Neuropsychology
2007, Vol. 21, No. 5, 532–539

0894-4105/07/$12.00 DOI: 10.1037/0894-4105.21.5.532

Age-Related Deficits in Component Processes of Working Memory

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Working memory deficits in normal aging have been well documented, and studies suggest that high memory load plus the presence of distraction negatively impacts successful memory performance to a greater degree in older individuals. However, characterization of the component processes that are impaired by these task manipulations is not clear. In this behavioral study, younger and older subjects were tested with a delayed-recognition and recall task in which the encoding and delay period were both manipulated. During the encoding period, the subjects were presented with either a single letter or multiple letters at their predetermined forward letter span, and the delay period was either uninterrupted or interrupted with a visual distraction. There was an age-related impairment of working memory recognition accuracy only in the combination of high memory load and distraction. These results suggest that when working memory maintenance systems are taxed, faulty recognition processes may underlie cognitive aging deficits in healthy older individuals.

Keywords: aging, distractor, working memory, delayed-recall task, delayed-recognition task

Memory loss is a frequent complaint in older adults, and it involves not only difficulty remembering recent events but also impairments in holding information "in mind" over short periods of time. The latter cognitive process is referred to as *working memory* (WM), and age-related deficits in WM have been demonstrated in many studies (Belleville, Peretz, & Malenfant, 1996; Dobbs & Rule, 1989; Foos & Wright, 1992; Salthouse, Babcock, & Shaw, 1991; Wingfield, Stine, Lahar, & Aberdeen, 1988).

WM refers to the temporary representation of information that was just experienced or just retrieved from long-term memory but is no longer accessible in the external environment (Baddeley, 1986). These internal representations are short lived but can be maintained for longer periods of time through active rehearsal or maintenance strategies, and they can be subjected to various operations that manipulate the information in such a way that makes it useful for goal-directed behavior. To maintain and manipulate relevant information that is not accessible in the environment, the brain needs a storage process as well as rehearsal or maintenance processes that can prevent the contents of the storage system from decaying (see, for example, D'Esposito & Postle, 1999).

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This work was supported by National Institutes of Health Grants AG025221, MH63901, AG15793, and NS40813; the National Research Service Award; the American Federation for Aging Research; and the Veterans Administration Research Service. We thank Marcia Johnson and Karen Mitchell for helpful comments on the article.

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Although not completely dissociable, these component processes of WM can be studied with some degree of isolation with the help of different task designs. Storage capacity is often assessed by a span test, in which a series of letters, digits, words, or images are presented to subjects for immediate recall. WM maintenance processes are often assessed with delay tasks, which require subjects to hold information in mind over an interval of time. In general, storage processes, as assessed by span tasks, are not affected by normal aging (see, for example, Wingfield et al., 1988). In contrast, WM maintenance processes, as assessed by delay tasks, have been found to be impaired in normal aging (Anders, Fozard, & Lillyquist, 1972; Byrd, 1986; Craik & Rabinowitz, 1985; Nielsen-Bohlman & Knight, 1995). However, not all studies that have assessed WM maintenance processes have found age-related impairments (e.g., Boaz & Denney, 1993). Moreover, in those studies that have found deficits, the precise nature of the deficit is not clear. There are several possible explanations for the discrepant findings in the cognitive aging literature. First, in studies that have not found age-related impairment on delay tasks it is possible that WM maintenance processes were not sufficiently taxed. For example, older individuals were not impaired on delay tasks that required the maintenance of only a single item (Chao & Knight, 1997; Della-Maggiore et al., 2000). In these studies, impairments may have been observed if more demands had been placed on WM maintenance processes by increasing the memory load.

Even in studies that have found an age-related impairment on delay tasks, it is still plausible that deficits in other processes, rather than WM maintenance processes, contributed to impairment on the task. For example, some delay tasks require free recall, whereas others test by recognition (e.g., Crook & Larrabee, 1992; Crook & West, 1990). Although both types of delay tasks tap WM maintenance processes, they differ in the types of cognitive processes that are necessary for retrieving information that is being actively maintained. Thus, impairment in retrieval-related processes, rather than maintenance processes, could account for the age-related impairments that were observed.

Finally, in some WM studies, distracting stimuli are presented during the delay period, resulting in age-related deficits (e.g., Chao & Knight, 1997). In these studies, the possibility exists that the age-related deficit is not in WM maintenance processes per se but in the ability to inhibit or suppress irrelevant information. In fact, Hasher and Zacks' (1988) inhibitory deficit hypothesis proposed that aging leads to an impaired ability to suppress task-irrelevant information in WM, resulting in performance deficits, and there are many studies that have supported age-related deficits in inhibitory control (Alain & Woods, 1999; Chao & Knight, 1997; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Sweeney, Rosano, Berman, & Luna, 2001). In this model of cognitive aging, WM maintenance processes were not considered to be the source of age-related WM impairments. Thus, the main purpose of this study was to precisely characterize the nature of the WM deficits found in normal aging and to distinguish among these possibilities. To our knowledge, a behavioral study of normal aging has not been performed in which individuals have been tested with a delay task in which WM maintenance processes are taxed at different load levels, interrupted with distracting stimuli, and tested with both recall and recognition.

In the current study, we employed a very simple WM maintenance task, in which it was expected that there would be no performance impairment in older adults (i.e., remembering a single letter over a short delay without distraction). However, we also manipulated the task design to assess different processes (e.g., maintenance, inhibition, retrieval mode) and evaluate which factors, or combination of factors, result in impairment. To accomplish this, 52 healthy younger and older adults were tested with a delay task in which both the encoding and delay period were manipulated and the influence on both recall and recognition performance was evaluated. During the encoding period, the subjects were presented with either a single letter (*low load*) or multiple letters (*high load*), and the delay period was either uninterrupted or interrupted by a distractor (a simple, visual attention task). Not all subjects were exposed to the same high load, because the demands of different loads may vary between subjects, especially across different age groups. Rather, subjects performed the high load task with the amount of letters equivalent to their individually predetermined storage capacity.

This experimental design allowed us to tax WM maintenance in two different manners: by increasing memory load, which introduces greater rehearsal demands, and by using distraction, which directly interrupts rehearsal processes. Furthermore, it allowed us to explore not only the impact of load and distraction on WM maintenance but also, for the first time, potential interactions between load and distraction on WM performance in older adults. Thus, by exploring the impact of these manipulations independently and in combination, we investigated factors that contribute to WM deficits in normal aging. We hypothesized that the demands of the WM task in both the low load and distractor-free version would be insufficient to impair performance in older adults but that the combination of these factors would lead to significant impairment.

Method

Subjects

Subjects consisted of 26 older adults (ages 60–82 years) and 26 younger adults (ages 18–30 years). Prior to the study, all subjects were screened for any disorders and/or medication usage that might affect cognitive functioning. All subjects reported no medical, neurological, or psychiatric disorders and were not taking medications that had central nervous system actions. This restriction included medications for heart disease, diabetes, and blood pressure, as well as psychotropic and sleeping medications.

Young adult subjects were recruited primarily from the population of undergraduates at the University of California, Berkeley. Older adult subjects were recruited in and around Berkeley, California. None of the older subjects exhibited evidence of depression as screened by the Beck Depression Inventory (Beck, 1978) or dementia as documented by a score of 27 or greater on the Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975) at the time of testing. Older subjects were well educated (range = 14–24 years). All subjects signed informed consent and were paid for their participation.

Behavioral Testing

Behavioral testing consisted of three parts. First, subjects received several neuropsychological tests. Next, they completed a task designed to assess their maximum WM span, and finally, they participated in the delay tasks. The entire testing session lasted between 2 and 3 hr.

Neuropsychological tests. Tests of emotional, cognitive, and motor functioning were administered to the older adult subjects. These included the Mini-Mental State Exam, the Beck Depression Inventory, and the Digit Symbol—Coding subtest from the Wechsler Adult Intelligence Scale—Third Edition (WAIS–III; Wechsler, 1997).

Immediate serial recall. Subjects viewed letters presented on a computer screen in a sequential manner. After seeing the initial presentation of two letters, subjects were required to immediately repeat aloud and in the same order the letters that they had just read. This was conducted for two trials. If both trials were performed correctly, then subjects were presented with two sequential trials of three letters. This process continued with increasing numbers of letters until the subjects were unable to correctly repeat the letters for either of the two trials. The number of letters for which a subject could correctly repeat at least one trial was then defined as the subject's WM span and was used in the delay task.

Delayed recall and recognition. After completing the span task, subjects performed the delayed-response task. During this task, they viewed letters presented sequentially on a computer screen for 750 ms per letter (encoding period), followed by a 6,500-ms delay period, and then were asked to indicate whether they remembered the letters presented during the encoding period (response period).

During the encoding period, subjects were required to remember either one letter (low load) or as many letters as was previously defined as their WM span (high load). During the delay period, subjects viewed either a simple fixation cross hair (distractor absent) or a series of nine words presented at a rate of 333 ms per word (distractor present). Subjects were instructed to view and pay attention to the words but not to attempt to remember them, because they would not be tested on them later. Words were randomly selected from a list of 57 unique words and were repeated randomly throughout the experiment. All words had one syllable; contained three to five letters; were restricted to nouns, verbs, and adjectives; and were medium to high on the scale for Brown verbal frequency, familiarity, concreteness, and meaningfulness (Coltheart, 1981). There were two types of response periods during the trials: recognition and recall. During half of the trials, subjects viewed a single letter and indicated with a right button press if the letter was a member of the set they had viewed at encoding and with a left button press if it was not (recognition). During the other half of the trials, subjects were required to state aloud, and in the same order they had seen them, the letters they had viewed at encoding (recall).

The combination of these conditions resulted in a 2 (load) × 2 (distractor) × 2 (response) × 2 (age group) mixed analysis of variance (ANOVA) design. The within-subject conditions were counterbalanced in the following way: There were two blocks of low load and two blocks of high load for each response condition (recognition and recall). Each block contained 40 trials of delay task. Blocks were presented in a set order, alternating between low and high loads and beginning with low load. All four blocks for one response condition were presented together, and the order of response condition was counterbalanced across subjects. For example, subjects would first complete 40 trials of the recognition condition at low load, then 40 trials of the recognition at high load; they then would perform another recognition low load block and finally a recognition high load block before moving to the recall condition. Half of the trials in each block had distractors during the delay period, and half did not. The presentation of these trials was varied randomly across the block. In total there were 320 delayed response trials.

Data Analysis

Recognition. During the recognition condition, response time and performance were automatically recorded for each subject's button press response. Performance was analyzed for hits, misses, correct rejections, and false alarms. From these variables we calculated accuracy (accuracy = hits + correct rejections/total possible items), response bias, and discriminability. Response bias is a subject's propensity to respond "yes" or "no" in situations of truly random noise and is calculated with the following formula: response bias = $0.5 \times [(z \text{ score of hits})^2 - (z \text{ score of false alarms})^2]$. Discriminability is the measure of a subject's ability to correctly remember an item that had been previously viewed and is uncontaminated by the subject's response bias. Discriminability is calculated with the following formula: (z score of hits) – (z score of false alarms). Z scores were determined on the basis of the normal distribution to avoid biases associated with the older or younger group mean and standard deviation.

Recall. During the recall condition, subjects gave their responses verbally, and an experimenter recorded them. Later, these responses were scored for accuracy. Because subjects had to repeat each letter in the same order that they were presented during the encoding period, this task was scored according to both lenient and stringent criteria. For the stringent standard, each trial was scored as either correct or incorrect. For the lenient standard, if subjects repeated the letters from the encoding period in the order presented, they received 2 points. If they missed one letter or made one transposition, they received 1 point. If they made more than one mistake of either kind, they received 0 points.

Power analysis. To determine the appropriate sample size for this investigation a power analysis was computed. We used Cohen's (1988) calculations for power of an F test at $\alpha = .05$ and $u = 3(2 \times 2 \times 2$ ANOVA; Cohen, 1988). Given the preponderance of evidence for a memory deficit in the elderly population (Folstein et al., 1975), we estimated a large effect size for our analysis. At predicted effect size of .40 and group $N = 26$, power for our analysis was .94. This was determined to be an acceptable level of power.

Effect size. In accordance with the requirements of the journal, for each significant comparison of interest, effect size was calculated. As a conservative measure of effect size Cohen's d was calculated for both independent and dependent comparisons on the basis of the mean and standard deviation for each group (Cohen, 1988).

Results

Memory Span

Older adults exhibited a significantly lower mean WM span than did younger subjects (older = 4.82, younger = 5.36; $t = 2.201$, $p = .033$; $d = 0.7$).

Delay Task

Because accuracy was calculated differently for the recognition and recall conditions, analysis of the delay tasks was performed independently for the recall and recognition tasks. Accuracy, discriminability, response bias, and response time on the recognition task and accuracy on the recall task were evaluated on the basis of an Age (young, old) × Load (span, single letter) × Distractor (present, absent) mixed ANOVA. Post hoc comparisons were performed only for significant interactions, and significance was set at $p < .05$ for all results.

Recall Task

The recall trials were scored on the basis of both strict and lenient criteria. When recall accuracy was scored according to the lenient standard, all subjects performed less accurately at high load, $F(1, 50) = 101.55$, $p < .001$, $d = 0.38$, and no other effects reached significance. Scoring recall accuracy according to the strict standard (see Table 1 and Figure 1) revealed a main effect of load, $F(1, 50) = 158.5$, $p < .001$, $d = 2.3$, and a main effect of distraction, $F(1, 50) = 8.45$, $p = .005$, $d = 0.10$. Additionally, there was a significant Load × Distraction interaction such that subjects were significantly less accurate when remembering multiple letters in the presence of distractors, $F(1, 50) = 9.814$, $p = .003$, $d = 1.28$. Neither scoring criteria revealed a significant main effect or interaction with age.

Recognition Task

Accuracy (see Table 1 and Figure 2A). There was a main effect of load, such that all subjects were less accurate when remembering multiple letters, $F(1, 50) = 22.7$, $p < .001$, $d = 0.75$. There was also a significant three-way interaction, Load × Distractor × Age, $F(1, 50) = 11.58$, $p = .001$, $d = 0.57$. When subjects performed the task at high load in the presence of dis-

Table 1
Means and Standard Deviations in Accuracy (Percent Correct)

	Younger subjects				Older subjects			
	Recall		Recognition		Recall		Recognition	
Criteria	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Low load								
No distractors	97	5	98	3	95	5	95	6
Distractors	98	4	97	6	94	4	97	5
High load								
No distractors	70	19	92	7	71	20	91	11
Distractors	70	19	93	8	69	18	88	11

tractors, older adults performed less accurately than did younger adults. There were no other main effects or interaction effects with age. In addition, there was no significant main effect of distraction on accuracy, nor was there a Load × Distraction interaction.

Discriminability (see Table 2). As was found for accuracy, older adults had significantly lower discriminability than did younger adults under conditions of high load in the presence of distractors, $F(1, 50) = 7.134$, $p = .01$, three-way interaction, $d = 0.73$. There was a main effect of load where all subjects had significantly lower discriminability when remembering multiple letters, $F(1, 50) = 21.57$, $p < .001$, $d = 0.64$. Two additional effects were significant when discriminability was examined. There was a significant Load × Distractor interaction, $F(1, 50) = 4.613$, $p = .037$, $d = 0.53$, where all subjects showed a greater effect of load in the presence of distraction. In addition, older subjects showed greater decrement in performance than did younger subjects in the presence of distractors, resulting in an Age × Distraction interaction, $F(1, 50) = 3.988$, $p = .05$, $d = 0.17$. There was no main effect of distraction on discriminability.

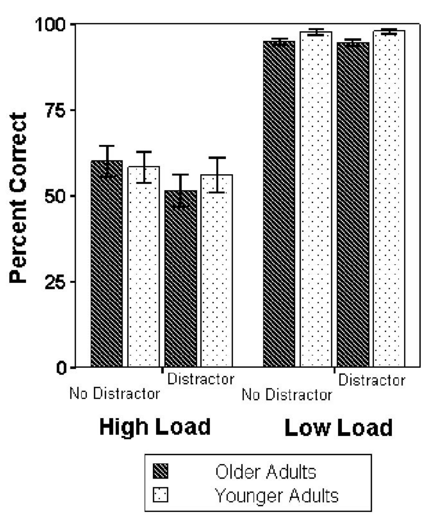

Figure 1. Bar graphs showing accuracy in the recall task for the strict scoring criteria. A Load × Distractor × Age analysis of variance reveals only a main effect of load and distractor, such that there is a decrease in recall accuracy at the higher load and with distractor but no age-related effect. Error bars indicate standard error of the mean.

Response bias. When recognition performance was analyzed with response bias as the dependent variable, no significant main effects or interactions emerged. There was no main effect of age; that is, older adults do not show a greater propensity to give affirmative or negative responses.

Response time (see Table 3 and Figure 2B). All subjects performed more slowly at high load relative to low load, $F(1, 50) = 47.622$, $p < .001$, $d = 0.99$. There were no other main effects or interactions for response time.

Digit Symbol—Coding Test

Older adults scored within the normal range for their age group on the Digit Symbol—Coding test, 48.3 ($SD = 8.3$), and this test was not correlated with any dependent measures from the delay or span tasks. The Digit Symbol—Coding test is used to evaluate motor and perceptual processing speed, which have been revealed to decline with age (Salthouse, 1992; Wielgos & Cunningham, 1999). It was used here to evaluate whether age-related changes in processing speed correlated with the changes in memory measures.

Discussion

In this study, age-related changes in WM performance on delay tasks were evaluated at two memory loads, with and without distraction during the retention period: a low load, consisting of a single letter, and a high load equivalent to each subject's predetermined digit span. The high memory load resulted in a decrease in accuracy on the recall and recognition task in both younger and older adults, consistent with increased difficulty in maintaining multiple items. The presence of distraction during the delay period resulted in a decrease in accuracy only in older subjects, and only when they were maintaining high loads during the recognition task, not the recall task. Thus, the principal aging finding of this study was that older adults compared with younger adults exhibit a significant impairment in accuracy on the delayed-recognition task, but only during high memory load when maintenance was interrupted with a distractor. The same finding of a three-way interaction was observed for discriminability, but for the discriminability measure it was also revealed that there was an Age × Distraction interaction, such that older subjects showed more of a detrimental impact by distraction alone.

It is of interest that the current study revealed an age-related WM deficit only in recognition performance and not for recall. It

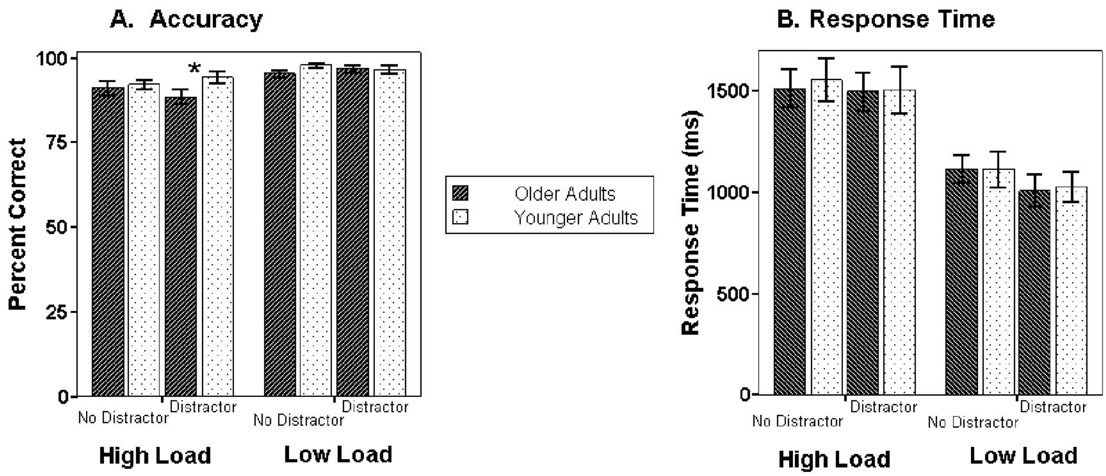

Figure 2. Bar graphs showing accuracy and response time in the recognition task. (A) For accuracy, a Load × Distractor × Age analysis of variance reveals a main effect of load, such that there is a decrease in accuracy at the higher load. Analysis also revealed an Age × Load × Distractor interaction (*$p < .05$), such that there is an age-related decrease in accuracy only at the higher load in the presence of distraction. (B) For response time, a Load × Distractor × Age analysis of variance reveals only a main effect of load, such that there is an increase in response time at the higher load but no age-related effect. Error bars indicate standard error of the mean.

may seem that this finding is disparate with studies that report an age-related recall deficit out of proportion to an impairment in recognition (Craik & McDowd, 1987; Erber, 1974; Gordon & Craik, 1974; Perlmutter, 1979; Shonfield & Robertson, 1966). However, previous studies used a very different experimental design, testing superspan memory only after all material had been presented, a more consolidated form of memory. Thus, the larger recall deficit in older adults has been reported for episodic memory, not WM, and so different processes were being tapped from those assessed in the current study. Studies that have used WM delay tasks similar in design to the task used in our study have documented recognition deficits with aging (Chao & Knight, 1997; Nielsen-Bohlman & Knight, 1995), but they did not also assess recall performance. Our finding of an age-related deficit in recognition, with preserved recall performance in a WM delay task, should lead us to question and further investigate the widely held view that aging preferentially impacts recall.

Although recall performance at high load with distraction was worse in both groups compared with recognition performance, it is unlikely that the lack of an age-related difference during recall was due to a floor effect. This is because recall performance in both age groups was well above what would be expected by chance on a recall task. The absence of an age-related deficit on the delayed recall task, even in the presence of high load and distraction, suggests that normal aging does not significantly affect WM maintenance/rehearsal processes. This leads one to question the mechanistic underpinnings of the selective recognition deficit.

The cognitive processes involved in recognition and recall are clearly different and suggest that normal aging preferentially affects cognitive processes engaged during the response period (Rypma, Berger, Genova, Rebbechi, & D'Esposito, 2005). Whereas recall on this task involved the "reading out" of items represented in WM (Kieras, Meyer, Mueller, & Seymour, 1999), recognition required at least two operations not required by the recall task: comparison of the probe against items represented in WM and a decision about how to interpret and act on the outcome of this comparison (Ratcliff, 1978; Sternberg, 1969). Our findings suggest that these recognition processes are differentially affected by aging and result in a performance deficit when the WM maintenance system is stressed under the presence of high load and

Table 2
Means and Standard Deviations in Discriminability on the Recognition Task

	Younger subjects		Older subjects	
Criteria	*M*	*SD*	*M*	*SD*
Low load				
No distractors	4.76	1.91	4.24	1.11
Distractors	5.07	1.45	4.94	1.25
High load				
No distractors	3.54	1.87	4.16	1.58
Distractors	4.80	1.46	3.11	1.46

Table 3
Means and Standard Deviations in Response Time (in Milliseconds) on the Recognition Task

	Younger subjects		Older subjects	
Criteria	*M*	*SD*	*M*	*SD*
Low load				
No distractors	1,117	450	1,186	426
Distractors	1,031	362	1,179	910
High load				
No distractors	1,525	509	1,505	518
Distractors	1,480	536	1,463	455

distraction. Signal detection methodology revealed that the recognition deficit was not the consequence of a more liberal response bias with aging but an impairment in the ability of older subjects to discriminate between old and new stimuli.

Given reports that a deficit in preventing distracting information from interfering with WM stores is associated with normal aging (Chao & Knight, 1997; Gazzaley et al., 2005; Hasher & Zacks, 1988; West, 1999), it is possible that an age-related deficit in inhibitory control contributes to the recognition performance deficits observed in this study. This inhibitory deficit may result in the older subjects' inadequately ignoring the distracting information presented during the delay period, thus leading to interference with maintaining relevant information (Gazzaley et al., 2005). Additionally, an inhibitory deficit may have expressed itself as proactive interference from previously presented letters (Bowles & Salthouse, 2003; Lustig, May, & Hasher, 2001), which may in turn be accounted for by a deficit in monitoring the source of information in WM (Hedden & Park, 2001; Henkel, Johnson, & De Leonardis, 1998; Mitchell, Raye, Johnson, & Greene, 2006). A source memory deficit would be consistent with our finding that an age-related deficit in the delayed recognition task occurs only under conditions of high load and distraction. It is during these conditions that subjects would have the greatest difficulty in tracking the source of the information, thus resulting in the most proactive interference and the worst recognition performance. Furthermore, this mechanism is consistent with a selective recognition impairment that is induced by confusion in distinguishing probes from previously presented cues during recognition trials, a source of confusion that is not present during the recall trials when the subjects must actively generate a representation of the item.

A search for a parsimonious neural explanation for how an interaction of distraction and memory load results in impaired WM recognition performance suggests the possibility of an age-related deficit in prefrontal cortical function. The prefrontal cortex has a well-established role in the protection of memories held in WM from distraction (Chao & Knight, 1995; Miller, Erickson, & Desimone, 1996; Sakai, Rowe, & Passingham, 2002), and increasing memory load leads to increased activity within the prefrontal cortex during WM recognition tasks (Braver et al., 1997; Druzgal & D'Esposito, 2001, 2003). Furthermore, an event-related potential experiment by Chao and Knight (1997) revealed that distractor-induced recognition accuracy deficits in older subjects was accompanied by reduced attention-related activity over frontal regions (Chao & Knight, 1997), and fMRI studies revealed a reduced ability of older adults to increase prefrontal cortex activity in response to increasing load relative to young adults (Mattay et al., 2006; Rypma, Prabhakaran, Desmond, & Gabrieli, 2001). Lastly, it has recently been revealed that age-related deficits in source monitoring may also be associated with neural changes in the prefrontal cortex (Mitchell et al., 2006). Thus, impairments in prefrontal cortical function, as proposed by the frontal hypothesis of aging (West, 1996, 2000), may represent an underlying etiology for WM performance deficits observed in this study. This does not imply that prefrontal cortical deficits are the only alteration that occurs with aging, rather that it may represent a unifying explanation for the observed interactions in this study.

Another interpretation to consider is that these findings may reflect a generalized slowing of information processing in older adults. This theory of cognitive aging promoted by Salthouse (1996, 2000) proposes that an age-related decline in processing speed results in deficits that cross a broad range of cognitive domains. We suspect that this is unlikely because of the specificity of age-related findings to one behavioral condition and the fact that no difference was observed in response time associated with that condition. Additionally, there was no correlation in the older subjects between recognition performance and a measure of processing speed (i.e., the Digit Symbol—Coding test).

Although not the primary focus of this study, the memory span analysis revealed that older adults exhibit a small but significantly reduced forward letter span compared with that of younger adults (older = 4.82, younger = 5.36). Simple span tests—when assessed with the immediate serial recall of letters, digits, words, or shapes—are thought to be a reflection of a storage system, or purely mnemonic portion of WM, as described by Baddeley (1986). There have been mixed results regarding the presence of age-related span deficits in other studies (Dobbs & Rule, 1989; Light & Anderson, 1985; Wingfield et al., 1988). One possible reason for such a discrepancy is the variability in the type of tasks used and the potential impact of subtle differences in design. For example, Wingfield et al. (1988) found no age-related difference on forward digit span; however, they used a verbal presentation of digits in contrast to the written presentation of letters used in our study. This discrepancy in findings may represent a difference in letter versus digit WM or an age-related difference in reading versus verbal processing efficiency rather than storage capacity. It is also important to acknowledge that the aging process contributes a great deal of performance variability, which can be reflected as differences in studies even with modestly large study populations. To address these confounds, a recent study involving 1,183 subjects whose ages ranged across the entire life span examined WM span with 11 different multimodal digit span tasks involving combinations of different input/output options (e.g., hearing and reading / writing and speaking; Karakas, Yalin, Irak, & Erzengin, 2002). Karakas et al. (2002) found that all measures of forward digit span, when controlled by education level, decreased across the life span after peaking at 18 years of age.

Our results and those of Karakas et al. (2002) suggest a decrease in WM storage capacity with aging. An alternative interpretation of this finding is that it does not represent a decrease in storage capacity per se but rather increased proactive interference in aging, as was hypothesized as one of the potential etiologies of the delayed recognition deficit. When reading span was tested in a manner to minimize proactive interference, span in older individuals increased (Lustig et al., 2001; May, Hasher, & Kane, 1999). Subjects in the present study performed a forward letter span task with items repeated across trials, which generates increasing proactive interference with each subsequent trial secondary to the presentation of items on the multiple preceding tests (May et al., 1999). Thus, differences in span may correspond to differences in the ability to suppress interference from competing items from previous trials and therefore may be a reflection of inhibitory deficits in aging.

In summary, this study revealed age-related impairments in WM recognition performance only for the combination of high memory load and distraction. These results suggest that recognition processes are differentially vulnerable to aging effects and result in a performance deficit when WM maintenance systems are taxed by the presence of high load and distraction. It is important to note that the older subjects in this study were well educated, healthy, and high performing, emphasizing the significance of these findings as features of normal aging. This study has generated several testable hypotheses of the neural mechanisms underlying cognitive aging.

References

Alain, C., & Woods, D. L. (1999). Age-related changes in processing auditory stimuli during visual attention: Evidence for deficits in inhibitory control and sensory memory. *Psychology and Aging, 14,* 507–519.

Anders, T. R., Fozard, J. L., & Lillyquist, T. D. (1972). Effects of age upon retrieval from short-term memory. *Developmental Psychology, 6,* 214–217.

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

Beck, A. T. (1978). *The Beck Depression Inventory.* New York: Psychological Corporation.

Belleville, S., Peretz, I., & Malenfant, D. (1996). Examination of the working memory components in normal aging and in dementia of the Alzheimer type. *Neuropsychologia, 34,* 195–207.

Boaz, T. L., & Denney, D. R. (1993). Speed of scanning in primary memory in persons with dementia of the Alzheimer type. *Psychology and Aging, 8,* 294–300.

Bowles, R. P., & Salthouse, T. A. (2003). Assessing the age-related effects of proactive interference on working memory tasks using the Rasch model. *Psychology and Aging, 18,* 608–615.

Braver, T. S., Cohen, J. D., Nystrom, L. E., Jonides, J., Smith, E. E., & Noll, D. C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *NeuroImage, 5,* 49–62.

Byrd, M. (1986). The effects of previously acquired knowledge on memory for textual information. *International Journal of Aging & Human Development, 24,* 231–240.

Chao, L. L., & Knight, R. T. (1995). Human prefrontal lesions increase distractibility to irrelevant sensory inputs. *NeuroReport, 6,* 1605–1610.

Chao, L. L., & Knight, R. T. (1997). Prefrontal deficits in attention and inhibitory control with aging. *Cerebral Cortex, 7,* 63–69.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Coltheart, M. (1981). The MRC Psycholinguistic Database. *Quarterly Journal of Experimental Psychology, 33A,* 497–505.

Craik, F. I., & McDowd, J. M. (1987). Age differences in recall and recognition. *Journal of Experimental Psychology, 13,* 474–479.

Craik, F. I., & Rabinowitz, J. C. (1985). The effects of presentation rate and encoding task on age-related memory deficits. *Journal of Gerontology, 40,* 309–315.

Crook, T. H., III, & Larrabee, G. J. (1992). Changes in facial recognition memory across the adult life span. *Journal of Gerontology, 47,* P138–141.

Crook, T. H., & West, R. L. (1990). Name recall performance across the adult life-span. *British Journal of Psychology, 81,* 335–349.

Della-Maggiore, V., Sekuler, A. B., Grady, C. L., Bennett, P. J., Sekuler, R., & McIntosh, A. R. (2000). Corticolimbic interactions associated with performance on a short-term memory task are modified by age. *Journal of Neuroscience, 20,* 8410–8416.

D'Esposito, M., & Postle, B. R. (1999). The dependence of span and delayed-response performance on prefrontal cortex. *Neuropsychologia, 37,* 1303–1315.

Dobbs, A. R., & Rule, B. G. (1989). Adult age differences in working memory. *Psychology and Aging, 4,* 500–503.

Druzgal, T. J., & D'Esposito, M. (2001). Activity in fusiform face area modulated as a function of working memory load. *Brain Research: Cognitive Brain Research, 10,* 355–364.

Druzgal, T. J., & D'Esposito, M. (2003). Dissecting contributions of prefrontal cortex and fusiform face area to face working memory. *Journal of Cognitive Neuroscience, 15,* 771–784.

Erber, J. T. (1974). Age differences in recognition memory. *Journal of Gerontology, 29,* 177–181.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12,* 189–198.

Foos, P. W., & Wright, L. (1992). Adult age differences in the storage of information in working memory. *Experimental Aging Research, 18*(1–2), 51–57.

Gazzaley, A., Cooney, J. W., Rissman, J., & D'Esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature Neuroscience, 8,* 1298–1300.

Gordon, S. K., & Craik, W. C. (1974). Application of signal detection theory to prose recall and recognition in elderly and young adults. *Journal of Gerontology, 29,* 64–72.

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, pp. 193–225). New York: Academic Press.

Hedden, T., & Park, D. (2001). Aging and interference in verbal working memory. *Psychology and Aging, 16,* 666–681.

Henkel, L. A., Johnson, M. K., & De Leonardis, D. M. (1998). Aging and source monitoring: Cognitive processes and neuropsychological correlates. *Journal of Experimental Psychology: General, 127,* 251–268.

Karakas, S., Yalin, A., Irak, M., & Erzengin, O. U. (2002). Digit span changes from puberty to old age under different levels of education. *Developmental Neuropsychology, 22,* 423–453.

Kieras, D., Meyer, D., Mueller, S., & Seymour, T. (1999). *Insights into working memory from the perspective of the epic architecture for modeling skilled perceptual-motor and cognitive human performance.* Cambridge, United Kingdom: Cambridge University Press.

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

Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *Journal of Experimental Psychology: General, 130,* 199–207.

Mattay, V. S., Fera, F., Tessitore, A., Hariri, A. R., Berman, K. F., Das, S., et al. (2006). Neurophysiological correlates of age-related changes in working memory capacity. *Neuroscience Letters, 392*(1–2), 32–37.

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

Miller, E. K., Erickson, C. A., & Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *Journal of Neuroscience, 16,* 5154–5167.

Mitchell, K. J., Raye, C. L., Johnson, M. K., & Greene, E. J. (2006). An fMRI investigation of short-term source memory in young and older adults. *NeuroImage, 30,* 627–633.

Nielsen-Bohlman, L., & Knight, R. T. (1995). Prefrontal alterations during memory processing in aging. *Cerebral Cortex, 5,* 541–549.

Perlmutter, M. (1979). Age differences in adults' free recall, cued recall and recognition. *Journal of Gerontology, 34,* 533–539.

Ratcliff, G. (1978). Spatial thought, mental rotation and the right cerebral hemisphere. *Neuropsychologia, 17,* 49–54.

Rypma, B., Berger, J. S., Genova, H. M., Rebbechi, D., & D'Esposito, M. (2005). Dissociating age-related changes in cognitive strategy and neural efficiency using event-related fMRI. *Cortex, 41,* 582–594.

Rypma, B., Prabhakaran, V., Desmond, J. E., & Gabrieli, J. D. (2001). Age differences in prefrontal cortical activity in working memory. *Psychology and Aging, 16,* 371–384.

Sakai, K., Rowe, J. B., & Passingham, R. E. (2002). Active maintenance in prefrontal area 46 creates distractor-resistant memory. *Nature Neuroscience, 5,* 479–484.

Salthouse, T. A. (1992). What do adult age differences in the Digit Symbol Substitution Test reflect? *Journal of Gerontology, 47,* P121–128.

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

Salthouse, T. A. (2000). Aging and measures of processing speed. *Biological Psychology, 54*(1–3), 35–54.

Salthouse, T. A., Babcock, R. L., & Shaw, R. J. (1991). Effects of adult age on structural and operational capacities in working memory. *Psychology and Aging, 6,* 118–127.

Shonfield, D., & Robertson, B. A. (1966). Memory storage and aging. *Canadian Journal of Psychology, 20,* 228–236.

Sternberg, S. (1969). Memory-scanning: Mental processes revealed by reaction-time experiments. *American Scientist, 57,* 421–457.

Sweeney, J. A., Rosano, C., Berman, R. A., & Luna, B. (2001). Inhibitory control of attention declines more than working memory during normal aging. *Neurobiology of Aging,* 22, 39–47.

Wechsler, D. (1997). The Wechsler Adult Intelligence Scale—Third Edition. San Antonio, TX: Psychological Corporation.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120,* 272–292.

West, R. (1999). Visual distraction, working memory, and aging. *Memory & Cognition, 27,* 1064–1072.

West, R. (2000). In defense of the frontal lobe hypothesis of cognitive aging. *Journal of the International Neuropsychological Society, 6,* 727–729; discussion, 730.

Wielgos, C. M., & Cunningham, W. R. (1999). Age-related slowing on the Digit Symbol task: Longitudinal and cross-sectional analyses. *Experimental Aging Research, 25,* 109–120.

Wingfield, A., Stine, E. A., Lahar, C. J., & Aberdeen, J. S. (1988). Does the capacity of working memory change with age? *Experimental Aging Research, 14*(2–3), 103–107.

Received April 17, 2006
Revision received April 18, 2007
Accepted April 23, 2007 ■