maintain (store) or preserve information during processing. Because WM involves the preservation (storage) of information during processing, we implemented a condition that examined whether LD readers are less accurate than skilled readers at maintaining relevant information. For this condition, maintenance, the same WM tasks that matched each participant's highest WM span (gain score or asymptotic level) are again administered, but this time without cues. We assume that performance in this condition captures processes beyond the learning of items presented in the earlier conditions. This is because previous studies have shown that the maintenance condition predicts unique variance related to reading beyond that of span scores derived from the initial and gain condition (Swanson, 1996). Thus, because each participant is at the same point in terms of successfully accessing information at his/her highest span level in the gain condition, a failure to maintain (access) critical information can be partly attributed to processing demands on a limited capacity system.

Deficits in the ability to maintain information are viewed as consequences of a limited capacity system (e.g., Salthouse, 1992). Of course, other influences may be operating, but it seems reasonable to assume that if differences between LD and skilled readers are partially related to WM capacity, then LD readers will have fewer resources available to them to maintain/activate old (previously accessed) information than skilled readers under high demand conditions.

The Swanson et al. (1996) results showed that although only poor verbal WM task performance emerged by LD readers in the initial condition, LD readers were deficient in both verbal and visual-spatial WM performance for the gain and maintenance conditions when compared to their chronologically-age-matched counterparts. Further, these performance differences held up when verbal STM scores (see Experiment 2) were partialed from the analysis. This finding suggested that there may be a general system that cuts across both verbal and visual-spatial WM tasks that influences LD readers' performance when processing demands are high.

Summary

The evidence on whether children with LD have any particular advantage on visual-spatial WM when compared to their normal achieving counterparts fluctuates with processing demands. Swanson (2000) proposed a model that may account for these mixed findings. There are two parts to this model. The first part of the model assumes that executive processes (domain general system) are used to maintain associations across high demand processing conditions. The maintenance of associations across processing conditions is related to changes, via experimenter feedback (cues or probes), in WM performance. A child with a learning disability has difficulty efficiently maintaining these associations. The predictions of the first part of the model are consistent with current models of executive functions that are called into play only when the activities of multiple components of the cognitive architecture must be coordinated (e.g., Baddeley, 1996; Engle et al., 1992: Salthouse, 1996). The second part of the model assumes that when excessive demands are not made on the executive system, performance differences between LD and skilled readers are limited to the verbal system. The second part of the model is consistent with earlier work suggesting that the visual-spatial system of LD readers is generally intact (see Shankweiler & Crain, 1986, for a review), but when excessive demands are placed on the executive system, their visual-spatial performance is depressed compared with chronological age-matched readers (Swanson et al., 1996). This model has yet to be tested across multiple age groups.

EXECUTIVE SYSTEM

The central executive monitors the control processes in WM. There have been a number of cognitive activities assigned to the central executive, including coordination of subsidiary memory systems, control of encoding and retrieval strategies, switching of attention in manipulation of material held related to the verbal and visual spatial systems, and the retrieval of knowledge from LTM (e.g., Baddeley, 1996; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Although there is an issue of whether the central executive is a unitary system [it is conceptualized as either being unitary (Baddeley, 1986)] or composed of multiple domain-specific executives (Goldman-Rakic, 1995), there is some agreement that the central executive has some capacity limitations that influence the efficiency of operations (e.g., for allocating attention to, performing operations on). We assume that executive function has separable operations (e.g., inhibition, updating), but these operations may share some underlying commonality (e.g., see Miyake et al., 2000, for a review).

We think that the crucial component of the central executive as it applies to learning disabilities is controlled attention. Controlled attention is defined as the capacity to maintain and hold relevant information in "the face of interference or distraction" (Engle et al., 1999a, p. 104). "We now review studies that have implicated deficits in executive processing for children with LD, particularly as it applies to controlled attention. The involvement of executive processing activities is inferred from three outcomes:

a. poor performance on complex divided attention tasks (e.g., Della Salla, Baddeley, Papagno & Spinler, 1995),

b. poor monitoring, such as an inability to suppress (inhibit) irrelevant information (e.g., Conway & Engle, 1994), and

c. depressed performance across verbal and visual-spatial tasks that require concurrent storage and processing (e.g., Turner & Engle, 1989).

Complex Divided Attention

Before we summarize the research on task complexity and divided attention, we must review two assumptions and one conclusion. First, executive processing activities are reflected on tasks in which subjects must successfully coordinate performance between a primary and secondary task (see Baddeley, 1986, Duncan, 1995, Miyake & Shah, 1999, for a review). It is assumed that optimal performance emerges on both the primary and secondary task when demands on processing are minimal. However, under conditions that place high processing demands on multiple tasks, processing adjustments (such as modifying and reprioritizing processing behavior) must be made by the executive system. Some of those adjustments include the prioritization of processes, selective attention to certain features, and item inhibition (to be discussed).

A second assumption is that performance is reduced substantially on tasks in which mental resources are limited (Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986). These limitations are due to insufficient information stored in LTM (variously referred to as data limitations, lack of prior knowledge) and/or attentional capacity (amount of cognitive space or controlled attention that can be allocated to the task). One can assume that individual differences in demands for mental resources become more pronounced with increases in information to be processed (e.g., span length).

One conclusion from the experimental literature is that individual differences in WM (of which executive processing is a component) are directly related to achievement (e.g., reading comprehension) in individuals with average or above average intelligence (e.g., Daneman & Carpenter, 1980). Thus, children or adults with normal IQs have difficulty (or efficiency varies) in executive processing and that such difficulties are not restricted to those with depressed intelligence (i.e., mentally retarded individuals).

We briefly review the research covering those aspects of executive processing related to control and regulation of mental resources between a primary and secondary task. In an early study, Swanson (1984a) showed that the mental allocation of attentional resources of students with LD was more limited than that of their counterparts. In the first study of three experiments, LD and non learning disabled (NLD) children were presented a primary task in which they were to solve anagrams. The anagrams involved two degrees of "cognitive effort." In the low effort condition, the anagrams were scrambled for only the first and second letters (e.g., play, lpay), and in the high effort condition, all the letters were rearranged (e.g., train, rnita). The correct solutions to lists of anagrams were also organized into categories by semantic (e.g., words that reflect food, transportation, etc.) and phonemic (e.g., words that rhyme, like cat, rat, etc.) word features, and word features not ostensibly related (nonsemantic). After the anagram solution (primary task), participants were asked to recall words (a secondary task) related to the anagram solution. A significant group x cognitive effort interaction emerged. No matter what the organizational characteristics of words (i.e., semantic, non semantic, or phonetic) were, words were better recalled by skilled than by LD readers under high effort conditions. Further, there was a trend in the lower effort condition for LD readers to recall more words than skilled readers, although this trend was not statistically significant. These results are shown in Figure 1. These results were replicated in two additional experiments. The results showed that no matter the type of word list, after a difficult primary task, secondary task performance was higher for skilled readers than it was for LD readers. However, LD readers' recall was at a statistically comparable level to skilled readers in low effort conditions. In general, these results show that LD readers have difficulty allocating attention resources on high demand tasks.

Monitoring Activities

Although the above studies show that ability groups can be separated in performance on high demand tasks, further information is needed to detect how ability groups differed in the actual monitoring of their limited attentional resources. Thus, our earlier work was extended by determining how limits in the allocation of attention resources were strategically handled. This monitoring of resources was measured in three ways.

First, we considered how children set priorities in resource allocation when there is a competition between the primary and secondary tasks for similar resources. There are two global strategies for dealing with this competition: dividing resources and sharing resources (e.g., Navon & Gopher, 1979). The strategy selected is reflected in the direction of the correlations between primary (central) task recall and secondary (incidental) task recall. For example, a division or "tradeoff" in resources occurs when there is a negative correlation between the primary and secondary task. On the other hand, if moderate demands are made on resources, then children may allocate comparable resources for both the primary and secondary task and therefore a positive correlation occurs between the central and secondary task.

Second, the child may voluntarily control (inhibit) the transfer of information between a primary and secondary task. For example, when participants are presented two lists of words to remember in which some words must be recalled immediately (a primary task) and others are delayed (a secondary task), they may monitor attention back and forth between the word lists. However, to effectively discriminate among items at recall, the non targeted words must be inhibited. That is, controls must be made to insure that insertions of words from the wrong list (primary task words are recalled in the secondary list and vice versa) are suppressed or inhibited during recall (see Chiappe et al., 2000, for a review).

Finally, children vary in their selective attention to certain features of the primary and secondary task. Not unlike the first strategy that reflects tradeoffs when demands are too high (i.e., the participant places the majority of resources into the primary task or distributes them nicely between the primary and secondary task), this strategy reflects the degree to which the participant seeks to allocate specific resources to isolated features of a word (e.g., phonological or orthographic). Selective attention is measured as the difference in recall between specific word features in the primary and secondary task. Difference scores that aggregate near zero (0) reflect attention given to both targeted and nontargeted word features, whereas scores greater than 0 reflect a focus on specific word features.

We investigated whether children with LD had greater trade-offs and weaker inhibition strategies than average achievers on divided attention tasks. Swanson (1989) compared the performance of slow learners, LD children, average achievers, and intellectually gifted children on a recall task that had words embedded in sentences. Children were presented 20 base and 20 elaborative sentences, read orally. A set of adjectives served as target words; the children were asked to select one of two adjectives presented in the context of two different types of sentences. One type of sentence consisted of a base sentence (e.g., The woman wore a pretty -----.) and the children completed the sentence by choosing between the words “dress” and “foot.” The other sentence (elaborative) consisted of a base sentence and a short phrase (e.g., The woman wore a pretty ----- at the dance). The choices related to the adjectives that would complete the sentence varied as to low effort and high effort. For example, consider the base sentence “The ----- went to school.” The set of responses may include an easy or low effort choice (children vs. house) or a hard or high effort choice (friends vs. children). Thus, children were told they would be given two words to choose from, and they would be asked to recall the word they had chosen (circled) first, and then after a short period of time, the word they would be asked to recall the word they did not choose. The word circled is the primary (central) task, and the word not circled is the secondary task.

The results produced three findings beyond the expected findings that the LD children performed poorer on the primary task than gifted and average achievers. To simplify the reporting of the results, only findings related to LD children and average achievers are highlighted.

First, as found in the previous studies, no differences occurred between ability groups in secondary recall for the low effort condition. However, high effort conditions favored the recall of secondary words by average achieving children when compared to children with LD.

Second, recall insertions (the proportion of nontargeted words incorrectly recalled between the secondary and the central task) were significantly higher in children with LD than average achievers. Thus, children with LD had greater difficulty inhibiting nontargeted words than average achievers.

Finally, clear differences emerged between ability groups in the prioritization of resources (direction of the correlations between the primary and secondary tasks). Tradeoffs (low positive or negative correlations) emerged for LD students between the primary and secondary task, whereas there was a sharing of resources (i.e., positive correlations) for average children.

Overall the results suggested that LD readers were clearly distinguished from average achievers in how they handled attentional demands. However, these experiments primarily required the processing of words. Thus, three additional experiments were designed to reflect attentional demands on both the verbal and visual-spatial system. As in the Swanson (1989) study, Swanson (1993b) varied the complexity of information to be remembered by varying encoding effort (complexity of decision), as well as by including material that was nonverbal or low in verbal familiarity. For example, in one of the experiments (Swanson, 1993b, Exp. 1), a concurrent memory task, adapted from Baddeley (Baddeley & Hitch 1974; Baddeley, Eldridge, Lewis, & Thomas, 1984), was administered to LD children and skilled readers. The task required participants to remember digit strings (e.g., 9, 4, 1, 7, 5, 2) while they currently sorted blank cards, cards with pictures of nonverbal shapes, and sorting of cards with pictures of items that fit into semantic categories (e.g., vehicles—cars, bus, truck; clothing—dress, socks, belt). Demands on the central executive capacity system were manipulated through the level of difficulty (3 vs. 6 digit strings) and type of sorting required (e.g., nonverbal shapes, semantic categories, blank cards). Sorting activities that placed demands on the verbal storage (phonological system) include the categorization of pictures into semantic categories, whereas sorting activities that made demands on the visual store (i.e., visual-spatial sketch pad) include discrimination among complex nonverbal shapes. Baddeley et al. (1984) found in such activities that the main task difficulty (sorting) interacts with concurrent memory load, but only with a memory load of 6 digits. The 3-digit load task places minimal demands on memory and, in fact, ceiling effects are usually reported (e.g., Baddeley & Hitch, 1974). Performance for the 6-digit memory load condition places processing demands on the central executive, thereby interfering with the main task. Swanson's (1993b) results indicated a clear effect for memory load. The results showed that LD readers can perform comparably to their chronological age (CA)-matched counterparts on verbal and visual-spatial sorting conditions that included 3-digit strings (low demands), and that only when the coordination of tasks becomes more difficult (6-digit strings) do ability group differences emerge. More important, the results for the high memory load condition (6-digit strings) showed that LD readers were inferior to the CA-matched readers (and reading matched controls for ordered recall) in their ability to recall digits during both verbal and nonverbal sorting. Because recall performance for LD readers was not restricted to a particular storage system (i.e., verbal storage), compared with the performance of CA-matched skilled readers, one can infer that processes other than a language-specific system accounted for the results.

We also explored LD children's selective attention to word features within and across the cerebral hemispheres, via a dichotic listening task. There has been an abundance of experimental evidence that left and right cerebral hemispheres are associated with variations in capacity demands. For example, the targeting of information in one ear is assumed to consume resources that would normally be used in processing information in the competing ear (e.g., see Friedman & Polson, 1981). Given this assumption, Swanson and Cochran (1991) compared 10-year-old children with LD with average achieving children matched on chronological age on a dichotic listening task. Participants were asked to recall words organized by semantic (e.g., red, black, green, orange), phonological (e.g., sit, pit, hit), and orthographic (e.g., sun, same, seal, soft) features presented to either the left or tight ear. The study included two experiments. Experiment 1 compared free recall with different orienting instructions to the word lists. One orienting instruction told children about the organizational structure of the words the other condition (non orienting) did not. For the orienting condition, children were told remember all words, “but to specifically remember words that go with -----” (e.g., colors) or “words that rhyme with ———” (e.g., it) or “words that start with the letter ———” (e.g., s) that the words go with certain categories (such as animals and furniture) or sounds (rhymes). For the nonorienying condition, children were told to remember all words but no mentioned was made of the distinctive organization features of words. Experiment 2 extended Exp. 1 by implementing a cued recall condition. In both experiments, children were told they would hear someone talking through the earphone in either the right or left ear. They would also hear words in the other ear. They were told that when they stopped hearing the information in the designated ear and the non-designated ear, they were to tell the experimenter all the words they could remember.

For both experiments, NLD children had high levels of target recall and nontargeted recall than disabled children. More important, ability group differences emerged in “how specific word features” were selectively attended to. The selective attention index focused on the targeted words in comparison to the background words (targeted word recall minus background word recall) from other lists within the targeted ear, as well as background items in the contra lateral ear. Regardless of word features, whether competing word features were presented within ear or across ear conditions, or whether retrieval conditions were non cued or cued, LD readers' selective attention scores were smaller (the difference score between targeted items and nontargeted items was closer to zero) than NLD readers. Thus, when compared with LD children, NLD children were more likely to ignore irrelevant information in the competing conditions. Taken together, the results of this study, as well as those of three earlier dichotic listening studies (Swanson, 1986; Swanson & Obrzut, 1986; Swanson & Mullen, 1983) suggest that disabled children suffer processing deficits related to resource monitoring, regardless of the type of word features, retrieval conditions, or ear presentation.

Combined Processing and Storage Demands

Recent work (Siegel, 1994; Siegel & Ryan, 1988; 1989; Swanson, 1992; Swanson, 1994; Swanson et al. 1996; Swanson & Ashbaker, 2000) on executive processing includes tasks that follow the format of Daneman and Carpenter's Sentence Span measure—a task strongly related to achievement measures (see Daneman & Merikle, 1996, for a review). This task is assumed to tap central executive processes related to "updating" (Miyake et al., 2000). Updating requires monitoring and coding information for relevance to the task at hand and then appropriately revising items held in WM.

A recent study (Swanson & Sachse-Lee, 2001a) compared skilled readers and LD readers across a broad age span. The study compared six age groups (7, 10, 13, 20, 35, 55) on phonological, semantic and visual-spatial WM measures administered under the conditions in the earlier referred to Swanson et al. (1996) study: initial (no probes or cues), gain (cues that bring performance to an asymptotic level), and maintenance conditions (asymptotic conditions without cues). This study also explored whether ability groups vary in their WM spans as a function of the type of WM task across age. This study included two verbal WM measures that required the processing of acoustically familiar rhyming words (phonological task, e.g., run, fun, gun; car, star, bar, far) or the processing of semantically related words (semantic task, e.g., pear, apple, prune; car, bus, truck), and a visual-spatial WM measure (visual-matrix task) that required the sequencing of dots on a matrix. Previous studies have shown that (a) LD readers perform poorly on rhyming (phonologically similar words) and semantic tasks (nonconfusable, phonologically dissimilar, or words of high association) when compared with skilled readers and (b) skilled readers' performance is significantly better on semantic measures than on phonologically confusing measures (Shankweiler et al., 1979; see Penney & Godsell, 1999, for a review). The greater differences in recall between semantic and phonological tasks for skilled readers when compared with LD readers is because skilled readers have greater reliance on (or more efficient use of) phonological codes (see Gathercole & Baddeley, 1993, pp. 151–160, for a review of the findings).

The general findings of the Swanson and Sachse-Lee (2001a) study were that

a. young adults (20 and 35 year olds) performed better than children and older adults,

b. skilled readers performed better than LD readers in all processing conditions (see left panel, Figure 2), and

c. the gain condition improved span performance from initial conditions, but performance declined when maintenance conditions were administered.

These findings were qualified, however, by age X ability group interactions related to memory conditions (initial, gain, maintenance) and type of WM task (verbal vs. visual-spatial). The important interactions are shown in Figure 2.

As shown in the right panel, both LD and skilled readers show continuous growth in verbal and visual-spatial WM that peaks at approximately 20 and 35 years of age. The results clearly show, however, that the LD readers were inferior to skilled readers across a range of age groups on WM tasks that required the processing of phonological, visual-spatial, and semantic information. Although LD and skilled readers' WM performance was comparable at some adult ages on the phonological and visual-spatial WM measures, comparable performance was not sustained across all adult age groups. Thus, the study provided little evidence that the LD readers' WM skills catch up with skilled readers as they age, suggesting that a deficit model rather than a developmental lag model best captures such readers' age-related performance.

Perhaps the most important findings of this study were that WM deficits for LD readers across a broad age range are the result of both a domain-general capacity system and an independent domain specific system. There were three findings suggesting that the differences between LD and skilled readers were partly monitored by a common capacity system. First, the study found that the magnitude of the difference (effect size) between LD and skilled readers increased on gain and maintenance conditions when compared with the initial conditions, suggesting that ability group differences are not eliminated by improving processing efficiency. Second, skilled readers experienced less reduction in performance in the maintenance condition, when compared with the gain condition, than LD readers. Thus, not only did LD readers have smaller WM spans than skilled readers across memory conditions, but they also experienced a greater capacity reduction when WM measures were presented under high demand conditions. Finally, LD readers' performance across a large age span was best captured by comparing their performance with adolescents (13 year old skilled readers) rather than with adult skilled readers who yield the highest WM performance (20 and 35-year-olds).

Although the above results provided support for the notion that a general system moderates reading ability group effects across age, there was also clear evidence that reading group differences are more pronounced for the semantic task than the other tasks. We found evidence that the phonological WM task provided greater interference (semantic WM task > phonological WM task performance) in skilled readers than LD readers, supporting the hypothesis that a phonological system is related to individual differences in reading. In addition, this modality-specific effect on reading remained significant in a regression analysis when variables related to capacity demands (costs) and procedures that enhanced processing efficiency (probe scores) were partialed from the analysis. Thus, the study was consistent with the current literature suggesting that isolated processes (i.e., phonological coding) moderate reading group differences on WM tasks.

Summary

We have selectively reviewed studies suggesting that LD children's WM deficits may, depending on the task and materials, reflect problems in controlled attention, an activity of the executive processing system. We think children with LD have difficulties in shifting and updating information in WM. We are uncertain if these monitoring problems in students with LD are specific to resource sharing or may merely reflect problems in task switching. Of course, it is possible that these monitoring problems are fundamentally related. The capacity sharing model suggests that all aspects of working performance have limitations in capacity. These limitations may be limited to a single common source (e.g., Kahneman, 1973) or to multiple sources (e.g., Navon & Gopher, 1979). There may be a single pool or multiple pools subserving various tasks. At each stage, children allocate capacity between tasks that have concurrent demands. The task switching model assumes that a bottleneck occurs in the responses. The capacity limitations between LD and NLD are the same, but LD readers have difficulty strategically allocating attention across processing demands.

As for the diversity of executive functions, we certainly assume that some fractionation exists. LD students are not deficient on all executive processing activities. We have not reviewed the evidence on executive processing tasks where strengths exist. For example, although planning (such as mapping out a sequence of moves) is considered a component of the executive system (e.g., however, see Miyake et al., 2000, p. 90), we have not found ability group differences between LD and NLD students on such tasks [e.g., Tower of Hanoi, Combinatorial, Picture Arrangement or Pendulum tasks (Swanson, 1988, 1993a)]. LD students can set up a series of subgoals for successful task solution. Although these subgoals may differ from, or are less sophisticated than, those of skilled readers (Swanson, 1988, 1993a), their performance is fairly close to their chronologically age matched peers. We now turn our attention to research linking WM to academic achievement.

ACADEMIC TASKS

Our research shows that WM plays a very important role in predicting academic performance. In general, we find for complex domains (e.g., reading comprehension) and low order domains (e.g., calculation) that both the executive system and the phonological loop predict performance. We briefly review studies that support these conclusions in the areas of reading comprehension, problem solving, writing and computation. We do not review research in the area of word recognition because this research was alluded to in our ~discussion of the phonological loop.

Complex Cognition

Reading comprehension

Several studies in the general literature show that the temporary storage of material that has been comprehended depends on WM (e.g., Baddeley, 1996; Cantor & Engle, 1993; Just & Carpenter, 1992; Kintsch, 1998). Consistent with this literature, several of our studies have shown that WM accounts for significant variance in LD readers' comprehension performance (e.g., Swanson, 1999a; Swanson & Alexander, 1997 Swanson & Sachse-Lee, in press). We select one study (Swanson, 1999b) that identifies those components of WM that are most important to reading comprehension. Swanson (1999b) tested two models of comprehension. One model, a bottom-up model of reading comprehension, suggests that phonological processes play a more important role in reading comprehension deficits than does the executive system. The rationale for this model is consistent with the work of Crain et al. (1990), which showed that poor readers are deficient in setting up phonological structures. Reading comprehension is compromised because inefficient phonological analysis creates a “bottleneck” that constricts information flow to higher levels of processing. In effect, lower-level deficits masquerade as deficits at higher levels. Thus, executive processing in their model has the task of relaying the results of lower-level linguistic analyses upward through the language system. The executive processor's regulatory duty is to begin at the lowest level by bringing phonetic processes into contact with “word-level” analysis. Phonologically analyzed information is then transferred to WM storage, which in turn is then transferred (thus freeing storage for the next chunk of phonological information) upward through the system to promote on-line extraction of meaning.

The study also tested a second model, which suggested that executive processing may relay the results of lower-level linguistic analyses upward through the language system, but it also serves as a general storage and/or monitoring system independent of those skills (e.g., Baddeley, 1986; 1996). Thus, the model suggests that there is variance unique to particular components of WM (executive processing, phonological coding) that predict reading comprehension, but that also operate independently of reading comprehension ability. According to this view, skilled readers have relatively higher WM capacity than LD readers, and therefore will have more resources related to the executive system to perform a task, regardless of the nature of the task. In this study, Swanson (1999b) found significant differences between LD students and non-LD counterparts matched for age and nonverbal IQ on measures of phonological processing accuracy (phonemic deletion, digit recall, phonological choice, pseudoword repetition), phonological processing speed (timed responses from phonemic deletion, digit recall, phonological choice, pseudoword repetition task), LTM accuracy (orthographic choice, semantic choice, vocabulary), LTM time (timed response from orthographic choice, semantic choice, vocabulary) and executive processing (Sentence span, Counting Span, Visual-matrix). The results showed that the chronologically age (CA)-matched group outperformed the LD reading group, whereas the LD readers were comparable to reading level (RL) matched children. The important findings, however, were that the results brought together two alternative models of WM and their influence on reading comprehension. How so?

Swanson (1999b) examined each hypothesis through a series of hierarchical regression analyses to assess the independent contribution of phonological, LTM, and executive processes to reading comprehension. The general pattern was that the significant relationship between executive processing and reading comprehension was maintained when LTM and phonological processing composite scores were partialed from the analysis. More importantly, Swanson found that the contribution of phonological processes, LTM, and executive processes to reading comprehension were statistically comparable. Thus, on the one hand, Swanson found support for the notion that the phonological system plays an important role in predicting reading ability group differences in reading comprehension. However, Swanson did not find support for the notion that the phonological system accounted for the influence of executive processing on reading comprehension. The attenuating effect of executive processing on reading comprehension also did not appear to be due to phonological processing speed or LTM. The implication of this finding was that no one process dominated another as underlying reading comprehension deficits.

Swanson also was interested in determining whether there were some fundamental processing differences between LD and skilled readers that supersede their problems in reading comprehension. He analyzed the processing variables as a function of reading conditions by reframing the comparison groups in terms of the regression-based design outlined by Stanovich and Siegel (1994). When reading comprehension was statistically controlled (partialed out of the analysis), the results showed that significant differences exist in WM and the speed of processing phonological information between LD readers and controls, independently of their reading comprehension level.

In summary, Swanson's results are consistent with studies on individual differences that suggest that general resources from a WM system play a critical role in integrating information during reading comprehension (e.g., Cantor & Engle, 1993; Engle et al., 1992), as well as those that highlight the importance of a domain specific language system (e.g., see Miyake, Just, & Carpenter, 1994, for a review). These models explicitly posit a dual role for WM:

a. it holds recently processed text to make connections to the latest input, and

b. it maintains the gist of information for the construction of an overall model of passage comprehension.

In terms of individual differences, if a reader has a large WM capacity, then the execution of various fundamental comprehension processes (such as word encoding, lexical access, syntactic and semantic analysis, etc.) does not delete the limited resource pool as much as for a reader with a smaller capacity (e.g., Miyake et al., 1994). As a result, readers with a larger WM capacity would have more resources available for storage while comprehending text. On the other hand, readers with a smaller WM capacity might have fewer resources available for the maintenance of information for comprehension. This view is supported by our findings showing that both verbal and visual spatial WM correlates highly with comprehension, and we suggest that this relationship holds (at least for children) even when the influence of the articulation speed and STM are partialed from the analysis (Swanson & Ashbaker, 2000).

Writing

Writing is viewed as a complex activity that involves many simultaneous subcomponents and interacting processes, all or some of which may be sensitive to a limited WM capacity. Several studies (see McCutchen, 1996; 2000, for a review) with adults have shown, for example, that individuals with large spans use more complex sentences and maintain coherence in their writing when compared to adults with low spans. Moreover, as children's writing matures, the correlation with WM increases (Swanson & Berninger, 1994). Within the framework of Hayes and Flowers' (1980) model of writing, Swanson and Berninger (1996a) tested whether WM affected one or all of three interactive processes: planning, translation, and revision. Planning involves setting goals, generating ideas, generating themes, and logical conclusions of text. Translation is the transformation of these ideas and goals into temporally sequenced discourse. Berninger and Swanson (1994) further divided translation into two subprocesses: text generation and transcription. Text generation involves language processing at the word, sentence, and text level, and results in the translation of ideas into linguistic representations in memory. Transcription draws on orthographic and phonological recoding processes in STM to translate linguistic representations in written symbols. Revision occurs when initial text is analyzed for possible errors or inconsistencies and adjustments are made.

Swanson and Berninger (1996a) found that in the development of children with average achievement ability, WM was primarily related to text generation rather than transcription (speed of writing, grammar, and spelling). Only one study is reported in the literature that focuses specifically on the relationship between WM and writing in learning-disabled samples. In this study (Swanson & Berninger, 1996b), children from a university clinic were administered a standardized WM battery (S-CPT, Swanson, 1995), Test of Written Language, Wide Range Achievement Test, and Peabody Achievement Test. The correlation analysis indicated a number of important outcomes. First, visual-spatial and verbal WM were significantly correlated with writing, reading recognition, and reading comprehension (rs ranged from .39 to .79 across measures). Second, the magnitude of the correlations between WM and writing did not vary as a function of processing conditions. That is. WM tasks were presented under the initial, gain, and maintenance conditions described earlier. Third, and more importantly, the influence of visual-spatial and verbal WM was pervasive across all writing tasks. That is, substantial correlations were found on text generation tasks as well as on transcription tasks. These correlations emerged whether the analysis was at the sentence level or the text level. Further, these correlations were maintained when vocabulary was partialed out in the analysis. Finally, the contribution of WM tasks to writing was not a function of reading ability. That is, the correlations between WM and writing were maintained when reading was entered first into a regression equation.

In summary, the above findings complement working models of writing (McCutchen, 2000), which suggest that cognitively demanding processes such as idea generation, translation of ideas into words, sentences, and discourse structure, and editing, strain the writer's WM resources. When writers encounter difficulty in managing the multiple processes of composing, additional WM resources are needed to juggle the multiple goals. For example, a writer's memory may be overloaded while simultaneously planning and organizing information for production, editing for spelling and grammatical forms, keeping in mind the audience, genre, and so forth. In addition to the resources needed to generate ideas and produce text, the writer must also use memory consuming cognitive executive routines to manage the whole writing endeavor. Thus, writing is an interactive process, whose overall quality is limited by the writer's WM resources.

Word problem solving

There is limited information on the contribution of WM to the problem solving accuracy in students with LD. In one of the few studies (Swanson & Sachse-Lee, 2001b), children with LD at approximately 12 years of age were compared with chronologically age-matched and younger comprehension/computation achievement-matched children on measures of verbal and visual-spatial WM, phonological processing, components of problem solving, and word problem solving accuracy. In this study, children were presented arithmetic word problems orally and asked a series of questions about the various processes they would use to solve the task. They also solved problems that required them to apply algorithms related to subtraction, addition, and multiplication. The study produced a number of important findings. First, phonological processing, verbal WM and visual WM each contributed unique variance to solution accuracy. More important, both verbal and visual-spatial WM performance predicted solution accuracy even when phonological processing was entered first into the regression model. Further, the results showed performance on phonological, verbal WM, and visual-spatial WM measures were statistically comparable in their contribution to ability group differences in solution accuracy. Thus, there was weak support for the assumption that low order processes (i.e., the phonological system) are the primary mediators of the influence of WM processing on solution accuracy.

Second, the contribution of the “knowledge of algorithms” to the regression equation eliminated the significant contribution of either verbal or visual-spatial WM to solution accuracy. This finding clearly supports the notion that verbal and visual-spatial systems, at least in the domain of problem solving, draw on LTM. This finding is consistent with Baddeley and Logie's (1999) notion that

> A major role of WM is retrieval of stored long-term knowledge relevant to the task at hand, the manipulation and combination of material allowing the interpretation of novel stimuli and discovery of novel information toward the solution to problems (p. 31).

Thus, our analysis suggested that both verbal and visual-spatial WM tasks draw upon common information in LTM facilitating solution accuracy.

Finally, ability group differences emerged on two of three components of WM. Through a confirmatory factor analysis, three independent factors were created. One was a second order factor that drew variance from both verbal and visual-spatial WM tasks, and two other factors reflected unique variance related to the verbal and visual-spatial tasks. We found significant differences between ability groups on the domain general second order factor, verbal WM factor, but not the visual-spatial WM factor. This was true even when we partialed out the influence of IQ. This finding is consistent with our earlier study by

Swanson and Alexander (1997), which found that LD readers suffered from both a domain general and a domain specific WM deficit.

In summary, our findings in the area of problem solving are consistent with models of higher order processing, which suggest that WM resources activate relevant knowledge from LTM (Baddeley & Logie, 1999; Ericsson & Kintsch, 1995). Our findings suggest that the contribution of WM to solution accuracy in children is critically related to the activation of information related to the knowledge algorithms. We also think that an important finding was that information activated from LTM, rather than phonological processing, mediated the relationship between executive processing (defined in this study as general effect across verbal and visual-spatial WM) and solution accuracy in children with LD.

Intelligence

Some attention should be given to the area of intelligence (or more generally referred to academic aptitude as measured by standardized intelligence tests). Some may argue that the studies by Swanson, as well as others in implicating problems in executive processing in LD samples (e.g., Bull & Johnston, 1999; de Jong, 1998; Passolunghi et al., 1998) are probably more relevant to a view of intelligence that focuses on a general factor, g (Crinella & Yu, 2000), or fluid crystallized intelligence [i.e.,. Cattell (1971) and Horn (1980) distinguish between a domain-free general fluid intelligence and domain-specific elements of crystallized intelligence, rather than referring to any particular type of knowledge or skill reflected in such areas as reading, writing, and mathematical computation]. However, we argue that individuals with comparable IQ scores can vary in the quality and skill of their domain-specific processes (i.e., skilled readers have a certain aptitude for accessing phonological information, whereas LD children with comparable IQ scores do not). We also accept the fact that LD and NLD children with comparable IQs can vary in their fluid ability to bring controlled attention to bear on managing information in their storage buffers. Thus, variability in WM tasks for children and adults with LD who score in the average range of intelligence can reflect individual differences in domain-specific processes and domain-free controlled attention. A recent study illustrates this point. A study by Swanson and Alexander (1997) (to be reviewed later) found that both a general factor of WM and a phonological domain-specific factor contributed unique variance to word recognition and reading comprehension measures in LD readers and skilled readers with average IQ scores.

Low order tasks

Arithmetic computation

In the area of arithmetic, there is support that problems in calculation are related to the executive system (e.g., Bull, Johnston, & Jennifer, 1999; Fuerst & Graham, 2000; McLean & Hitch, 1999; Wilson & Swanson, in press) as well as to the articulatory system (e.g., Logie, Gilhooly, & Wynn, 1994). For example, Wilson and Swanson (2001) examined the relationship between verbal and visual-spatial WM and mathematical computation skill in children and adults either skilled or disabled in mathematics, across a broad age span. Participants ranged from 11 to 52 years in age. Criteria for mathematics disabilities were operationally defined as participants with standardized mathematics scores below the 25th percentile and reading scores above the 25th percentile. Those individuals whose reading and mathematics scores were above the 25th percentile were designated as average or skilled in mathematics and were referred to in the subsequent analysis as the non math-disabled group. Our major finding was that groups without math disabilities were superior to those with math disabilities on factor scores that included variance partitioned into domain general and domain-specific verbal and visual-spatial WM. These results were the same when both the linear and quadratic components of age were partialed from the analysis. The results also showed that both the verbal and visual-spatial WM composite scores predicted mathematics performance. Further, these results held when reading ability was partialed from the analysis.

In general, our results converged with studies on individual differences that suggest that general resources from a WM system play a critical role in mathematics (e.g., Bull et al., 1999; Swanson & Sachse-Lee, 2001b) and those that highlight the importance of a domain specific system, such as language (e.g., Dark & Benbow, 1994). The question emerges, however, in determining how each of these systems contributes to problem solving for individuals with math disabilities. To address this question, we focus first on domain general processing and then domain-specific processing.

In terms of the contribution of domain general processing, Wilson and Swanson's (2001) results are in line with the hypothesis that the central executive system (variance related to both the verbal and visual-spatial tasks) plays an important role in predicting math performance (Bull et al., 1999; Swanson & Sachse-Lee, in press). Although there is no consensus about whether the executive system has storage capacity (e.g., Baddeley & Logie, 1999; then see Engle et al., 1999a; Ericsson & Kintsch, 1995), the system is influenced by information activated from LTM. On this assumption, Wilson and Swanson (2001) argued that because participants with math disabilities (MD) in their sample lacked a general knowledge of arithmetic facts (based on their WRAT-R subtest scores), these deficits in LTM may have placed unnecessary demands on central processing. That is, the central processing system was unable to activate a sufficient amount of information from LTM to meet processing demands. These deficits may be due to a limited knowledge of mathematical strategies (see Keeler & Swanson, in press; Swanson & Rhine, 1985) or algorithms (Swanson & Sachse, in press) stored in LTM memory.

These speculations are also consistent with Clark and Campbell's (1991) discussion that even though number concepts are coded as modality specific, they are also an element of a larger interconnected network in LTM. Although Clark and Campbell designate digits as a nonverbal code for the WM system to process, they posit that when one is working with a highly familiar digit format (e.g., automated, basic math facts), rich associative collections of verbal and visual mental representations are activated to lead to the solution.

The associative interconnections among the multiple codes

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could result in one stimulus format (e.g., words)
activating the entire encoding complex, including codes for
alternative formats (e.g., digits). Different stimulus
codes may all be translated into a dominant number-word or
visual-digit format (i.e., common but specific code),
analogous to phonological recoding in reading (p. 213),
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thus explaining the findings of equal contributions from both WM components in most of our hierarchical regression models and also the specificity for verbal and visual-spatial WM that was found in the regression analysis.

Some comments should be made about the domain-specific contribution of WM to arithmetic performance. The results of the regression analysis in the Swanson and Wilson (2001) study showed that verbal WM measures accounted for a larger percentage of the variance than visual-spatial WM measures in predicting mathematics. The findings are consistent with those of Boden (1988), who suggests that arithmetic processes involve syntactic rules to form numerators along with semantic content (e.g., sum, divisor, remainder) in its operations. The importance of verbal WM also gives confirmation to the preliminary work of Geary on memory and mathematics disabilities. Geary, Brown, and Samaranayake (1991) view computational skill as a domain represented within a semantic network. Geary (1993) further suggests that the underlying problem with semantic memory for individuals with a combination of MD and reading disabilities is based on difficulties in representation and retrieval of information from semantic memory. Early learning problems are exacerbated in this group because verbal skills mediate the learning of arithmetic procedures. According to Geary, multiple computation errors brought on by WM deficits might have an iterative effect, contributing to an even greater frequency of errors in fact retrieval. These errors are not due to a lack of practice or a developmental delay, but to more fundamental semantic processing deficit. The difficulty with this conclusion is that reading disabilities are attributed primarily to a phonological deficit (Siegel, 1993, for a review) and, therefore, math difficulties may be more directly related to processes that mediate reading disabilities. Because the MD participants were not disabled readers in the Wilson and Swanson (2001) study, the results provide direct evidence that verbal processes other than those related to reading mediate computational difficulties. Although it is important to note that the results suggest that the MD sample have verbal WM deficits that do not affect their reading ability, this finding does not preclude the possibility that for some LD people the same verbal deficits contribute to computational and reading problems (Geary, Hoard, & Hamson, 1999).

Summary

We have selectively reviewed studies related to various components of WM. There is evidence in the literature indicating that participants with LD suffer deficits in both the phonological loop and the executive system. Either one or both of these components play a significant role in predicting complex cognitive activities such as reading comprehension, arithmetic problem solving, writing, as well as to basic skills such as arithmetic coyputation. We now address questions related to the independence and overlap between the two systems, as well as how the two systems potentially operate across a life span.

HOW DO THE EXECUTIVE AND PHONOLOGICAL SYSTEM WORK TOGETHER AND/OR SEPARATELY?

This is not an easy question to answer because experimental research on this issue is not only limited in the field of LD, but also in the general area of WM (Baddely & Logie, 1999; Miyake & Shah, 1999). However, we will review our evidence on the independent and interdependent contributions of both systems to achievement.

In terms of independence, a few studies have partitioned variance related to a general system from that related to a specific WM system (Swanson & Alexander, 1997; Wilson & Swanson, 2001). For example, the Wilson and Swanson (2001) study discussed above partitioned the variance in verbal and visual-spatial WM tasks in math disabled and non math disabled participants across a broad age span. They partitioned the variance in WM performance, via structural equation modeling, by creating two first order factors (the verbal WM tasks reflected factor 1 and the visual-spatial WM tasks reflected factor 2) to capture unique variance and a single second high-order factor that reflected shared variance or domain general performance among all the tasks. When the ability groups were compared on these factor scores, groups without math disabilities were superior to those with math disabilities on factor scores that included variance partitioned into domain general, verbal WM and visual-spatial WM. Thus, it appears, at least in the area of mathematics, that ability group differences emerge in a domain general and specific systems of WM. This pattern also emerged in comparing groups with reading disabilities (Swanson & Sachse-Lee, 2001a).

In terms of interdependence, Swanson and Alexander (1997) examined the interrelationship among cognitive processes in predicting learning-disabled (LD) readers' word recognition and reading comprehension performance. The correlations among phonological, orthographic, semantic, metacognitive, and verbal/visual-spatial WM measures and reading performance were examined in LD and skilled readers, ages 7 to 12. To explain the interrelationship among the aforementioned processes, three hypotheses were considered:

1. processes that are not part of a general system (phonological processes) were more likely than central processes to predict reading failure,
2. LD readers engage in compensatory processing (e.g., rely on a semantic rather than a phonological system) to gain information from text because of specific processing deficits related to word recognition, and
3. a general resource WM system interacts with several cognitive processes and this general system accounts for individual differences in reading performance.

The study yielded the following important results:

a. LD readers were deficient in all cognitive processes when compared to skilled readers, but these differences were not a reflection of IQ scores;

b. LD readers were deficient compared to skilled readers in a general factor primarily composed of verbal and visual-spatial WM measures, and unique components, suggesting that reading ability group differences emerge on both general and specific (modular) processes;

c. the general WM factor best predicts reading comprehension for both skilled and LD readers groups; and

d. phonological awareness best predicts skilled readers' pseudoword reading, whereas the general WM factor best predicts LD readers' pseudoword performance.

Overall, Swanson and Alexander's study showed that verbal and visual-spatial WM tasks share variance with a common system, but also have some unique variance related to a specific system. Further, both the general system and specific system predicted reading.

Summary

Our findings show that variance related to a specific and general WM system moderate reading and mathematic performance in children with LD. No doubt, how the source of connection between a general or domain specific underlies reading or mathematics needs further investigation. This sentiment is also provided by Gathercole and Baddeley (1993), when they considered the constraints of WM on reading, "…the limitation could be either in the operation of the phonological loop, or the central executive (p. 228)." They further suggested that one could create the argument that executive processing may play a more critical role in some stages of reading for poor readers than for skilled readers. That is, because poor readers do not have fully automatized procedures, they may need to rely heavily on the general resources furnished by the central executive component of WM.

How Do the Two Systems Operate Across a Life Span?

Our research suggests that the interrelationship between phonological and executive processes, as well as related processes (i.e., semantic, orthographic), may be qualitatively different in predicting LD participants' academic performance in some age groups (Swanson & Alexander, 1997). We summarize our observations across various age ranges as follows:

For ages 6 to 75 in skilled and LD readers we find:

a. both domain general WM and domain-specific WM are related to word recognition (Siegel, 1994; Swanson, 1996: Swanson & Sachse, 2001a, 2001b),

b. age-related changes in WM in skilled readers are best explained by a capacity rather than a processing efficiency model (Swanson, 1999),

c. LD readers, defined by word recognition deficits, experience WM deficits into adulthood (Swanson & Sachse-Lee, 2001a), and

d. LD readers' WM performance is changeable via probing or cued procedures: however, significant differences still reside between reading groups because of greater domain general capacity limitations in LD readers (Swanson et al., 1996, Swanson & Sachse-Lee, in press)

For ages 9 to 15, we find that

a. domain general WM differences between skilled and LD readers are not eliminated when reading comprehension is partialed from the analysis (Swanson, 1999b),

b. phonological and executive processes are equally important in predicting reading comprehension, as well as problem solving (Swanson, 1999b; Swanson & Alexander, 1997; Swanson & Sachse-Lee, 2001b),

c. deficits in executive processing and reading comprehension are only partially mediated by the phonological system or LTM (Swanson, 1999b),

d. domain specific (verbal) deficits emerge on verbal WM tasks on initial (noncued) conditions, but general WM deficits (deficits in both verbal and visual-spatial WM) emerge as processing demands increase under gain (cued) and maintenance (high demand) conditions (Swanson et al., 1996), and

e. WM deficits related to poor readers are best attributed to a capacity rather than a processing efficiency model (Swanson, 1994; Swanson & Sachse-Lee, 2001b).

We also have some recent observations of adults diagnosed with dyslexia in childhood (Ransby & Swanson, 2001). Diagnosis of childhood dyslexia (CD) was at approximately 9 years of age. The sample of young adults with CD were alumni from of a private elementary school that specializes in the treatment of developmental dyslexia. The primary reading intervention program was based on a phonics program (i.e., Orton-Gillingham). In this study, performances of adults with CD were compared to CA-matched adults, and reading-level (RL)-matched children on measures of phonological processing, naming speed, WM, general knowledge, vocabulary, and comprehension. The study focused primarily on the contribution of phonological, oral language, and WM processes to reading comprehension. We tested two possibilities: (1) reading comprehension in adults with CD is primarily mediated by the phonological system and (2) high order processes related to oral language skills operate independently of the phonological system and therefore contribute unique variance to reading comprehension beyond the phonological system. Several measures from the Bruck (1992) testing battery were administered to the ability groups. Additional measures were selected from studies on reading disabilities related to high order processing (e.g., Swanson & Berninger, 1996a). The results showed that

a. adults with CD were inferior on measures of phonological processing, naming speed, WM, general knowledge, and vocabulary when compared to CA matched readers, but were comparable to RL children on most of these measures;

b. measures of phonological processing, naming speed, vocabulary/general knowledge, and listening comprehension contributed significant independent variance to reading comprehension accuracy, whereas composite measures of WM, naming speed, and listening comprehension contributed significant independent variance to reading comprehension fluency, and

c. when word recognition and intelligence were partialed from the analysis, adults with CD were inferior to CA-matched adults and superior to RL matched children on measures of lexical processing, WM, listening and reading comprehension.

The results from a hierarchical regression analysis suggested that CD experience constraints in reading comprehension related to phonological processing and speed of processing; however, these constraints mediate only partially some of the influence of high order processes (vocabulary/general knowledge, WM, listening comprehension) on reading comprehension. Further, adults with CD suffer difficulties in lexical processing, WM, listening and reading comprehension nonspecific to their word recognition problems and intelligence scores.

Based on these observations, as well as others, it appears to us that the phonological system may play its primary role in predicting reading recognition and comprehension (accuracy and fluency) in the younger ages (5–9). Between ages 9 and 16, the executive system and the phonological system play an equal, as well as an independent, role in predicting word reading and reading comprehension accuracy and fluency (Swanson, 1999b; Swanson & Alexander, 1997). We also suggest that for adult poor readers (drawing on our pilot work, and Engle et al., 1992), that executive processes play a more important role in predicting reading, especially reading comprehension, than does the phonological system. That is, we find with older participants (junior high to adult) that a general WM system, not specific to reading, separates skilled and LD readers (Swanson, 1999b; Swanson et al., 1999). Our previous research with older samples shows that skilled readers have relatively higher WM capacity than LD readers, even when reading comprehension (Swanson, 1999b), word recognition (Swanson et al., 1999), word recognition and IQ (Ransby & Swanson, 2001; Swanson & Sachse-Lee, in press) and articulation speed (Swanson & Ashbaker, 2000) are partialed from the analysis. Depending on age and reading fluency, we assume that although the executive system plays a role relaying the results of lower-level phonological analyses upward through the language system, it also serves as a monitoring system independent of those skills (e.g., Baddeley, 1986; 1992).

Summary

The importance of the executive and phonological system in predicting reading performance may be related to age. As children age, the executive system may play more of a primary role in separating good and poor readers than at the younger ages. Further, difficulties in the executive system may develop independent of LD readers' specific difficulties in reading. That is, based on the above observations, we speculate that as children age, skilled readers have relatively higher WM capacity than LD readers, and therefore will have more available resources related to the executive system to perform a task regardless of the nature of the task. Support for this notion is also found for college age adults. Turner and Engle (1989) suggest that people are poor readers because they have a small general working-memory capacity and that this capacity is not entirely specific to reading (also see Cantor et al., 1991; Engle, Nations, & Cantor, 1990; and Engle et al., 1992). That is, poor readers have weaker WM than skilled readers, not as a consequence of poor reading skills, but because they have less working-memory capacity available for performing reading and nonreading tasks. Of course, individuals will vary in the efficiency (e.g., speed of activation) of their mental operations on some specific tasks, but other things being equal, high WM capacity individuals still have more attentional resources available to them than do low WM capacity individuals.

CONCLUSIONS

Our conclusions from approximately two decades of research are that WM deficits are fundamental problems of children and adults with LD. Further, these WM problems are related to difficulties in reading and mathematics, and perhaps writing. Although WM is obviously not the only skill that contributes to academic difficulties [e.g., vocabulary and syntactical skills are also important (Siegal and Ryan, 1988)], WM does play a significance role in accounting for individual differences in academic performance. Depending on the academic task, age, and type of disability, general and specific WM systems are involved in their disabilities. We generally conclude that students with LD in reading and/ or math suffer WM deficits related to the phonological loop, a component of WM that specializes in the retention of speech-based information. We also find that this system is of service in complex cognition, such as reading comprehension, problem solving, and writing. We argue, however, that this simple subsystem is not the only aspect of WM that is deeply rooted in more complex activities experienced by children and adults with LD. We find that in situations that place high demands on processing, which in turn place demands on controlled attentional processing (such as monitoring limited resources, suppressing conflicting information, updating information), children and adults with LD are at a clear disadvantage when compared with their chronological aged counterparts. Further these deficits are sustained when articulation speed, phonological processing, and verbal STM are partialed from the analysis. We believe that LD students' executive systems (and more specifically, monitoring activities linked to their capacity for controlled sustained attention in the face of interference or distraction) are impaired. This impaired capability for controlled processing appears to manifest itself across visual-spatial and verbal WM tasks, and therefore reflects a domain-general deficit. LD students' executive processing difficulties may include

a. maintaining task relevant information in the face of distraction or interference,

b. situations in suppressing and inhibiting information irrelevant to the task if necessary, and (in some situations—e.g., problem solving) accessing information from LTM (see Engle et al., 1999a, for further discussion).

We also recognize that although these differences in controlled attention can be domain free, they can, based on the kind of task and processing demands, reflect domain specific codes. We also find evidence that LD children's and adults' WM can be improved upon [i.e., with dynamic testing (e.g., Swanson, 1992)] or perhaps may even be developed with practice or expertise in a particular domain (Ericsson & Kintsch, 1995) but these levels of improvement are substantially below that of their average achieving counterparts.

Although we find that students with LD suffer deficits unique to both the phonological loop and the executive system, we can only speculate on the problems related to the interchange of information between these two systems. These problems may be related to coordinating two levels of processing. Readers with LD may be viewed as having difficulty accessing higher-level information and/or lower-order skills (phonological codes), or switching between the two levels of processing. For example, their executive systems may fail to compensate for a deficient lower-order specialized process. This lack of compensatory processing may be characterized by a WM system either not contributing enough information to a specialized system or failing to provide an adequate capacity of processing resources given their problems in a specialized system (see Swanson, 1993b, for a related discussion). It is also possible that the executive system indirectly accounts for low-order processing deficits (especially on language-related tasks) because of excessive processing demands. For example, in Baddeley's (1986) earlier model the central executive system served as an undifferentiated generic system that stored information used to support low-order systems. However, if the executive system's “capacity” was overtaxed it could not contribute resources to low-order processing. That is, given that the phonological (articulatory) loop is controlled by the central executive (Baddeley & Logie, 1999), any deficits in phonological functioning may partially reflect deficiencies in the controlling functions of the central executive itself (see Baddeley, 1996; Gathercole & Baddeley, 1993). Recently, however, Baddeley and Logie (1999) have suggested that the executive system is not equipped with storage capacity. This changes Baddeley's earlier model (Baddeley & Hitch, 1974) by placing greater reliance on the executive system to access resources from LTM. Thus, another individual difference variable related to executive processing is the ability to retrieve stored LTM knowledge relevant to the task and to manipulate and recombine that material with the novel stimuli when demands on the phonological and visual-spatial system are exceeded. We argue however, that regardless of whether or not the executive system has storage capability, this system fails under certain conditions to efficiently monitor the storage of information so it can be used to support low-order systems in children and adults with LD.

No doubt, there are gaping holes in our knowledge about how WM and learning disabilities are related, and therefore additional research is needed. Some areas of “residual ignorance” (to coin a phrase by Baddeley) are as follows:

1. How processes are represented. We do not know how the basic mechanisms of WM are represented in the student with LD. Although some progress has been made in mapping the mental representations related to problem solving (e.g., Picture Arrangement, Tower of Hanoi, Pendulum, Combinatorial—see Swanson 1988; 1993a), basic mechanisms related to encoding, maintenance, and retrieval of WM are understudied. Basic mechanisms have been explored in some detail in the area of STM (see Swanson et al., 1998), however, processes related to the integrated nature of storage and processing characteristic of WM tasks have not been adequately studied. In addition, research is unclear about primary mechanisms within the executive system that separate LD groups from average achievers as it applies to information maintenance. This is because monitoring activities are intertwined with maintaining information. That is, monitoring activities such as

a. switching attention between multiple tasks,

b. active inhibition or suppression of irrelevant information,

c. updating information, and

d. planning and sequencing intended actions are very much related to information maintenance.

Further, it is difficult to know how all of these particular activities are related to one another, or if, in fact, they are independent.

2. Environmental contributions. We have reviewed some occasions when a domain specific model (e.g., Siegel, 1994; Swanson et al., 1996, Exp. 1) and a domain general model come into play (e.g., Swanson et al., 1996, Exp. 2), as well as some conditions that improve WM performance (Swanson, 1992). We have not identified all factors amenable to particular manipulations, such as extended practice, specific instructions, and strategy use. In addition, our research requires reference to genetic studies to decouple the role of genetic and environmental factors to the WM deficits of LD students. For instructional purposes, specific research needs to be directed toward the ways in which LTM contribute to WM (Swanson & Sachse-Lee, 2001b). Further research is necessary to determine how LTM representations can be activated or taught to support WM operations. If we can show that a domain specific WM factor is primarily related to a learned skill or knowledge, then clearly an environmental factor plays an important role. There is some indirect evidence that cognitive activities related to the phonological loop are a product of an interaction with the social-cultural environment. For example, phonological and orthographic complexity in a learning environment, as well as the teaching method, could aggravate or ameliorate the effects of the postulated modular deficit in dyslexia. As suggested in a study by Frith, Wimmer, and Landerl (1998), dyslexic children who are taught transparent orthography of German have a milder reading impairment than dyslexic children learning the irregular orthography of English, even though these children were equally impaired in pure phonological tasks (for example, spoonerisms).

In addition, although there has been significant progress in understanding the neural basis of WM in general (e.g., Smith & Jonides, 1999), most of these studies have focused on rather simple experimental tasks. Very little work has been done to explain how different regions of the brain dynamically work together as a whole to perform more complex cognitive tasks. Thus, it is important for subsequent research in LD to separate the environmental influences from the constitutional constraints in the cognitive system.

3. Why is WM related to academic achievement? Very little research has been directed toward explaining why WM tasks are good predictors of academic performance. Although, for example, it makes sense that controlled attention ability (e.g., the ability to switch attention between processing and storage requirements) may be particularly good for reading comprehension but not necessarily for simple mathematical computation, this has not been tested experimentally. We argue from our research that the complexity of the task determines whether general or domain specific factors come into play. However, different capacity limited factors may come into play in predicting achievement across elementary, junior high, and high school. Further, we can only speculate on how individuals with LD are able to attain normal levels of functioning in everyday cognition. Only one study we are aware of has linked a laboratory measure of WM to everyday cognition in children with LD (Swanson, Reffel & Trahan, 1991).

Before leaving this topic, we should make some comments about the possible reasons why LD students acquire normal intelligence given their dismal performance on several activities related to WM. No studies to our knowledge clearly explain the link between WM and intelligence in LD samples. Interestingly, although there is extensive evidence that children with LD (especially those with reading disabilities) suffer from phonological deficits, it is not obvious why this phonological loop deficit would not cripple general cognition. It is certainly possible that they achieve normal intelligence by using different cognitive routes (visual-spatial rather than verbal strategies, general heuristics rather than specific algorithms—see, for example, Swanson, 1988; 1993a) than average achievers. We do find, however, that children and adults with LD have at least average ability to comprehend what they do hear, given that they score in the average range of intelligence (see Kavale & Forness, 1994, for a systematic meta-analysis of performance of LD students on the Wechsler Intelligence Test). How do we put together deficits in the phonological loop and/or the executive system with the concept of normal intelligence? A simple answer to this question is that inefficiencies in the phonological loop are only one component of WM that is clearly deficient, leaving other aspects, including key aspects of the central executive (e.g., control of action plans for scheduling multiple cognitive activities) as unimpaired. This modularity argument makes good sense and has been well articulated in the literature (Stanovich, 1990). However, we show that LD readers have impairments in some specific aspects of a central system (Swanson & Alexander, 1997), even when reading is partialed from the analysis (Swanson, 1999b) and IQ is at the same level as their chonological-aged (CA) matched counterparts. Further, even in studies invoking modularity (domain-specific informationally encapsulated processes that operate independent of a general system), some flexibility is given in terms of specifying the modular system as "open" (see Mattingly & Liberman,

1990) or susceptible to interpretation by a central system (e.g., Moscovitch, 1992). Thus, we have no simple answer to this question.

We speculate, however, that learning-disabled individuals can achieve normal intelligence because the information they experience in their environment does not always place high demands on their WM. A standardized test of WM (S-CPT, Swanson, 1995) shows, for example, that the majority of individuals with LD scored in the 21st percentile on WM measures (scaled scores across 11 subtests hovered around 8, or a standard score of 88-see Swanson, 1995, p. 167), suggesting they have very weak but adequate WM ability to process information and then store information over the long term. Of course, they may use other experiences by pulling up from LTM things that they already know to help in the processing of information. With the accumulation of LTM links and connections, there is some control over the processing demands of new information. No doubt, these are speculations on our part and in need of testing.

In summary, our results suggest that a limited-capacity WM system underlies some of the academic problems experienced by students with LD. We generally conclude that although students with LD suffer WM deficits related to the phonological loop, they also suffer deficits in some of the executive components of WM. Our analysis is consistent with that of several theorists who adopt a resource-interaction approach in which individual differences emerge when academic processes compete for a limited supply of WM resources.

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GRAPH: FIGURE 1. Effect of processing demands on secondary performance for students with and without learning disabilities.

GRAPH: FIGURE 2. Memory span across age as a function of processing demands (right panel) and modality (left panel) for readers with and without learning disabilities.

REFERENCES

Anderson, J. R., Reder, L. M., & Lebiere, C. (1996). Working memory: Activation limitations on retrieval. Cognitive Psychology, 30, 221–256.

Atkinson, R.C., & Shiffrin, R.M. (1971). The control of short-term memory. Scientific American, 225, 82–90.

Awh, E., Smith, E. E., & Jonides, J. (1995). Human rehearsal process and the frontal lobes: PET evidence. Annals of the New York Academy of Science, 769, 97–117.

Baddeley, A. D. (1986). Working memory. London: Oxford University Press.

Baddeley, A. D. (1996). Exploring the central executive. Quarterly Journal of Experimental Psychology, 49a(1), 5–28.

Baddeley, A. D., De la Sala, S., Papagno, C., & Spinnler, H. (1997). Dual-task performance in dysexecutive and nondysexecutive patients with a frontal lesion. Neuropsychology, 11 187–194.

Baddeley, A. D., Gathercole, S.E., & Papagno, C. (1998). The phonological loop as a language learning device. Psychological Review, 105, 158–173.

Baddeley, A. D., & Hitch G. J. (1974). Working memory. In G. Bower (Ed.), The psychology of learning and motivation Vol. 8, (pp. 47–90). New York: Academic Press.

Baddeley, A. D., Lewis, V. J., & Vallar, G. (1984). Exploring the articulatory loop. Quarterly Journal of Experimental Psychology, 36, 223–252.

Baddeley, A. D., & Logie, R.H. (1999). Working memory: The multiple component model. I. A.Miyake & P.Shah (Eds.) Models of working memory: Mechanisms of active maintenance and executive control (pp. 28–61). New York: Cambridge University Press.

Baddeley, A.D., Eldridge, M, Lewis, V., & Thomson, N. (1984). Attention and retrieval from long-term memory. Journal of Experimental Psychology: General, 113, 518–540.

Berninger, V.W., & Swanson, H. L. (1994). Modification of the Hayes and Flower model to explain beginning and developing writing. In E. Butterfield (Eds.) Children's writing: Toward a process theory of development of skilled writing (pp. 57–82). Greenwich, CT: JAI Press.

Boden, M.A. (1988). Computer models of minds. Cambridge University Press.

Bradley, L., & Bryant, P. E. (1978). Difficulties in auditory organization as a possible cause of reading backwardness. Nature, 271 (5647), 746–747.

Brown, G. D. A., & Hulme, C. (1992). Cognitive psychology and second-language processing: The role of short-term memory. In Richard Jackson Harris, (Ed.), et al. Advances in Psychology: Cognitive Processing in Bilinguals (pp. 105–121). North-Holland, Amsterdam: Netherlands.

Bruck, M. (1990). Word recognition skills of adults with childhood diagnosis of dyslexia. Developmental Psychology, 26. 439–454.

Bruck, M. (1992). Persistence of dyslexics' phonological awareness deficits. Developmental Psychology, 28,874–886.

Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visual-spatial sketch pad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. Developmental Neuropsychology, 15, 421–442.

Burgess, N., & Hitch, G. (1992). Toward a network model of the articulatory loop. Journal of Memory and Language, 31, 429–460.

Cantor, J, & Engle, R.W. (1993). Working memory capacity as long-term memory activation: An individual-differences approach. Journal of Experimental Psychology: Learning, Memory, and Cognition. 19, 1101–1114.

Cantor, J., Engle, R. W., & Hamilton, G. (1991). Short-term memory, working memory, and verbal abilities: How do they relate? Intelligence, 15, 229–246.

Carpenter, P.A., Miyake, A., & Just, M. (1994). Working memory constraints in comprehension: Evidence from individual differences, aphasia, and aging. In M.A. Gernsbacher (Ed.) Handbook of Psycholinguistics (pp. 1075–1121), San Diego: Academic Press.

Carroll, J.B. (1993). Human cognitive abilities: A survey of factor-analytic studies. Cambridge, England: Cambridge University Press.

Cattell, R.B., (1971). Abilities: Their structure, Growth, and Action: Boston: Houghton Mifflin.

Chiappe, P., Hasher, L., & Siegel, L. S. (2000). Working memory, inhibitory control, and reading disability. Memory & Cognition, 28, 8–17.

Clark, J. M., & Campbell, J. I. D. (1991). Integrated versus modular theories of number skills and acalculia. Brain and Cognition, 17, 204–239.

Conway, R. A., & Engle, R. W. (1994). Working memory and retrieval: A resource-dependent inhibition model. Journal of Experimental Psychology: General, 123,354–373.

Cowan, N. (1995). Attention and memory: An integrated framework. Oxford, England: Oxford University Press.

Crain, S. & Shankweiler, D. (1990). Exploring failure in spoken language comprehension by children with reading disabilities. In D. Balota, G. Flores d'Arcais, K. Rayner (Eds.). Comprehension processes in reading (pp. 539–555). Hillsdale, NJ: Erlbaum.

Crain, S., Shankweiler, D., Macaruso, P., & Bar-Shalom, E. (1990). Working memory and sentence comprehension: Investigations of children with reading disorder. In G. Vallar & T. Shallice (Eds.), Impairments of Short-Term Memory (pp 477–508). Cambridge: Cambridge University Press.

Crinella, F. M., & Yu, J. (2000). Brain mechanisms and intelligence. Psychometric g and executive function. Intelligence, 27, 299–327.

Crosson, B. (1999). Subcortical mechanisms in language: Lexical and semantic mechanisms and the thalamus. Brain & Cognition, 40, 414–438.

Daneman, M. (1987). Reading and working-memory. In J. R. Beech & A. M. Colley (Eds.), Cognitive approaches to reading (pp. 57–86). New York: Wiley.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. Journal of Verbal Learning and Verbal Behavior, 19, 450–466.

Daneman, M., & Merikle, P.M. (1996). Working memory and language comprehension: A meta-analysis. Psychonomic Bulletin & Review, 3, 442–433.

Daneman, M., & Tardif, T. (1987). Working memory and reading skill reexamined. In M. Coltheart (Ed.), Attention and performance Vol. XII (pp. 491–508). Hillsdale, NJ: Erlbaum.

Dark, V. J., & Benbow, C. P. (1994). Type of stimulus mediates the relationship between working-memory performances and type of precocity. Intelligence, 19, 337–357.

De Beni, R., Palladino, P., Pazzaglia, F., & Cornoldi, C. (1998). Increases in intrusion errors and working memory deficit of poor comprehenders. Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 51, 305–320.

De Jong, P. (1998). Working memory deficits of reading disabled children. Journal of Experimental Child Psychology, 70, 75–95.

Delia Sala, S., Baddeley, A., Papagno, C., & Spinnler, H. (1995). Dual-task paradigm: A means to examine the central executive. Annals of the New York Academy of Sciences, 769, 161–171.

Dempster, F. (1985). Short-term memory development in childhood and adolescence. In C. Brainerd & M. Presseley (Eds.) Basic processes in memory (pp. 209–248). New York: Springer-Verlag.

Denckla, M. B., & Rudel, R. G. (1976). Rapid "automatized" naming (R.A.N.): Dyslexia differentiated for other learning disabilities. Neuropsychological, 14, 471–479.

Duncan, J., (1995). Attention, intelligence and the frontal lobes. In M. S. Gazzaniga (Ed.) The cognitive neurosciences (pp. 721–733). Cambridge, MA: MIT press.

Engle, R. W. (1996). Working memory and retrieval: An Inhibition-resource approach. In J. Richardson, R.W. Engle, L. Hasher, R. Logie, E.R., Stoltzfus, & R.T. Zacks, (eds.) Working Memory and Human Cognition (pp 89–119). NY:Oxford University Press.

Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. Journal of Experimental Psychology: Learning, Memory and Cognition, 18,972–992.

Engle, R. W., Kane, M. J., & Tuholski, S. (1999a). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.) Models of working memory: Mechanisms of active maintenance and executive control (pp. 102–134) Cambridge, U.K: Cambridge University Press.

Engle, R. W., Nations, J., & Cantor, J. (1990). Is working memory capacity just another name for word knowledge? Journal of Educational psychology, 82, 799–804.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999b). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. Journal of Experimental Psychology: General 128, 309–331.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. Psychology Review, 102, 211–245.

Fletcher, J. M. (1985). Memory for verbal and nonverbal stimuli in learning disability subgroups: Analysis by selective reminding. Journal of Experimental Child Psychology, 40, 244–259.

Friedman, A., & Polson, M.V. (1991). Hemispheric as independent resource systems: Limited-capacity processing and cerebral specialization. Journal of Experimental Psychology: Human Perception and Performance, 8, 625–650.

Frith, U., Wimmer, H., & Landerl, K. (1998). Differences in phonological recording in German- and English-speaking children. Scientific Studies of Reading, 2, 31–54.

Fuerst, A. J., Hitch, & Graham J. (2000). Separate roles for executive and phonological components of working memory in mental arithmetic. Memory & Cognition, 28, 774–782.

Gathercole, S. E. (1998). The development of memory. Journal of Child Psychology and Psychiatry, 39, 3–27.

Gathercole, S. E., & Baddeley, A. D. (1989). Evaluation of the role of phonological STM in the development of vocabulary in children: A longitudinal study. Journal of Memory and Language, 28, 200–213.

Gathercole, S. E., & Baddeley, A. D. (1993). Working Memory and Language. Hillsdale, NJ: Erlbaum.

Gathercole, S. E., & Picketing, S. J. (2000). Assessment of working memory in six- and seven-year-old children. Journal of Educational Psychology, 92, 377–390.

Gathercole, S. E., & Pickering, S. J. (2000). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. British Journal of Education Psychology, 70, 177–194.

Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological and genetic component. Psychological Bulletin, 114, 345–362.

Geary, D. C., Brown, S. C., & Samaranayake, V. A. (1991). Cognitive addition: A short longitudinal study of strategy choice and speed-of-processing differences in normal and mathematically disabled children. Developmental Psychology, 27, 787–797.

Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. Journal of Experimental Child Psychology, 74, 213–239.

Gieselmam, R. E., Woodward, J. A., & Beatty, J. (1982). Individual differences in verbal performance: A test of alternative information processing models. Journal of Experimental Psychology: General, 111, 109–134.

Goldman-Rakic, P. S. (1995). Architecture of the prefrontal cortex and the central executive. Annals of the New York Academy of Sciences, 769, 71–83.

Hayes, J., & Flower, L. (1980). Identifying the organization of the writing process. In L.W. Gregg & E.R. Steinberg (Eds.). Cognitive processes in writing (pp. 3–30). Hillsdale, NJ: Erlbaum.

Henry, L. A. & Millar, S. (1993). Why does memory span improve with age? A review of the evidence for two current hypotheses. European Journal of Cognitive Psychology, 5, 241–287.

Hitch, G. J., & McAuley, E. (1991). Working memory and children with specific arithmetical learning difficulties. British Journal of Psychology, 82, 375–386.

Hohnen, B., & Stevenson, J. (1999). The structure of genetic influences on general cognitive, language, phonological, and reading abilities. Developmental Psychology, 35, 590–603.

Horn, J.L. (1980). Concepts of intellect in relation to learning and adult development. Intelligence, 4, 285–317.

Hulme, C., Maughan, S., & Brown, G. D. A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. Journal of Memory and Language, 30, 685–701.

Hulme, C., & Snowling, M. (1992). Phonological deficits in dyslexia: A "sound" reappraisal of the verbal deficit hypothesis? In N. N. Singh & I. L. Beale (Eds.), Learning Disabilities: Nature, Theory, and Treatment (pp. 270–301). New York: Springer-Verlag.

Hulme, C., Thomas, N., Muir, C., & Lawrence, A. (1984). Speech rate and the development of short-term memory span. Journal of Experimental Child Psychology, 47, 72–87.

Hulme, C., Thomas, N., Muir, C., & Lawrence, A. (1984). Speech rate and the development of short-term memory span. Journal of Experimental Child Psychology, 38, 241–253.

Jones, D. M., Farrand, P., Stuart, G. P., & Morris, N. (1995). Functional equivalence of verbal and spatial information in serial short-term memory. Journal of Experimental Psychology: Learning, Memory, & Cognition, 21, 1008–1018.

Jonides, J. (2000). Mechanism of verbal working memory revealed by neuroimaging studies. In B. Landau et al. (Eds.) Perception, Cognition, and Language (pp. 87–104). Cambridge, MA: US, The MIT Press.

Jorm, A. F. (1983). Specific reading retardation and working memory: A review. British Journal of Psychology, 74, 311–342.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. Psychological Review, 99, 122–149.

Kahneman, D. (1973). Attention and effort. Englewood cliffs. NJ: Prentice-Hall.

Kavale, K., & Forness, S.R. (1994). Learning disabilities and intelligence. In T. Scruggs, & M. Mastropieri (Eds.) Advances in Learning and Behavioral Disabilities, (Vol. 8), (pp. 1–64). Greenwich, CT: JAI Press.

Keeler, M. L., & Swanson, H. L. (2001). Does strategy knowledge influence working memory in children with mathematical disabilities? Journal of Learning Disabilities, 34, 418–434.

Kintsch W. (1998). Comprehension: a paradigm for cognition. Cambridge: Cambridge University Press.

Klapp, S. T., Marshburn, E. A., & Lester, P. T. (1983). Short-term memory does not involve the "working-memory" of intellectual processing: The demise of a assumption. Journal of Experimental Psychology: General, 112, 240–264.

Lazar, J. W., & Frank, Y. (1998). Frontal systems dysfunction in children with attention-deficit/hyperactivity disorder and learning disabilities. Journal of Neuropsychiatry & Clinical Neurosciences, 10, 160–167.

Liberman, I. Y., Mann, V. A., Shankweiler, D., & Werfelman, M. (1982). Children's memory for recurring linguistics and nonlinguistic material in relation to reading ability. Cortex, 18, 367–375.

Logie, R. H. (1986). Visuo-spatial processing in working memory. Quarterly Journal of Experimental Psychology, 38A, 229–247.

Logie, R. H., Gilhooly, K. J., & Wynn, V. (1994). Counting on working memory in arithmetic problem solving. Memory & Cognition, 22, 395–410.

Mattingly. I. G., & Liberman, A.M. (1990). Speech and other modules. In G. Endelman, W. Gall, & W. Cowan (Eds.). Sign and sense: local and golobal order in perceptual maps (pp. 501–520). New York: Wiley.

McCutchen, D. (1996). A capacity theory of writing: working memory in composition. Educational Psychology Review, 8, 299–325.

McCutchen, D. (2000). Knowledge, processing and working memory: Implication for a theory of writing. Educational Psychologist, 35, 13–23.

McCutchen, D., Bell, L. C., France, I. M., & Perfetti, C. A. (1991). Phoneme-specific interference in reading: The visual tongue-twister effect revisited. Reading Research Quarterly, 26, 87–103.

McDougall, S., Hulme, C., Ellis, A., & Monk, A. (1994). Learning to read: The role of short-term memory and phonological skills. Journal of Experimental Child Psychology, 58, 112–133.

McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. Journal of Experimental Child Psychology, 74 (3), 240–260.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. Cognitive Psychology, 41, 49–100.

Miyake, A., Just, M., & Carpenter, P. (1994). Working memory constraints on the resolution of lexical ambiguity, Cognitive Neuropsychology, 33, 175–202.

Miyake, A., & Shah, P. (1999). Toward unified theories of working memory: Emerging general consensus, unresolved theoretical issues, and future research directions. In A Miyake & P. Shah (Eds.) Models of working memory: Mechanisms of active maintenance and executive control (pp. 442–481). New York: Cambridge University Press.

Morrison, S.R., Siegel, L. (1991). Learning disabilities: A critical review of definition and assessment issues. I. J.E. Obrzut & G. W. Hynd (eds.) Neurological foundations of *learning disabilities: A handbook of issues, methods, and practice (pp 79–95). San Diego: Academic Press.*

Moscovitch, M. (1992). Memory and working-with-memory component process model based on modules and central systems. Journal of Cognitive Neuroscience, 4, 257–267.

Nation, K., Adams, J.W., Bowyer-Crane, C., & Snowling, M. (1999). Working memory deficits in poor comprehenders reflect underlying language impairments. Journal of Experimental Child Psychology, 73, 139–158.

Navon, D., & Gopher, D. (1979). On the economy of the human processing system. Psychological Review, 86, 214–255.

Nelson, H. E., & Warrington, E. K. (1980). An investigation of memory functions in dyslexic children. British Journal of Psychology, 71, 487–503.

Norman, D. & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R.J., Davidson, G.E. Schwartz, & D. E. Shapiro (Eds.) Consciousness and self-regulation: Advances in research and theory (Vol. 4, pp. 1–18). New York: Plenum.

Oakhill, S. & Kyle, C. (2000). The relationship between phonological awareness and working memory. Journal of Experimental Child Psychology, 75, 152–164.

O'Shaughnessy, T., & Swanson, H. L. (1998). Do immediate memory deficits in students with learning disabilities in reading reflect a developmental lag or deficit? A selective meta-analysis of the literature. Learning Disability Quarterly, 21, 123–148.

Obrzut, J., Hynd, G., Obrzut, A., & Pirozzolo, F (1981). Effect of directed attention on cerebral asymmetries in normal and learning disabled children. Developmental Psychology, 17, 118–125.

Parkin, A. J., Yeomans, J., & Bindschaedler, C. (1994). Further characterization of the executive memory impairment following frontal lobe lesions. Brain & Cognition, 26, 23–42.

Passolunghi, M. C., Cornoldi, C., & De Liberto, S. (1999). Working memory and intrusions of irrelevant information in a group of specific poor problem solvers. Memory & Cognition, 27, 779–790.

Paulesu, E., Frith, U., Snowling, M., Gallagher, A. et al, (1996). Is developmental dyslexia a disconnection syndrome? Evidence from PET scanning. Brain, 119 (1), 141–157.

Penney, C. G., & Godsell, A. (1999). Unusual modality effects in less-skilled readers. Journal of Experimental Psychology: Learning, Memory, & Cognition, 25 (1), 284–289.

Perfetti, C. (1985). Reading Ability. New York: Oxford University Press.

Picketing, S. J., Gathercole, S. E., & Peaker, S. M. (1998). Verbal and visuospatial short-term memory in children: Evidence for common and distinct mechanisms. Memory & Cognition, 26, 1117–1130.

Pugh, K. R., Mencl, W. E., Shaywitz, B. A., Shaywitz, S. E., Fulbright, R. K., Constable, R. T. et al., (2000). The angular gyrus in developmental dyslexia: Task-specific differences in functional connectivity within posterior cortex. Psychological Science, 11, 51–56.

Ransby, M., & Swanson, H. L. (2001). Reading comprehension skills of young adults with childhood diagnosis of dyslexia. Unpublished manuscript, University of California, Riverside.

Rapala, M. C., & Brady, S. (1990). Reading ability and short-term memory: The role of phonological processing. Reading and Writing: An Interdisciplinary Journal, 2, 1–25.

Reichle, E. D., Carpenter, P. A., & Just, M. A. (2000). The neural bases in strategy and skill in sentence-picture verification. Cognitive Psychology, 40, 261–295.

Roodenrys, Hulme, & Brown, G. (1993). The development of short-term memory: Separable effects of speech rate and long-term memory. Journal of Experimental Child Psychology, 56, 431–442.

Rosen, V.M., & Engle, R.W. (1997). The role of working memory capacity in retrieval. Journal of Experimental Psychology: General, 126, 211–227.

Ruchkin, D. S., Berndt, R. S., Johnson Jr., R., Grafman, J., Rotter, W., & Canoune, H. L. (1999). Lexical contributions to retention of verbal information in working memory: Event-related brain potential evidence. Journal of Memory and Language, 41, 345–364.

Salthouse, T. A. (1990). Working memory as a processing resource in cognitive aging. Developmental Review, 10, 101–124.

Salthouse, T. A. (1992). Working memory mediation of adult age differences in integrative reasoning. Memory & Cognition, 20, 413–423.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. Psychological Review, 103, 403–428.

Salway, A. F., & Logie, R. H. (1995). Visual spatial working memory, movement control and executive demands. British Journal of Psychology, 86, 253–269.

Scarborough, H. S. (1990). Very early language deficits in dyslexic children. Child Development, 61, 1728–1743.

Schretlen, D., Pearlson, G. D., Anthony, J. C., Aylward, E. H., Augustine, A. M., Davis, A., & Barta, P. (2000). Elucidating the contributions of processing speed, executive ability, and frontal lobe volume to normal age-related differences in fluid intelligence. Journal of the International Neuropsychological Society, 6, 52–61.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. Journal of Experimental Psychology: General, 125, 4–27.

Shallice, T. (1988). From neuropsychology to mental structure. New York: Cambridge University Press.

Shankweiler, D., & Crain, S. (1986). Language mechanisms and reading disorder. Cognition, 24, 139–168.

Shankweiler, D., Crain, S., Katz, L., Fowler, A. E., Liberman, A. M., Brady, S. A., et al., (1995). Cognitive profiles of reading disabled children: Comparison of language skills in phonology, morphology, and syntax. Psychology Science, 6, 149–156.

Shankweiler, D., Liberman, I. Y., Mark, L. S., Fowler, C. A., & Fischer, F. W. (1979). The speech code and learning to read. Journal of Experimental Psychology: Human Learning and Memory, 5, 531–545.

Shaywitz, S. E., Shaywitz, B. A., Pugh, K. R., Fulbright, R. K., Constable, R. T., Mencl, W. E. et al., (1998). Functional disruption in the organization of the brain for reading in dyslexia. PNAS (On-line), 95, 2636–2641. Available: http://www.pnas.org/cgi/content/full/9515/2636

Siegel, L. S. (1988). Evidence that IQ scores are irrelevant to the definition and analysis of reading disability. Canadian Journal of Psychology, 42, 201–215.

Siegel, L. S. (1992). An evaluation of the discrepancy definition of dyslexia. Journal of Learning Disabilities, 25, 618–629.

Siegel, L. S. (1993). Phonological processing deficits as a basis for reading disabilities. Developmental Review, 13, 246–257.

Siegel, L. S. (1994). Working memory and reading: A life-span perspective. International Journal of Behavioral Development, 17, 109–124.

Siegel, L. S., & Ryan, E. B. (1988). Development of grammatical-sensitivity, phonological, and short-term memory skilled in normally achieving and learning disabled children. Developmental Psychology, 24, 28–37.

Siegel, L. S., & Ryan, E. B. (1989). The development of working memory in normally achieving and subtypes of learning disabled. Child Development, 60, 973–980.

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. Sciences, 283 (5408), 1657–1661. American Association for the Advancement of Sciences, US.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. Cognitive Psychology, 33, 5–42.

Stanovich, K. (1990). Concepts in developmental theories of reading skill: Cognitive resources, automaticity and modularity. Developmental Review, 10, 72–100.

Stanovich, K. E., & Siegel, L. (1994). Phenotypic performances profile of children with reading disabilities: A regression-based test of the phonological-core variable-difference model. Journal of Education Psychology, 86, 24–53.

Studdert-Kennedy, M., Mody, M., & Brady, S. (2000). Speech perception deficits in poor reading: A reply to Denenberg's critique. Journal of Learning Disabilities, 33, 317–321.

Swanson, H. L. (1984). Effects of cognitive effort and word distinctiveness on learning disabled readers' recall. Journal of Educational Psychology, 76, 894–908.

Swanson, H. L. (1986). Do semantic memory deficiencies underline disabled readers encoding processes? Journal of Experimental Child Psychology, 41, 461–488.

Swanson, H. L. (1988). Learning disabled children's problem solving: An information processing analysis of intellectual performance. Intelligence, 12, 261–278.

Swanson, H. L. (1989). The effects of central processing strategies on learning disabled, mildly retarded, average, and gifted children's elaborative encoding abilities. Journal of Experimental Child Psychology, 47, 370–397.

Swanson, H. L. (1990). Influence of metacognitive knowledge and aptitude on problem solving. Journal of Educational Psychology, 82, 306–314.

Swanson, H. L. (1992). Generality and modification of working memory among skilled and less skilled readers. Journal of Educational Psychology, 84, 473–488.

Swanson, H. L. (1993a). An information processing analysis of learning disabled children's problem solving. American Education Research Journal, 30, 861–893.

Swanson, H. L. (1993b). Executive processing in learning disabled readers. Intelligence, 17, 117–149.

Swanson, H. L. (1993c) Individual differences in working memory: A model testing and subgroup analysis. Intelligence, 17, 285–332.

Swanson, H. L. (1993d).Working memory in learning disability subgroups. Journal of Experimental Child Psychology, 56, 87–114.

Swanson, H. L. (1994). Short-term memory and working memory: Do both contribute to our understanding of academic achievement in children and adults with learning disabilities? Journal of Learning Disabilities, 27, 34–50.

Swanson, H. L. (1995). Swanson Cognitive Processing Test (S-CPT): A Dynamic Assessment Measure (p. 122). Austin, TX: PRO-ED.

Swanson, H. L. (1996) Individual and age-related differences in children's working memory. Memory & Cognition,24,70–82.

Swanson, H. L. (1999a). What develops in working memory? A life span perspective. Developmental Psychology, 35, 986–1000.

Swanson, H. L. (1999b). Reading comprehension and working memory in skilled readers: Is the phonological loop more important than the executive system? Journal of Experimental Child Psychology, 72, 1–31.

Swanson, H. L. (2000). Are working memory deficits in readers with learning disabilities hard to change? Journal of Learning Disabilities, 33, 551–566.

Swanson, H.L., & Alexander, J. (1997). Cognitive processes as predictors of word recognition and reading comprehension in learning disabled and skilled readers: Revisiting the specificity hypothesis. Journal of Educational Psychology, 89, 128–158.

Swanson, H. L., & Ashbaker, M. (2000). Working memory, STM, articulation speed, word recognition, and reading comprehension in learning disabled readers: Executive and/or articulatory system? Intelligence,28, 1–30.

Swanson, H. L., Ashbaker, M., & Lee, C. (1996) Working-memory in learning disabled readers as a function of processing demands. Journal of Child Experimental Psychology,61,242–275.

Swanson, H.L., & Berninger, V. W. (1995). The role of working memory and STM in skilled and less skilled readers' word recognition and comprehension. Intelligence, 21, 83–108.

Swanson, H. L., & Berninger, V. W. (1996). Individual differences in children writing: A function of working memory or reading or both processes? Reading and Writing: An Interdisciplinary Journal, 8, 357–383.

Swanson, H.L., & Berninger, V. W. (1996). Individual differences in children's working memory and writing skill. Journal of Experimental Child Psychology, 63,358–385.

Swanson, H. L., & Cochran, K. (1981). Learning disabilities, distinctive encoding, and hemispheric resources. Brain and Language, 40, 202–230.

Swanson, H.L., Cooney, J.B., & O'Shaughnessy, T. (1998). Memory and learning disabilities. In B.Y. Wong (Ed.). Understanding Learning Disabilities (2nd ed.) (pp. 107–162) San Diego: Academic Press.

Swanson, H.L., Mink, J., & Bocian, K.M. (1999). Cognitive processing deficits in poor readers with symptoms of reading disabilities and ADHD: More alike than different? Journal of Educational Psychology, 91,321–333.

Swanson, H. L., & Mullen, R. (1983). Hemisphere specialization in learning disabled readers' recall as a function if age and level of processing. Journal of Experimental Child Psychology, 35, 457–477.

Swanson, H. L., & Obrzut, J. E. (1985). Learning disabled readers' recall as a function of distinctive encoding, hemispheric processing, and selective attention. Journal of Learning Disabilities, 18, 409–418.

Swanson, H. L., Reffel, J., & Trahan, M. (1990). Naturalistic memory in learning disabled and skilled readers. Journal of Abnormal Child Psychology, 18, 549–563.

Swanson, H. L., & Rhine, B. (1985). Strategy transformation in learning disabled children's math performances: Clues to the development of expertise. Journal of Learning Disabilities, 18, 596–603.

Swanson, H. L., & Sachse-Lee, C. (2001a). Learning disabled readers' working memory: What does or does not develop? Unpublished manuscript, University of California, Riverside.

Swanson, H. L., & Sachse-Lee, C. (2001b). Mathematical problem solving and working memory in children with learning disabilities: Both executive and phonological processes are important. Journal of Experimental Child Psychology, 79, 294–321.

Tallal, P., & Piercy, M. (1973). Developmental aphasia: Impaired rate of non-verbal processing as a function of sensory modality. Neuropsychologia, 11, 389–398.

Taylor, H., G.,Lean, D., & Swartz, S. (1989). Pseudoword repetition ability in learning disabled children. Applied Psycholinguistics, 10, 203–219.

Teasdale, J. D., Dritschel, B. H., Taylor, M. J., Proctor, L., Lloyd, C. A., Nimmo-Smith, I., & Baddeley, A. D. (1995). Stimulus-independent thought depends on central executive resources. Memory & Cognition, 23, 551–559.

Teasdale, J. D., Proctor, L., Lloyd, C. A., & Baddeley, A.D. (1993). Working memory and stimulus-independent thought: Effect of working memory load and presentation rate. European Journal of Cognitive Psychology, 5, 417–433.

Towse, J.(1998). On random generation and the central executive of working memory. British ~Journal of Psychology, 89, 77–101.

Turner, M. L., & Engle, R. W. (1989). Is working-memory capacity task dependent? Journal of Memory and Language, 28, 27–154.

Vellutino, F., Scanlon, D. M., & Spearing, D. (1995). Semantic and phonological coding in poor and normal readers. Journal of Experimental Child Psychology, 59, 76–123.

Wilson, K. & Swanson, H.L. (2001). Are mathematics disabilities due to a domain-general or domain-specific working memory deficit? Journal of Learning Disabilities, 34, 237–248.

Zachs, R.T., & Hasher, L. (1988). Capacity theory and the processing of inferences. In L Light, & Burke (Eds.) Language, Memory, and Aging (Pp. 154–170), NY: Cambridge University Press.

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