WORKING MEMORY, INHIBITION AND READING SKILL

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ABSTRACT

We examined the relationships among working memory, inhibitory control and reading disability. A total of 966 individuals (ages 6-49) received a standardized measure of word recognition, a measure of phonological awareness, and a listening span task in the standard, blocked format (three sets containing 2-, 3- or 4- item trials) or in a mixed format (three sets each containing 2-, 3- and 4- item trials). Intrusion errors were investigated in order to determine whether deficits in working memory were associated with the access, deletion, or restraint functions of inhibitory control. We found that deficits in working memory and phonological awareness were characteristic of individuals with reading disabilities at all ages. These deficits may be associated with the access and restraint functions of inhibition. Working memory skills increased until the age of 19. The blocked format showed a gradual decline in adulthood whereas the mixed format did not. The different patterns suggest that the decline in working memory skills associated with aging may result from the deletion function of inhibitory control.

Working memory has been used to explain performance on a variety of tasks (*e.g.*, Baddeley, 1983, 1986; Daneman & Carpenter, 1980). Working memory refers to the ability to retain information in short-term memory while simultaneously processing

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incoming information or retrieving information from long-term storage. Thus, working memory can be thought of as a cognitive process in which some data are held in a short-term memory store that is characterized by rapid decay, while other data are retrieved from long-term storage.

Working memory has been conceptualized as consisting of a central processor, known as the central executive, which controls the subsidiary systems, the visual-spatial sketch pad and the phonological loop. These subsidiary systems operate on and store specific information about the items being processed (Baddeley, 1983). An important feature of working memory is that it has limited capacity. Its limited capacity may be considered a limited pool of attentional resources or a finite work space that must be shared between processing and data storage (Tirre & Peña, 1992). From this perspective, when more demands are placed on the central executive, fewer cognitive resources remain available for the subsidiary systems.

Working memory is thought to play an important role in reading (e.g., Baddeley, 1983; Daneman & Carpenter, 1980). When decoding new words, the central executive must retrieve and perform operations on grapheme-phoneme correspondences while the phonological loop retains the phonemes and syllables so that words may be recognized. Similarly, the central executive must retrieve and process syntactic, semantic, and text-specific information while the phonological loop retains the words, phrases and sentences as they are being processed so that larger units of text may be comprehended.

Several studies have shown that working memory capacity varies as a function of individual differences and age (e.g. Daneman & Carpenter, 1980; Gick, Craik & Morris, 1988; Hasher & Zacks, 1988; Siegel & Ryan, 1988; Swanson & Sachse-Lee, 2001; Wilson & Swanson, 2001). For example, several studies have found declines in working memory as a function of aging (Hasher & Zacks, 1988; Masunaga & Horn, 2001; Reuter-Lorenz et al., 2000; Waters & Caplan, 2001). More specifically, working memory performance has been shown to increase throughout childhood and adolescence, and then decline gradually through adulthood (Siegel, 1994).

Similarly, individuals with reading disabilities experience significant difficulties with working memory (Siegel, 1994; Siegel & Linder, 1984; Siegel & Ryan, 1988; Swanson, 1993a, 1993b, 1994). Similar difficulties in working memory have been reported for disabled readers in languages as diverse as Chinese (So & Siegel, 1997), Korean (Song & Won, 1998), Hebrew (Geva & Siegel, 2000), and Portuguese (Da Fontoura & Siegel, 1995).

There are a number of factors that may contribute to individual differences in working memory performance. First, variance in working memory capacity may underlie individual differences in functional working memory. For example, Swanson (1993a, 1993b) has argued that the weaker working memory performance shown by learning disabled children results from limited capacity. Similarly, some developmental theorists argue that growth in functional working memory through childhood is the result of increases in working memory capacity through "hardware" changes (e.g., Case, Kurland, & Goldberg, 1982; Hitch & Halliday, 1983). Likewise, changes in frontal lateralization may reduce the resources people have available for the storage and processing of information as they grow older (Reuter-Lorenz et al., 2000). As a result, older individuals

demonstrate performance decrements on measures of working memory (*e.g.*, Campbell & Charness, 1990; Gick, et al., 1988; Light & Anderson, 1985; Morris, Gick & Craik, 1988; Salthouse & Babcock, 1991; Swanson, 1999). Thus, capacity constraints may contribute to individual differences in working memory.

Individual differences in working memory performance may also result from inefficiencies in either of the subsidiary systems. In such situations, one would expect individuals to show impaired working memory performance in either verbal working memory tasks or visual working memory tasks, but not in both types of tasks. One possible test of this possibility would be the case of reading disabilities. There is considerable evidence that individuals with reading disabilities have difficulties in processing phonological information (Brady, 1997; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987). Although deficits in phonological processing may interfere with the operation of the phonological loop, they would leave the functioning of the visual-spatial sketch pad undisturbed. Thus, one would expect individuals with reading disabilities to show selective impairments in verbal but not visual working memory. In fact, a number of studies have found that individuals with reading disabilities do show greater impairments in verbal working memory tasks than visual-spatial working memory tasks (Liberman, Mann, Shankweiler & Werfelman, 1982; Siegel & Ryan, 1989). Therefore, processing inefficiencies within the subsidiary systems, such as the phonological loop, may contribute to individual differences in working memory.

Finally, attentional control may also contribute to individual differences in working memory performance (Gernsbacher, 1990; Hasher, Stoltzfus, Rympa, & Zacks, 1991; Rockstroh & Schweizer, 2001). Both Hasher and her colleagues (Hasher et al., 1991; Hasher & Zacks, 1988; Hasher, Zacks & May, 1999) and Gernsbacher and her colleagues (1990; Gernsbacher & Faust, 1991) have hypothesized that individual differences in working memory may result from inefficient inhibitory control of attention. For example, comparisons of more and less skilled university-age readers revealed that less-skilled readers were less efficient at rejecting irrelevant information, such as irrelevant words and pictures and incorrect forms of homophones, and revising incorrect inferences (Gernsbacher & Faust, 1991; Gernsbacher, Varner & Faust, 1990; Whitney, Ritchie, & Clark, 1991).

Similarly, declines in working memory associated with aging have been attributed to decreases in the ability to suppress irrelevant or no-longer-relevant information rather than decreases in working memory capacity. For example, studies using garden-path stories revealed that although older adults were as likely as young adults to encode the correct interpretation, they were more likely to maintain the original, incorrect interpretation (Hamm & Hasher, 1992). However, the failure to inhibit the initial, incorrect interpretation results in difficulties in recalling the stories (Zacks & Hasher, 1988). Similarly, the phenomenon of negative priming is seen in tasks in which stimuli that had been used as distracters (and were to be ignored by subjects) are switched to targets (that required responses from subjects). Items that are switched from distracters to targets tend to elicit slower responses as a result of inhibition. Although young adults tend to show negative priming, older adults often do not (May, Kane & Hasher, 1995; Stoltzfus, Hasher, Zacks, Ulivi & Goldstein, 1993). Thus, declines in working memory

associated with aging may result from deficits in the ability to suppress both irrelevant information and formerly relevant information that is no longer relevant.

Inhibition may control the contents of working memory through the three functions of access, deletion and restraint (Hasher et al., 1999). First, inhibition may control access to working memory by preventing any activated but goal-irrelevant information from entering working memory. In this manner, inhibition restricts access to working memory only to information that is relevant to the task at hand. Second, inhibition controls the contents of working memory by suppressing the activation of irrelevant information or information that had once been relevant and is no longer relevant. That is, the deletion function of inhibition clears irrelevant information out of the working memory buffer. Proactive interference, a disrupted pattern of recall in which information that is no longer relevant competes with relevant information, results from failures of the deletion function. Finally, inhibition performs a restraining function. Inhibitory processes prevent strong responses from immediately seizing control of thought and action effectors so that other, less probable responses can be considered. Accordingly, the restraining function of inhibition suppresses likely but erroneous interpretations of text and language. Taken together, the three functions of inhibitory control ensure that information in the working memory buffer is restricted to goal-relevant information.

The main goal of this study was to examine the extent to which the inhibitory control hypothesis may account for individual differences in working memory as a function of age and reading skill. We studied the working memory performance of people who ranged in age from 6 to 49 using two versions of a listening span task. Some of the participants were given the listening span task in the standard, blocked procedure, while others received a listening span task that used a mixed design. When the listening span task is presented with blocked sets, sets with fewer items precede the longer sets that are worth more points. With this design, individuals with deficient inhibitory control may make more errors on the trials that are worth the most points as a result of proactive interference. In contrast, the mixed design may reduce or eliminate age differences in working memory because the sets that are richer in points are presented before individuals are likely to succumb to the effects of proactive interference. Indeed, May, Hasher and Kane (1999) found that although adults aged 60 and older had lower span scores than young adults when span measures were presented in the typical ascending order, age differences completely disappeared when span measures were presented in descending order. Therefore, if declines in working memory spans are the result of diminished inhibitory control, we would expect to find age effects on the span measures using the blocked design but not the mixed design.

A second way of investigating individual differences in inhibitory control is by analyzing the errors on the listening span tasks. Errors associated with aging have been hypothesized to reflect failures of the deletion and restraining functions of inhibitory control. Therefore, intrusion errors that were either previous targets (reflecting failures of deletion) or new words (reflecting failures of restraint) were hypothesized to increase with age.

In addition to examining age's relationships with error patterns and span scores, we tested these relationships for people with and without reading disabilities. In much of the

research investigating the relationship between inhibitory mechanisms and reading skill, the less skilled readers were university students who read within the "normal" range of adult reading skill (*e.g.,* Gernsbacher & Faust, 1991; Gernsbacher & Robertson, 1995; Gernsbacher et al., 1990; Whitney et al., 1991). Even though these students were less skilled at comprehending text than their peers, they did not have reading disabilities. Thus, these studies demonstrated that limitations in inhibitory control disrupted reading comprehension among normal adult readers, not individuals with reading disabilities.

While there is now considerable evidence that reading disability is characterized by deficits in phonological awareness, the ability to make judgments about the phonological structure of oral language (Jorm & Share, 1983; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987), there is little evidence that inefficient suppression mechanisms may contribute to this impairment. Typically, impaired phonological awareness is thought to result from deficits in the ability to encode phonological representations (Brady, 1997; Fowler, 1991; Metsala, 1997), short-term memory and working memory (McBride-Chang, 1995; Oakhill & Kyle, 2000). However, impairments in inhibitory control may also contribute to poor phonological awareness. For example, in a typical phonological awareness task, a participant must perceive the stimulus, maintain it in working memory, perform mental operations on that stimulus, and report the results. Because disabled readers may have less distinct phonological representations (Elbro, 1996), they must inhibit phonologically similar alternatives to target words. Failures to inhibit incorrect options may further reduce performance on measures of phonological awareness. Therefore, it is possible that deficits in inhibitory control may contribute in part to the deficits in phonological awareness characteristic of reading disability.

METHOD

The Participants

The analyses presented here amalgamated the data from adults and children who have participated in one of a series of published studies (*e.g.,* Chiappe & Siegel, 1999; Gottardo, Stanovich & Siegel, 1994; Siegel, 1994). This total sample included 996 individuals; 488 skilled readers and 508 individuals with reading disabilities. Participants from these studies were recruited from schools, universities, colleges, community agencies or they were volunteers from the community. The sample was predominantly middle class. All participants were educated in English.

Because reading disability is characterized by deficits in word recognition (Siegel, 1993), participants were classified as reading disabled or skilled readers based on their performance on the Wide Range Achievement Test (WRAT; Jastak & Wilkinson, 1978; WRAT-R, Jastak & Wilkinson, 1984; WRAT-3, Wilkinson, 1995). All variations of the WRAT are untimed naming tasks that require individuals to read lists of words in isolation. The 508 participants who had obtained WRAT reading scores below the 26th percentile were classified as reading disabled. The use of the 25th percentile as the cut-

off score has been recommended as an appropriate criterion for identifying individuals with significant difficulties in reading (Siegel & Heaven, 1986). There were 488 participants who obtained WRAT reading scores above the 29th percentile. They were classified as skilled readers. Although an IQ-discrepancy score was not used because of serious problems with discrepancy-based definitions (*e.g.*, Fletcher et al., 1994; Siegel, 1989), we only included participants with IQ scores greater than 79 on an abbreviated version of the WISC-R (Sattler, 1982; Weschler, 1974) or the WAIS-R (Silverstein, 1982; Weschler, 1981) that was based on the Vocabulary and the Block Design subtests.

Participants were arbitrarily divided into five age groups: 6-9, 10-19, 20-29, 30-39, and 40-49. The numbers of skilled readers (first number in parentheses) and disabled readers (second number in parentheses) within each age group were: 6-9 (165, 235), 10-19 (101, 84), 20-29 (117, 100), 30-39 (69, 72), and 40-49 (36, 17).

The Measures

Participants were given one of two listening span tasks that were based on the work of Daneman and Carpenter (1980). The listening span task was designed to assess both the storage and processing components of working memory. In the listening span task, participants listened to a series of unrelated sentences and comprehended each sentence, while preparing to recall the final word of each sentence at the end of the set. As the number of sentences increased, demands on working memory were also assumed to increase.

In the current study, the listening span task was presented to participants using either the traditional, blocked design or a mixed design.

Blocked Design: In the blocked design, the experimenter read sets of sentences that were missing their final words. Participants supplied the missing word for each sentence. On completion of the set, participants attempted to recall the missing words in the order they had generated them. Sets contained two, three, or four sentences. Each set size, or level, contained three trials. To reduce difficulties in word retrieval, the sentences were selected so that the final word was virtually predetermined. None of the participants experienced difficulties in providing the final word. For example, in a set of two sentences, participants would hear, "In a baseball game, the pitcher throws the ___"; "On my two hands, I have ten ___". On completion of the set, participants attempted to repeat the two words that they had generated (in this case, *ball* and *fingers*). The task was discontinued when an individual failed all three trials at a given level.

Mixed Design: For the mixed design, we used Gottardo et al.'s (1996) adaptation of Daneman and Carpenter's (1980) listening span task. In this task, the experimenter read sets of sentences to the participants, who decided whether each sentence was true or false. At the end of each set, participants attempted to report the final word of each sentence in the order they had heard them. Like the blocked design, there were three trials containing two sentences, three trials with three sentences, and three trials with four sentences. However, unlike the blocked design, trials of the same length were not blocked. Instead,

each of the three sets contained a 2-item trial followed by a 3-item trial, and ended with a 4-item trial.

For both listening span tasks, an Absolute Span score was calculated for each participant using the procedure developed by Engle and his colleagues (*e.g.*, Engle, Cantor & Carullo, 1992; Engle, Nations & Cantor, 1990). To calculate the Absolute Span score, the number of words recalled on perfectly recalled trials was summed. In perfectly recalled trials, participants were not penalized for recalling the words in an incorrect order. Thus, if a participant perfectly recalled all three trials of set length 2, two trials of set length 3, and recalled none of the trials with a set length of 4 perfectly, the Absolute Span Score would be 12. The highest possible Absolute Span score was 27.

Error Analyses

Because we wished to examine the role of inhibition in working memory, two types of errors, no responses (or omissions) and intrusion errors, were analyzed. For Omission errors, we considered the total number of items in which participants did not provide a response or said, "I don't know." Intrusion errors occurred when participants responded by substituting a target word with another word. Three types of mutually exclusive intrusion errors were considered. First, Current Nonfinal (CNF) intrusions were errors in which the response was a word from the current trial but was not one of the target words. CNF intrusions reflected deficient inhibition that resulted in increased entry into working memory of irrelevant information. Second, Previous (P) intrusions were responses in which target words were substituted with words from earlier trials, regardless if they were in the final or nonfinal position. Previous intrusions reflect proactive interference that may result from the failure to delete or inhibit information that was no longer relevant. Finally, Extraneous (E) intrusions were errors in which the response was a word that had not been presented in the current or previous trials. Extraneous intrusions may reflect deficiencies in the restraining function of inhibition. The total number of intrusion errors and the number of each type of error were used as dependent variables.

Phonological Awareness

A subgroup of 335 participants had been given the Rosner's Auditory Analysis Test (Rosner & Simon, 1971) as a measure of phonological awareness. Use of this measure enables us to investigate phonological awareness's relationships with working memory and inhibitory control. This task requires participants to delete segments from words. It is arranged approximately in ascending difficulty, requiring participants to delete syllables from compound words and single phonemes from the initial and final positions in words. For example, a simple item would require one to say *birthday* without *day*, whereas a more challenging item would require the participant to say *glow* without /l/. This test contained two practice items and 40 test items. The Rosner test was discontinued when a participant made three consecutive errors.

RESULTS AND DISCUSSION

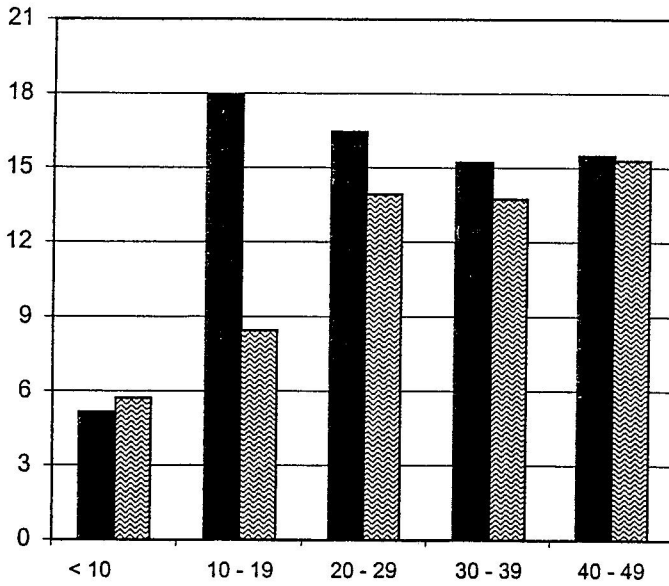### Working Memory and Reading Skill

The results for the Absolute Span scores are shown in Figure 1. In general, reading disabled individuals obtained lower span scores than skilled readers, $F(1,953) = 68.93$, $p < .001$. In fact, individual comparisons for each age group (t-tests) indicated that skilled readers had higher scores than disabled readers at each age level. Furthermore, the interaction between task and reading group was not significant, indicating that reading disabled showed comparable impairments on both the blocked and mixed designs of the listening span tasks. These findings are consistent with the view that difficulties in working memory appear in childhood for disabled readers and persist into adolescence and adulthood (Isaki & Plante, 1997; Siegel, 1994).

Working Memory and Aging

In exploring the influence of age on working memory performance, we found a significant main effect of age, $F(4,953) = 91.03$, $p < .001$. Overall, Scheffé post-hoc tests revealed that the span scores obtained by children under 10 were significantly lower than those obtained by all the older participants. These data are consistent with other studies that have found that functional working memory increases throughout childhood (*e.g.*, Case et al., 1982; Hitch & Halliday, 1983).

However, only examining the main effect of age overlooks the complexity of the relationship between age and working memory. To better understand how aging influences working memory, we explored how age interacted with task design. First, we found a significant interaction between age and task, $F(4,953) = 15.01$, $p < .001$. In fact, the two working memory tasks revealed very different patterns associated with aging. For the blocked design, there were significant differences between the first three adjacent age groups (under 10, 10-19, and 20-29). The scores of children under 10 were significantly lower than those of the other groups, while the scores obtained by individuals between the ages of 10 and 19 were significantly higher than all other groups. The latter finding is consistent with other studies that have reported age-related declines in working memory (Campbell & Charness, 1990; Gick, et al., 1988; Reuter-Lorenz et al., 2000; Salthouse & Babcock, 1991; Siegel, 1994).
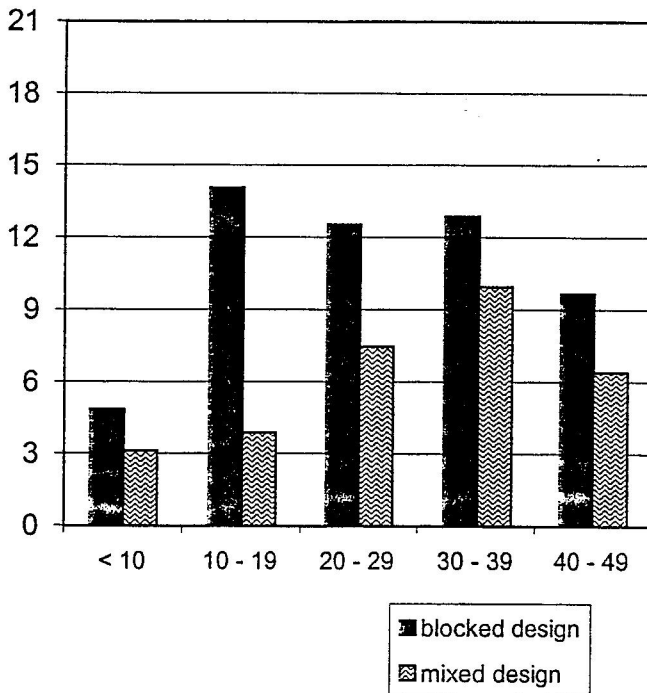
Skilled Readers

Disabled Readers

Figure 1. Listening Span scores as a function of age and working memory task design for skilled and disabled readers.

In contrast, although the both versions of the working memory task revealed an increase in working memory capacity through childhood and adolescence, the patterns of performance diverged in adulthood. Whereas the blocked design showed a decline in working memory performance after the age of 20, the mixed design revealed growth in working memory performance beyond the age of 20. Indeed, on the mixed task children under 10 obtained lower span scores than children in the 10-19 age group, who, in turn, had lower span scores than all groups of adults. The absence of age-related declines in working memory performance cannot be attributed to the mixed design being a less demanding task than the blocked design, as participants obtained significantly higher span score when the listening span task was administered using the blocked design, $F(1,953) = 49.91$, $p < .001$. Instead, these findings, together with those of May et al. (1999) suggest that proactive interference plays an important role in the decline of working memory performance associated with aging. Both the procedural changes used in the present study and the changes used by May et al. (1999) demonstrated that working memory spans do not decline with age if proactive interference is minimized.

Working Memory, Reading Skill and Aging

In addition to examining the independent contributions of reading skill and aging to working memory performance, we wished to explore how they interact. There was a significant interaction between age and reading group, $F(4,953) = 4.90$, $p < .001$. This interaction reflects two important differences in functional working memory for disabled readers and skilled readers. First, skilled readers showed a greater increase than disabled readers in working memory performance between childhood and adolescence. Thus, reading disabled individuals showed greater impairments in working memory performance in adolescence and early adulthood than they did in childhood. Second, reading disabled adults between the ages of 40 and 49 showed greater declines in functional working memory than skilled readers. Thus, reading disabled adults showed smaller growth in functional working memory in adolescence, and greater declines between the ages of 40 to 49.

Error Analyses

Next, we analyzed the errors that participants produced on the listening span tasks. These analyses enabled us to develop a better understanding of the strategies people use when they are presented with the listening span task.

Omissions. The first type of error we examined was Omission, or failures to provide a response. Omissions may result from a failure to hold information in working memory either because of capacity limitations, processing deficits or interference. However, they may also reflect participants' unwillingness to provide responses when they are unsure of the answer. Therefore, Omission errors must be interpreted with caution.

The number of Omissions for both the blocked and mixed designs are shown in Table 1. All error types were analyzed using 2 (design) X 5 (age) X 2 (reading group) ANOVAs. Participants were less likely to attempt items in the blocked design, as Omission errors were more common in the blocked design, $F(1,921) = 36.00$, $p<.001$. We also found a significant main effect of age, $F(4,921) = 8.46$, $p < .001$. Scheffé post-hoc comparisons indicated that children under 10 produced more Omission errors than the adolescents and adults of all ages. While this pattern would be consistent with the view that working memory capacity grows in childhood (Case et al., 1982; Hitch & Halliday, 2000), it is also possible that young children are less likely to guess when they unsure of the response than older participants. No other effects were significant.

Total Intrusions. Simply stated, Intrusions may be thought of as incorrect responses. Intrusions provide some insight into the processes and strategies that participants used in the listening span task.

Table 1. Mean Number of Omissions for Skilled and Disabled Readers as a Function of Age and Design

	Skilled Readers		Disabled Readers	
	Blocked Design	**Mixed Design**	**Blocked Design**	**Mixed Design**
Under 10	16.52	8.45	16.59	9.59
	(6.64)	(3.11)	(7.06)	(3.32)
10 – 19	18.06	8.44	14.25	3.88
	(6.63)	(4.76)	(5.77)	(4.47)
20 – 29	16.67	13.94	12.54	7.47
	(6.38)	(6.12)	(5.61)	(5.15)
30 – 39	15.16	14.00	12.87	9.96
	(6.78)	(6.75)	(5.21)	(6.82)
40 – 49	15.50	15.30	9.67	6.40
	(7.23)	(8.21)	(6.88)	(5.13)

The mean number of Intrusion errors is shown in Table 2. The significant main effect of age, $F(4,953) = 2.51$, $p<.05$, and Scheffé post-hoc tests revealed that children under the age of 10 made more intrusion errors than older participants. Because we found that young children both produced more Intrusions and committed more Omission errors than older participants, our data support the view that working memory capacity grows during childhood.

Table 2. Mean Number of Intrusion Errors on the Blocked and Mixed Designs of the Working Memory Task as a Function of Age and Reading Skill

Blocked Design	Total Intrusions		Current Nonfinal Intrusions		Previous Intrusions		Extraneous Intrusions	
Age	Skilled Readers	Disabled Readers	Skilled Readers	Disabled Readers	Skilled Readers	Disabled Readers	Skilled Readers	Disabled Readers
6-9	1.48	1.42	0.79	0.74	0.39	0.35	0.31	0.32
	(1.39)	(1.62)	(0.92)	(1.10)	(0.74)	(0.78)	(0.66)	(0.68)
10-19	0.81	1.29	0.44	0.72	0.22	0.38	0.15	0.19
	(1.06)	(1.32)	(0.64)	(0.83)	(0.61)	(0.65)	(0.48)	(0.47)
20-29	0.81	1.64	0.40	1.1	0.35	0.42	0.05	0.21
	(0.99)	(1.59)	(0.67)	(1.31)	(0.61)	(0.95)	(0.22)	(0.49)
30-39	1.28	1.44	0.77	1.1	0.40	0.24	0.12	0.11
	(1.22)	(1.41)	(0.81)	(1.16)	(0.73)	(0.53)	(0.32)	(0.32)
40-49	0.92	2.0	0.73	1.33	0.19	0.33	0	0.33
	(1.09)	(1.65)	(0.92)	(1.23)	(0.40)	(0.78)	0	(0.49)

Mixed Design	Total Intrusions		Current Nonfinal Intrusions		Previous Intrusions		Extraneous Intrusions	
Age	Skilled Readers	Disabled Readers	Skilled Readers	Disabled Readers	Skilled Readers	Disabled Readers	Skilled Readers	Disabled Readers
6-9	2.55	4.76	1.31	3.03	0.79	0.71	0.45	1.02
	(2.29)	(3.77)	(1.75)	(3.03)	(1.12)	(1.34)	(0.76)	(1.23)
10-19	2.69	4.63	1.44	3.25	1.13	0.75	0.13	0.63
	(2.98)	(3.90)	(2.28)	(2.89)	(1.09)	(0.86)	(0.50)	(1.09)
20-29	1.61	4.00	0.61	3.0	0.78	0.79	0.22	0.21
	(1.29)	(4.26)	(0.70)	(3.93)	(0.88)	(1.32)	(0.43)	(0.54)
30-39	1.81	3.33	0.65	2.07	0.96	1.07	0.19	0.19
	(1.74)	(2.73)	(0.80)	(2.06)	(1.25)	(1.39)	(0.49)	(0.40)
40-49	1.10	5.40	0.60	3.60	0.30	1.40	0.20	0.40
	(1.00)	(3.78)	(0.70)	(2.70)	(0.68)	(1.14)	(0.42)	(0.55)

Note: Standard deviations are presented in parentheses.

We did find preliminary evidence that disabled readers may have less efficient inhibitory control, as they produced more Intrusion errors than skilled readers, $F(1,953) = 55.40$, $p<.001$. Furthermore, while the mixed design tended to elicit more Intrusions than the blocked version of the working memory task, $F(1,953) = 89.77$, $p<.001$, the interaction between reading group and task design was significant, $F(1,953) = 23.66$, $p<.001$. This interaction showed that the differences between skilled and disabled readers were greater for the mixed design than the blocked design. In fact, although disabled readers tended to produce 50% more Intrusions with the blocked design, they produced twice as many Intrusions than skilled readers when the mixed design was administered. Thus, disabled readers may be less efficient in some of the functions of inhibitory control. These functions are examined below.

Current Nonfinal Intrusions. Current Nonfinal intrusions are thought to reflect failures of the access function of inhibition. These errors are words that had been activated when the examiner read the sentences in the current set, but they had not been prevented access to the working memory buffer Thus, Current Nonfinal intrusions occurred when participants failed restrict access to working memory only to task-relevant information. These errors are shown in Table 2.

Disabled readers made significantly more Current Nonfinal intrusions, $F(1,953) = 63.10$, $p < .001$, suggesting that they were less efficient than skilled readers in the access function of inhibition. Although Current Nonfinal intrusions were more common in the mixed version of the listening span task, $F(1,953) = 55.60$, $p < .001$, task design did interact with reading group, $F(1,953) = 29.65$, $p<.001$. In fact, although disabled readers showed deficient inhibitory control with both the mixed and blocked versions of the span task, these impairments were greater in the mixed design. Recall, participants generated the target words in the blocked design, but only listened to the target words in the mixed design. Hence, the increased processing of the target words in blocked design might have helped ameliorate disabled readers' deficits in the access function of inhibition.

Although deficits in inhibitory control are thought to be associated with aging (May et al., 1999), the main effect of age was not significant, $F(4,953) = 1.25$, *ns*. Furthermore, the interaction between task design and age, $F(4,953) = 2.77$, $p<.05$, contradicted the hypothesis that deficits in inhibition increased with age. Although Current Nonfinal intrusions were relatively stable across the lifespan with the blocked design, they were more common for participants younger than the age of 20 for the mixed design. Therefore, the current study provided little evidence that the access function of inhibition declines with age.

Previous Intrusions. Previous intrusions are thought to reflect failures of the deletion function of inhibition. These errors are words that had been activated in previous sets, but had not been deleted from the working memory buffer at the onset of the current set. Thus, Previous intrusions occurred when participants failed to delete information from working memory once it had ceased to be relevant. These errors are shown in Table 2.

Like the Current Nonfinal intrusions, Previous intrusions were produced with greater frequency using the mixed design, $F(1,953) = 40.78$, $p<.001$. Once again, generating the target words in the blocked design might have increased their distinctiveness and reduced competition from previously activated candidates.

Previous intrusions were produced with comparable frequency by disabled and skilled readers, $F(1,953) = 1.02$, *ns*. This pattern suggests that proactive interference was not problematic for disabled readers.

Although Previous intrusions were hypothesized to increase as a function of age, the Previous intrusion rates did not differ significantly among the five age groups, $F(4,953) < 1$, *ns*. Furthermore, neither the age by task interaction, $F(4,953) < 1$, *ns*, nor the three way interaction, $F(4,953) = 1.40$, *ns*, were significant. Thus, older adults produced as many Previous intrusion errors as younger participants. These findings are surprising in light of other studies that have shown greater susceptibility to proactive interference in older adults (*e.g.*, Kane & Hasher, 1996; May et al., 1999).

Extraneous Intrusions. Extraneous intrusions are thought to reflect failures of the restraint function of inhibition. These errors are words that had not been directly activated by the examiner, as they were not included in any of the sentences read to the participants. Instead, participants had independently generated these task-irrelevant words and allowed them to enter the working memory buffer. Thus, Extraneous intrusions occurred when participants failed to restrict access to working memory to relevant information. The frequency of these errors is also shown in Table 2.

Once again, the mixed design of the listening span task produced more intrusions than the blocked design, $F(1,953) = 8.72$, $p<.01$. In fact, Extraneous intrusions were about three times more common when the mixed procedure of the working memory task had been administered.

There was a significant main effect of age, $F(4,953) = 11.49$, $p<.001$. Scheffé post-hoc comparisons indicated that children under the age of 10 produced significantly more Extraneous intrusions than all other participants. The greater incidence of both Extraneous intrusions and Omissions would suggest that the more limited working memory capacity of children under the age of 10 is impeded even further by difficulties in preventing irrelevant information from entering the working memory buffer. In fact, the interaction between age and task design, $F(4,953) = 2.68$, $p<.05$, showed that children under the age of 10 showed greater impairments in the mixed design. Hence, increasing the salience of relevant information by generating the target words ameliorated young children's deficits in the restraint function of inhibitory control.

Disabled readers tended to produce more Extraneous intrusions than skilled readers, $F(1,953) = 8.16$, $p<.01$, suggesting that they may also have deficits in the restraint function of inhibition. Although reading skill did not interact with task design, $F(1,953) = 1.15$, *ns*, the three-way interaction was significant, $F(4,953) = 2.45$, $p<.05$. This interaction showed that the selective difficulties shown by the younger children with the mixed design were most pronounced among children with reading disabilities.

Phonological Awareness's Relationships with Working Memory and Inhibitory Control

First, we wished to determine if the reading disabled individuals showed the phonological deficits that are known to characterize reading disability. Performance on the Rosner Auditory Analysis task as a function of age is shown in Figure 2. Analysis of variance confirmed that disabled readers obtained lower scores on the Rosner than skilled readers, $F(1,313) = 125.15$, $p<.001$. Thus, the results from this sample of disabled readers converged with those from the majority of other samples in the literature by displaying significant deficits in phonological awareness (Adams, 1990; Bradley & Bryant, 1985; Stanovich & Siegel, 1994; Wagner & Torgesen, 1987).

GENERAL DISCUSSION

At each age, there were differences between skilled and disabled readers on the working memory tasks. Thus, difficulties in working memory for disabled readers extend beyond childhood into adolescence and adulthood. The persistence of disabled readers' working memory deficits through the life span is consistent with the literature (Siegel, 1994).

Deficits in inhibitory control may contribute to disabled readers' lower span scores. Overall, disabled readers produced more intrusion errors than skilled readers. In fact, Current Nonfinal intrusions and Extraneous intrusions were particularly difficult for disabled readers, suggesting that disabled readers were less efficient in the access and restraint functions of inhibition. Deficits in the access and restraint functions of inhibition would permit irrelevant information increased entry into working memory. However, although Previous intrusions are considered an index of proactive inhibition, disabled readers did not produce more Previous intrusions than skilled readers. Similarly, the mixed design failed to eliminate differences between skilled readers and disabled readers. Together, these two findings suggest that disabled readers' deficits in working memory are not the result of proactive interference. Thus, the current findings suggest that deficits restricted to the access and restraint functions of inhibitory control may contribute to the difficulties experienced by disabled readers in working memory.

Impairments in the access and restraint functions of inhibition also explained variance in phonological awareness. Although deficient inhibitory control may not cause the phonological deficits characteristic of reading failure, inefficient inhibitory mechanisms may exacerbate weak performance on phonological awareness tasks. Consider the following. In phonological awareness tasks, individuals must accurately perceive and represent the speech stimulus while holding it in working memory. According the phonological distinctiveness hypothesis, disabled readers' lexical representations are less completely specified and have less robust phonemic details (Elbro, 1996). As a consequence, when performing phonological awareness tasks, disabled readers may be confronted with a number of competing, phonologically similar alternatives in the working memory buffer. If incorrect alternatives are not prevented from entering working memory, the individual may provide an incorrect response because he/she had performed the correct operations on the wrong alternative. Therefore, individuals who have less distinct phonological representations would need efficient inhibitory mechanisms to avoid such confusion. However, disabled readers showed difficulties in preventing irrelevant information from entering the working memory buffer. Thus, reading disabled may have to contend with more alternatives in working memory both because of their less completely specified lexical representations and less efficient inhibitory mechanisms.

With both procedures of the listening span task, we found that working memory performance increased steadily until adolescence. However, the two listening span tasks produced divergent patterns for adult participants. Although the standard blocked design revealed that working memory performance gradually declined after age 20, the mixed

design did not reveal such a decline, except for disabled readers. In fact, with the mixed design of the working memory task adults over the age of 19 had significantly higher span scores than children and adolescents. These findings suggest the importance of inhibitory control for older adults. Simply by changing the procedure of the listening span to diminish proactive interference, middle aged adults performed as well as young adults. Thus, the span data are consistent with other studies that suggest declines in working memory reported for older adults may result from difficulties in inhibiting irrelevant information rather than declines in working memory capacity (Hartman & Hasher, 1991; Hasher & Zacks, 1988; May et al., 1999).

However, the error analyses provided limited support for the relationship between inhibitory control and aging. Because declines in working memory are thought to result from diminished efficiency in inhibitory control (Hasher & Zacks, 1988; Kane & Hasher, 1996), we expected to find intrusions to be more common for older participants. Instead, we found that young children made the most intrusion errors. More specifically, children under the age of 10 made more Current Nonfinal and Extraneous intrusions than all other participants, indicating that they had greater difficulty in preventing irrelevant information from entering working memory. Similarly, younger children also produced more Omissions than adolescents and adults. Therefore, growth in functional working memory in childhood may result from both increases in capacity and greater efficiency in the use of inhibitory mechanisms.

CONCLUSIONS

In summary, deficits in working memory are characteristic of disabled readers throughout the life span. Working memory skills develop through childhood and adolescence, however the standard, blocked design revealed declines in middle adulthood whereas the mixed design did not. The different patterns suggest that the decline in working memory skills associated with aging may result from growing inefficiencies in inhibitory control, rather than diminished capacity. In contrast, disabled readers' difficulties in working memory result from smaller working memory capacity in addition to difficulties in restricting access to the working memory system to relevant information.

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REFERENCES

Adams, M. J. (1990). *Beginning to read: Thinking and learning about print*. Cambridge, MA: MIT Press.

Baddeley, A. D. (1983). Working memory. *Philosophical Transactions of the Royal Society of London, B302*, 311-324.

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

Bradley, L., & Bryant, P. E. (1985). *Rhyme and reason in reading and spelling*. Ann Arbor: University of Michigan Press.

Brady, S. A. (1997). Ability to encode phonological representations: An underlying difficulty of poor readers. In B. Blachman (Ed.). *Foundations of Reading Acquisition and Dyslexia: Implications for Early Intervention*, (Pp. 21-47). Mahwah, NJ: Erlbaum.

Campbell, J. I. D., & Charness, N. (1990). Age-related declines in working-memory skills: Evidence from a complex calculation task. *Developmental Psychology, 26*, 879-888.

Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology, 28*, 386-404.

Chiappe, P., & Siegel, L. S. (1999). Phonological awareness and reading acquisition in English and Punjabi-speaking Canadian children. *Journal of Educational Psychology, 91*, 20-28.

Da Fontoura, H. A., & Siegel, L. S. (1995). Reading, syntactic, and working memory skills of bilingual Portuguese-English Canadian children. *Reading and Writing: An Interdisciplinary Journal, 7*, 139-153.

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

Ehri, L. C., & Wilce, L. S. (1980). The influence of orthography on readers' conceptualization of the phonemic structure of words. *Applied Psycholinguistics, 1*, 371-385.

Elbro, C. (1996). Early linguistic abilities and reading development: A review and a hypothesis. *Reading & Writing: An Interdisciplinary Journal, 8*, 453-485.

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., Nations, J. K., & Cantor, J. (1990). Is "working memory capacity" just another name for word knowledge? *Journal of Educational Psychology, 82*, 799-804.

Fletcher, J. M., Shaywitz, S. E., Shankweiler, D. P., Katz, L., Liberman, I. Y., Stuebing, K. K., Francies, D. J., Fowler, A. E., & Shaywitz, B. A. (1994). Cognitive profiles of reading disability: Comparisons of discrepancy and low achievement definitions. *Journal of Educational Psychology, 86*, 6-23.

Fowler, A. E. (1991). How early phonological development might set the stage for phoneme awareness. In S. Brady & D. Shankweiler (Eds.), *Phonological processes in literacy: A tribute to Isabelle Y. Liberman* (Pp. 97-117). Hillsdale, NJ: Erlbaum.

Gernsbacher, M. A. (1990). *Language comprehension as structure building.* Hillsdale, NJ: Erlbaum.

Gernsbacher, M. A., & Faust, M. E. (1991). The mechanism of suppression: A component of general comprehension skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 245-262.

Gernsbacher, M. A., & Robertson, R. R. W. (1995). Reading skill and suppression revisited. *Psychological Science, 6,* 165-169.

Gernsbacher, M. A., Varner, K. R., & Faust, M. E. (1990). Investigating differences in general comprehension skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 430-445.

Geva, E., & Siegel, L. S. (2000). The role of orthography and cognitive factors in the concurrent development of basic reading skills in bilingual children. *Reading and Writing: An Interdisciplinary Journal, 12,* 1-30.

Gick, M. L., Craik, F. I. M., & Morris, R. G. (1988). Task complexity and age differences in working memory. *Memory & Cognition, 16,* 353-361.

Gottardo, A., Stanovich, K. E., & Siegel, L. S. (1996). The relationships between phonological sensitivity, syntactic processing, and verbal working memory in the reading performance of third-grade children. *Journal of Experimental Child Psychology, 63,* 563-582.

Hamm, V. P., & Hasher, L. (1992). Age and the availability of inferences. *Psychology and Aging, 7,* 56-64.

Hartman, M., & Hasher, L. (1991). Aging and suppression: Memory for previously relevant information. *Psychology and Aging, 6,* 587-594.

Hasher, L., Stoltzfus, E. R., Rympa, B., & Zacks, R. T. (1991). Age and inhibition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17,* 163-169.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.). *The psychology of learning and motivation* (Vol. 22). San Diego, CA: Academic Press. Pp. 193-225.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.). *Attention and performance.* Cambridge, MA: MIT Press. Pp. 653-675.

Hitch, G. J., & Halliday, M. S. (1983). Working memory in children. *Philosophical Transactions of the Royal Society of London, B302,* 325-340.

Isaki, E., & Plante, E. (1997). Short-term and working memory differences in language/learning disabled and normal adults. *Journal of Communication Disorders, 30,* 427-437.

Jastak, J. R., & Jastak, S. R. (1978). *Wide Range Achievement Test.* Wilmington, DE: Jastak Associates.

Jastak, S., & Wilkinson, G. S. (1984). *The Wide Range Achievement Test - Revised.* Wilmington, DE: Jastak Associates.

Jorm, A. G., & Share, D. L. (1983). Phonological recoding and reading acquisition. *Applied Psycholinguistics, 4,* 103-147.

Kane, M. J., & Hasher, L. (1996). Interference. In G. Maddox (Ed.), *Encyclopedia of aging* (second edition). New York: Springer Publishing Co.

Kerlinger, F. N., & Pedhazur, E. J. (1973). *Multiple regression in behavioral research.* New York: Holt, Rinehart and Winston.

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

Light, L. L., & Anderson, P. A. (1985). Working-memory capacity, age, and memory for discourse. *Journal of Gerontology, 40*, 737-747.

Malicky, G. V., & Norman, C. A. (1999). Phonological awareness and reading; An alternative interpretation of the literature from a clinical perspective. *The Alberta Journal of Educational Research, 45*, 18-34.

Masunaga, H., & Horn, J. (2001). Expertise and age-related changes in components of intelligence. *Psychology & Aging, 16*, 293-311.

May, C. P., Kane, M. J., & Hasher, L. (1995). Determinants of negative priming. *Psychological Bulletin, 118*, 35-54.

May, C.P., Hasher, L., & Kane, M.J. (1999). The role of interference in memory span. *Memory & Cognition, 27*, 759-767.

McBride-Chang, C. (1995). Phonological processing, speech perception, and reading disability: An integrative review. *Educational Psychologist, 30*, 109-121.

Metsala, J. L. (1997). Spoken word recognition in reading disabled children. *Journal of Educational Psychology, 89*, 159-169.

Morris, R. G., Gick, M. L., & Craik, F. I. M. (1988). Processing resources and age differences in working memory. *Memory & Cognition, 16*, 362-366.

Oakhill, J., & Kyle, F. (2000). The relation between phonological awareness and working memory. *Journal of Experimental Child Psychology, 75*, 152-164.

Perfetti, C., Beck, I., Bell, L., & Hughes, C. (1987). Phonemic knowledge and learning to read are reciprocal: A longitudinal study of first grade children. *Merrill Palmer Quarterly, 33*, 283-319.

Reuter-Lorenz, P. A., Jonides, J., Smith, E. E., Hartley, A., Miller, A., Marshuetz, C., & Koeppe, R. A. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience, 12*, 174-187.

Rockstroh, S., & Schweizer, K. (2001). The contributions of memory and attention processes to cognitive abilities. *Journal of General Psychology, 128*, 30-42.

Rosner, J. & Simon, D. P. (1971). The auditory analysis test: An initial report. *Journal of Learning Disabilities, 4*, 1-15.

Salthouse, T. A., & Babcock, R. L. (1991). Decomposing age differences in working memory. *Developmental Psychology, 27*, 763-776.

Siegel, L. S. (1989). IQ is irrelevant to the definition of learning disabilities. *Journal of Learning Disabilities, 22*, 469-478, 486.

Siegel, L. S. (1993). The development of reading. *Advances in Child Development and Behavior, 24*, 63-97.

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

Siegel, L. S., & Heaven, R. (1986). Categorization of learning disabilities. In S. J. Ceci (Ed.), *Handbook of cognitive, social, and neuropsychological aspects of learning disabilities* (Vol. 1; Pp. 95-121). Hillsdale, NJ: Erlbaum.

Siegel, L. S., & Linder, B. A. (1984). Short-term memory processes in children with reading and arithmetic learning disabilities. *Developmental Psychology, 20*, 200-207.

Siegel, L. S., & Ryan, E. B. (1988). Development of grammatical sensitivity, phonological, and short-term memory skills 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 children. *Child Development, 60*, 973-980.

So, D., & Siegel, L. S. (1997). Learning to read Chinese: Semantic, syntactic, phonological and short-term memory skills in normally achieving and poor Chinese readers. *Reading and Writing: An Interdisciplinary Journal, 9*, 1-21.

Song, J. Y., & Won, H. T. (1998). Working memory, short-term memory, words-reading speed and syntactic knowledge of Korean children with reading-comprehension disability. *Korean Journal of Clinical Psychology, 17*, 105-121.

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

Stoltzfuz, E. R., Hasher, L., Zacks, R. T., Ulivi, M. S., & Goldstein, D. (1993). Investigations of inhibition and interference in younger and older adults. *Journal of Gerontology: Psychological Sciences, 48*, 179-188.

Swanson, H. L. (1993a). Individual differences in working memory: A model testing and subgroup analysis of learning-disabled and skilled readers. *Intelligence, 17*, 285-332.

Swanson, H. L. (1993b). 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. (1999). What develops in working memory? A life span perspective. *Developmental Psychology, 35*, 986-1000.

Swanson, H. L., & Sachse-Lee, C. (2001). A subgroup analysis of working memory in children with reading disabilities: Domain-general or domain-specific deficiency? *Journal of Learning Disabilities, 34*, 249-263.

Tirre, W. C., & Peña, C. M. (1992). Investigation of functional working memory in the reading span test. *Journal of Educational Psychology, 84*, 462-472.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 30*, 73-87.

Waters, G. S., & Caplan, D. (2001). Age, working memory, and on-line syntactic processing in sentence comprehension. *Psychology & Aging, 16*, 128-144.

Wechsler, D. (1974). *Wechsler intelligence scale for children: Revised.* New York: Psychological Corporation.

Wechsler, D. (1981). *WAIS-R manual.* New York: Psychological Corporation.

Whitney, P., Ritchie, B. G., & Clark, M. B. (1991). Working-memory capacity and the use of elaborative inferences in text comprehension. *Discourse Processes, 14,* 133-146.

Wilkinson, G. S. (1995). *The Wide Range Achievement Test - 3.* Wilmington, DE: Jastak Associates.

Wilson, K. M., & 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.

Zacks, R. T., & Hasher, L. (1988). Capacity theory and the processing of inferences. In L. L. Light & D. M. Burke (Eds.), *Language, memory and aging.* New York: Cambridge University Press. Pp. 154-170.