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Age Differences in Updating Working Memory: Evidence from the Delayed-Matching-To-Sample Test*

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ABSTRACT

The Delayed Matching-to-Sample (DMTS) Test was used in four experiments to test the hypothesis that older adults are less able than young to update the contents of working memory. Large age differences in working memory were found whenever there was a delay between presentation and test, and they did not vary as a function of delay length. Increasing the intertrial interval (ITI) reduced interference from the previous trial, but benefited old and young equally. In addition, although age differences in perceptual processing speed were correlated with reduced working memory, incomplete perception of the stimuli could not account for the findings. Together these results demonstrate age differences in updating working memory and the usefulness of the DMTS task to test hypotheses about the nature of these differences. Final discussion centers on the implications of these findings for the frontal lobe hypothesis of aging

Age-related declines in working memory have been the object of study for several decades and remain a topic of continued interest. Although it is well established that older adults perform more poorly than younger adults on tests of working memory (e.g., Salthouse, 1990), it has proven difficult to identify the underlying cognitive changes (Light, 1991; Verhaeghen, Marcoen, & Goossens, 1993). The experiments reported here take as their starting point the hypothesis that working memory declines result from changes in the ability to update working memory with currently relevant information and to maintain that information across delay intervals in the absence of rehearsal. This hypothesis, which we will refer to as the *updating hypothesis*, further posits that updating involves three elementary activation processes, of which one or more may be affected by aging. These include the initial activation of new information in working memory, maintenance of activation in the face of distraction, and suppression of activation of irrelevant information. The updating hypothesis draws heavily on previous research that emphasizes the role of low-level processes in explaining declines in complex cognitive functions and on theories that stress the importance of attentional mechanisms in cognitive aging.

Motivation for the focus on elementary processes comes in part from work showing that age differences in many cognitive domains can often be accounted for by declines in low-level processes, such as speed of perception or efficiency of inhibitory function. For instance, it has been demonstrated repeatedly that the effects of age on higher level tasks involving problem solving, reasoning, and working memory are greatly reduced if one controls statistically for

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performance on simple, speeded perceptual tasks (Salthouse, 1996). Furthermore, inefficient inhibition of irrelevant information appears to explain age differences on some tests of selective attention (Hasher & Zacks, 1988). Results such as these lend credence to the notion that the locus of age differences in working memory is at the level of basic cognitive processes.

More specific support for the importance of elementary cognitive processes to age differences in working memory comes from evidence that age differences are often similar in magnitude regardless of the complexity of the task. Consider, for example, tests of working memory span. Both a comprehensive meta-analysis (Verhaeghen et al., 1993) and a recent large-scale study (Gregoire & Van der Linden, 1997) have demonstrated significant and equivalent age differences in forwards and backwards digit span, although only the latter requires reorganization of stimuli. Similarly, age effects are the same size for simple word span tests as for complex reading span tasks that require simultaneous storage and processing (Verhaeghen et al., 1993). This pattern has been observed in other types of working memory studies as well. Age differences may remain stable with increases in processing demands (e.g., Babcock & Salthouse, 1990; Belleville, Rouleau, & Caza, 1998) and dual task paradigms frequently show no increases in age differences under divided as compared to full attention conditions (e.g., Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986; Foos, 1989; Morris, Gick, & Craik, 1988; Somberg & Salthouse, 1982). Taken together, these findings suggest that age differences in working memory result primarily from declines in cognitive processes that are present even in simple working memory tasks. This line of reasoning led to our formulation of the updating hypothesis, with its emphasis on elementary components of working memory.

More specifically, we focused on three elementary processes that are included in most theories of working memory (Anderson, Reder, & Lebiere, 1996; Baddeley & Hitch, 1994; Engle, Tuholski, Laughlin, & Conway, 1999): initial activation, maintenance of information, and suppression of irrelevant information. We defined *activation* as the creation of a representation in working memory for information that has been independently processed by perceptual mechanisms. *Maintenance* is characterized as a process that preserves above-baseline activation of information in working memory over time and in the face of distracting information. *Suppression* consists of the inhibition of irrelevant activation. The updating hypothesis treats these three components as independent aspects of working memory that can be separated experimentally and may be affected to different degrees by normal aging.

Testing the Updating Hypothesis: The Delayed Matching-to-Sample (DMTS) Task

In order to test the updating hypothesis, we developed a simple task in which parameters could be systematically manipulated. We modified the Delayed Matching-to-Sample (DMTS) task for this purpose.

The DMTS task is a working memory test that was first used by neurobiologists studying animal models of memory (see Fuster, 1989, for a review). On each trial of the original version, participants were required to remember the identity of a single object over an unfilled delay period. In our version of the task, three stimuli are presented on each trial, and the study phase is followed by a distraction-filled delay interval. On each trial, the contents of working memory must be updated so that information needed to perform the memory test will be available after the stimuli have been removed from sight and following a distraction task.

The modified DMTS task has multiple requirements. First, both activation of new information and suppression of information from previous trials are necessary. In addition, once relevant information is present in working memory, activation must be maintained without overt rehearsal. Furthermore, our version of the task makes few demands on recognition memory because it draws from the same small set of stimuli on all trials. It differs from versions that use unique stimuli on each trial, where accurate performance depends primarily on the ability to recognize the stimuli as familiar (Alvarez, Zola-Morgan, & Squire, 1995; Colombo & Gross, 1994; Wilson, Riches, & Brown, 1990). With repeated stimuli, performance depends on the ability to control activation levels of information available to working memory.

The DMTS task was considered an ideal choice for several reasons. Firstly, the original version is sensitive to aging, as shown in studies with both monkeys and humans (Dean & Bartus, 1988; Oscar-Berman & Bonner, 1985; Rapp & Amaral, 1989). Our modifications to the original task were expected to show particularly robust age effects, because the largest age differences have been found in modifications that utilize a small number of stimuli repeatedly across trials (Rapp & Amaral, 1989), and a delay period filled with a distractor task (Chao & Knight, 1997).

A second reason to utilize the DMTS task is that it provides a convenient vehicle for examining the elementary processes of activation, maintenance, and inhibition. In fact, this conceptualization of the task has been validated through electrophysiological recording from single neurons in monkeys' prefrontal cortex (PFC; Fuster, 1989; Goldman-Rakic, 1987). Of particular interest are findings identifying individual neurons that are selectively involved in either the activation of information or its maintenance across a delay.[1] Inhibitory mechanisms are also believed to exist in the same region of the brain, although they have not been as clearly localized (Fuster, 1989).

Although previous studies of age differences have not examined these components of the DMTS individually, there are preliminary indications from a similar task, the Brown-Peterson task (Brown, 1958; Peterson & Peterson, 1959), that they play a role in age differences on this type of task. Although the literature on the Brown-Peterson task is often summarized as indicating no age differences, in fact there are statistically significant age-related decrements in many of the studies (Elias & Hirasuna, 1976; Fozard & Waugh, 1969; Inman & Parkinson, 1983; Kausler, Wiley, & Lieberwitz, 1992; Lorsbach, 1990; Parkin & Walter, 1991; Parkinson, Inman, & Dannenbaum, Experiment 1, 1985; Ryan & Butters, 1980; Schonfield, Davidson, & Jones, 1983; but see Dobbs & Rule, 1989; Keevil-Rogers & Schnore, 1969; Kriauciunas, 1968; Mistler-Lachman, 1977; Parkinson et al., Experiment 2, 1985; Puckett & Lawson, 1989; Puckett & Stockburger, 1988; Talland, 1967). Furthermore, several studies have shown that equating performance of young and old under no-delay conditions by manipulating encoding conditions can eliminate age differences (Parkinson et al., 1985; Puckett & Lawson, 1989; Puckett & Stockburger, 1988). These findings suggest that age differences under delay conditions may be the result of decreased entry of information into working memory. There are also data suggesting that older adults lose information more quickly during the delay interval, although these results are quite mixed (Inman & Parkinson, 1983; Parkin & Walter, 1991; Ryan & Butters, 1980). Evidence concerning reduced suppression of irrelevant information is inconsistent as well, but some studies indicate that older adults show a greater buildup of proactive interference across trials (Fozard & Waugh, 1969; Keevil-Rogers & Schnore, 1969; Mistler-Lachman, 1977; Schonfield et al., 1983).

A final reason for using the DMTS task is that it offers the possibility of linking the neurobiological and cognitive literatures on age differences in working memory. Animal studies have linked working memory to PFC (Fuster, 1989; Goldman-Rakic, 1987), and neuroimaging studies of humans have produced similar findings, using DMTS-like tasks (see Smith & Jonides, 1999, for a review), as well as other types of working memory tests (Cabeza & Nyberg, 2000). Furthermore, a prominent hypothesis suggests that age-related cognitive declines result in large part from changes in PFC (see West, 1996, for a review). This is supported by both neuroanatomical (Raz, Gunning-Dixon, Head, Dupuis, & Acker, 1998; Raz et al., 1997) and neuropsychological studies (Brady, McGlinchey-Berroth, & Balota, 1999; Whelihan & Lesher, 1985). Taken together, these lines of evidence suggest that changes in PFC functioning underlie age differences in working memory. Thus, studying age differences on the DMTS task may provide an additional test of the frontal lobe hypothesis of aging.

Overview of Current Experiments

The current experiments build on previous work with the DMTS task. The overarching goal was

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[1] Neurons involved in response preparation during similar types of tasks have also been identified (Fuster, 1989), but are of less relevance here.

to create a measure of working memory that could be used to test the updating hypothesis. The aim of the first experiment was to test our version of the DMTS task for sensitivity to age differences. It was also important to ascertain that working memory decrements on the DMTS task are not tied to a specific type of stimulus. Thus, we tested the generalizability of working memory deficits across three DMTS tasks using colors, spatial locations, and temporal order of a series of colored rectangles as the to-be-remembered stimuli.

An additional goal for the first, and all subsequent experiments, was to be sure that age decrements on the DMTS could not be attributed to failures of perception. In other words, because older adults have reduced perceptual ability (see Schneider & Pichora-Fuller, 2000, for a review), we wished to be sure that poor working memory was not due to inadequate perception. This distinction has not always been made in the past. For example, one previous study of age differences on the DMTS (Oscar-Berman & Bonner, 1985) showed greater age differences with rapid presentation rates (i.e., less than 100 ms). In addition, age differences on the Brown-Peterson task appear most frequent in studies using short display intervals (Elias & Hirasuna, 1976; Inman & Parkinson, 1983; Parkin & Walter, 1991; Parkinson et al., 1985). Thus, in the current experiments, we included a 0-delay (i.e., Matching-To-Sample, or MTS) condition and used presentation times that were expected to produce near-perfect performance when there was no delay. Statistical analyses provided an additional check for the possible influence of incomplete perception of the stimuli.

Once a valid measure of working memory was established in Experiment 1, the next goal was to test the updating hypothesis. Experiments 2-4 focused on age differences in maintenance of information and inhibition of irrelevant information. Experiment 2 tested the hypothesis that age differences are due to a failure to maintain information after it has been activated in working memory. Experiments 3 and 4 tested whether decrements in older adults are due to failures to suppress interference from previous trials. Ancillary measures in Experiment 4 also examined the relationship of the DMTS task to independent measures of working memory and perceptual speed.

EXPERIMENT 1

The goal of the first experiment was to demonstrate the viability of the DMTS test as a model task to study age differences in updating working memory. We also created three versions of the test using different types of stimuli, in order to examine the generalizability of our results. One version tested working memory for colors, one for spatial locations, and one for temporal order. The three tests were developed to be of equivalent difficulty for young adults and then used to test for age differences. It was expected that age differences would be similar across the three types of stimuli. We also predicted that these differences would remain even after controlling for possible age differences in perception, as indexed by performance under MTS conditions. In other words, the decline in working memory was predicted to occur even when perceptual differences were removed from consideration.

METHOD

Participants

Participants included 24 younger adults (17 female and 7 male) and 24 older adults (17 female and 7 male). The younger adults were undergraduate students with a mean age of 20.1 years ($SD = 1.7$). The older adults were healthy volunteers with a mean age of 72.4 years (range $= 65-85, SD = 5.0$). The latter were recruited through notices and advertisements in local newspapers, and reported good or excellent health, with vision that was normal or corrected to normal. None reported histories of neurological disorders, uncontrolled hypertension, diabetes, heart attacks, emphysema, kidney disease, or recent psychiatric illness, nor were they currently taking psychoactive medication or consuming excessive amounts of alcohol. All were screened for dementia with the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) and scored well above the suggested cutoff of 24 ($M = 29.3$; range $= 27-30$). Older adults achieved higher scores than younger adults on the Shipley-Hartford Vocabulary Test (Shipley, 1940; 37.3 vs. 31.1, out of a maximum of 40, $p < .05$). Despite this difference, vocabulary was not correlated with performance on the DMTS test for either age group.

Materials and Design

The three DMTS tests each used a different type of stimulus material. On each trial of the first test, participants studied 3 colored rectangles drawn from a set of 5. On the second test they studied the locations of 3 yellow rectangles placed in a grid of 5 possible locations. On the third test, they had to learn the temporal positions of yellow rectangles in a sequence comprising 3 yellow and 2 gray rectangles. The three tests were designed so that they would be similar in difficulty for younger adults. An additional consideration was that performance of both young and old would be free of ceiling effects under delay conditions. Each test was presented on an IBM-clone computer using Micro Experimental Laboratory software (Schneider, 1988).

All three tests were administered under 0-delay (MTS) and 6-s delay (DMTS) conditions, with one 15-trial block of each. Memory was tested with a forced-choice recognition procedure, in which one of the to-be-remembered stimuli was re-presented along with 2 foils. The latter consisted of the 2 colors, locations, or temporal positions not presented for study. Thus, all 5 possible stimuli appeared on each trial, 3 as the to-be-remembered stimuli and the other 2 as foils on the memory test. In each test, the selection of stimuli at study and test was pseudorandom and counterbalanced across trials.

Pilot testing was conducted with younger adults to determine the amount of study time needed to produce three tests of equal difficulty. Additional adjustments to the procedures were made to ensure that older adults could comprehend the instructions and perform under 0-delay conditions with high levels of accuracy (i.e., greater than 90%). As a result of the preliminary testing, different study times were established for each test. Each set of 3 stimuli was presented for 2000 ms on the color test and 1500 ms for the location test. On the temporal order test, each stimulus was presented for 1000 ms.

Each trial in the color test proceeded as follows: A *get-ready* signal consisting of three +'s was presented for 500 ms, followed by a blank screen for 150 ms. Three colored rectangles, 1.4 × 0.7 cm in size, were then presented in a vertical arrangement in the center of the screen. In the MTS condition, the test followed 500 ms after the removal of the study stimuli. In the DMTS condition, there was a 6-s filled delay before the memory test. In both cases the test consisted of 3 rectangles, one of which matched a studied color from that trial. The stimuli were again positioned vertically on the screen. The location of the correct response varied pseudorandomly but was never the same as at the time of study. Participants were required to point to the correct response, and the experimenter recorded the response. There was no time limit for responding and no feedback was given. An intertrial interval (ITI) of 1000 ms followed each response. At the end of this interval, the next get-ready signal appeared.

The location task was similar except that the stimuli were presented in a vertical grid of 5 locations. On each trial, 3 locations were filled with yellow rectangles 1.4 × 0.7 cm in size. The memory test followed either a blank screen lasting 500 ms (MTS) or the 6-s distraction task (DMTS). For the test, the grid again appeared with 3 filled locations, only one of which was the same as those studied. Participants had to identify and point to that location. The next trial began after an ITI of 1000 ms.

Each trial of the temporal order task began with the *get-ready* message followed by a 250 ms blank screen. Participants next viewed a sequence of 5 screens. Three of these contained a yellow rectangle 1.4 × 0.7 cm in size; the other 2 contained a gray rectangle of the same size. Each screen was displayed for 1000 ms and followed by a blank screen lasting 250 ms. Recognition memory was tested by displaying a yellow rectangle and presenting 3 possible serial positions in verbal format (e.g., Did you see this stimulus first, third, or fourth?), only one of which was correct. Participants responded aloud, and the experimenter recorded their responses.

For all three DMTS tests, the distraction task presented during the 6-s delay was designed to disrupt both visual and verbal rehearsal strategies, without introducing stimuli that could be confused with the critical stimuli. In addition, the difficulty level of the distraction task was equated across participants as much as possible by creating a self-paced task with instructions to respond as quickly as possible without making errors. The task itself consisted of a display containing 16 pairs of letters, arranged in 4 columns with 4 pairs in each. Each pair consisted of 2 identical or 2 different uppercase letters (e.g., GG or PX). Participants were told to start at the upper left and proceed down each column, saying *yes* or *no* for each pair, depending on whether it contained letters that were the same or different. If they completed all 16 pairs, they were to begin again, this time proceeding across each row from left to right. No participant completed the entire task before the end of the delay period. Performance was monitored to be sure that participants were engaged in the task and followed instructions correctly.

Table 1. Experiment 1: Percentage of Errors on the Matching-to-Sample (MTS) and Delayed Matching-to-Sample (DMTS) Tests.

	Test type						
	Color		Location		Temporal Order		
	MTS	DMTS	MTS	DMTS	MTS	DMTS	
Young	4.2	26.4	3.6	23.6	2.5	22.5	*M*
	(6.8)	(13.8)	(6.8)	(10.8)	(5.5)	(13.0)	(*SD*)
Old	5.3	43.2	6.3	39.3	7.4	31.9	*M*
	(6.5)	(14.1)	(9.0)	(16.9)	(9.4)	(17.0)	(*SD*)

Note. Chance performance – 66.7% errors.

Procedure

Participants were tested individually in sessions lasting approximately 60 min. At the beginning of the session, older adults were administered the MMSE (Folstein et al., 1975), and all participants were screened for color blindness with the Dvorine Color Plates (Dvorine, 1953). Participants were then seated approximately 60 cm from the computer monitor and given practice on the distraction task for the DMTS tests. An opportunity to practice the MTS task preceded each type of test as well. Practice trials were organized into blocks of 10 trials. All participants received at least one block of practice trials, and some were given additional practice as needed.

The order of the three tests was counterbalanced across participants, but both MTS and DMTS blocks for each test were administered before proceeding to a different DMTS test. The order of the MTS and DMTS blocks was counterbalanced across participants but kept consistent across the three tests for each participant. One sample and 3 additional practice trials were given before each block of trials. Breaks between blocks and between tests were given as needed. At the end of the session participants completed the Shipley-Hartford Vocabulary Test (Shipley, 1940).

RESULTS

Five older adults were excluded, 4 because of failure to understand the MTS condition even after extended practice, and 1 because of difficulty discriminating the colors on the color task. These 5 did not differ from the remaining 19 older adults in age, vocabulary scores, or health status.

In all analyses the level of significance was set at .05 except when noted otherwise. Note also that we report η^2 as a measure of effect size: $\eta^2 = .01$ represents a small effect, $\eta^2 = .06$ a medium effect, and $\eta^2 = .12$ a large effect (Cohen, 1988).

The percentage of errors was calculated for each participant for each of the three tests (see Table 1).[2] The first analysis tested whether the three tests were of equivalent difficulty for younger adults. Thus, we conducted a 3 (test: color, location, and temporal order) × 2 (delay: MTS vs. DMTS) repeated measures ANOVA with data from just the younger adults. No effects involving test were significant (Fs < 1), although MTS performance was significantly better than DMTS performance, $F(1, 46) = 179.70, \eta^2 = .89$. Thus, the working memory component strongly affected accuracy, but the three tests were similar in difficulty.

The overall strategy for examining age differences involved three steps. First, MTS performance was examined to determine older adults' ability to perceive the stimuli. Second, performance in the DMTS condition was analyzed. The final step reanalyzed DMTS condition perfor-

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[2] Preliminary analyses examined effects of order of administration in each test. The only significant effect was an interaction between administration order and age for the MTS color task, $F(2, 37) = 4.42, \eta^2 = .19$. Older adults showed higher accuracy when this condition was administered later in the session, whereas younger adults had higher accuracy when it was administered first. Data were collapsed across this variable for all subsequent analyses.

mance after controlling for age differences in perception by: (a) experimentally covarying MTS performance, and (b) analyzing only the subset of participants who performed at near-perfect levels in the MTS condition.

To determine whether there were age differences in the MTS condition, an ANOVA was conducted with age as a between-subjects factor and test type (color, location, and temporal order) as a within-subjects factor. This yielded a marginal effect of age, $F(1,41)=3.86, p< .056, \eta^2=.09$. There were no effects involving test type ($Fs < 1$). Planned follow-up tests conducted separately for each test indicated no age differences for the color or location test ($ps > .25$), but a significant advantage for younger adults on the temporal order test, $F(1,41) = 4.51, \eta^2 = .10$. Thus, we were successful in creating an MTS condition with high levels of accuracy, and although small age differences were observed, they were significant only on the temporal order test.

Scores from the DMTS test were analyzed with age as a between-subjects factor and test type as a within-subjects factor. This ANOVA revealed significant effects of age, $F(1,41) = 25.50, \eta^2 = .38$, and test type, $F(2,82) = 3.35$, $\eta^2 = .08$, but no interaction ($F < 1$). Older adults performed more poorly than young. The effect of test resulted from a higher error rate in the color test compared to the temporal order test. Location test performance did not differ from either of the other two tests.

Additional analyses of the DMTS condition were conducted after controlling for the small age differences observed at 0 delay. In the first analysis, we used MTS scores as a covariate. For the color and location tests, age differences remained significant: color, $F(1,36)=14.85, \eta^2 = .27$; location, $F(1,36) = 12.43, \eta^2 = .24$. Different results were obtained for the temporal order test, however; age differences in errors disappeared when controlling for MTS performance ($p < .26$). Identical patterns of age differences were obtained when only those participants who made fewer than 2 errors in the MTS condition were included in the analyses: color test, $n = 19$ younger and 14 older adults; location test, $n = 22$ younger and 14 older adults; temporal order, $n = 21$ younger and 12 older adults. Age differences were observed on the color and location tests, but not on the temporal order test.

DISCUSSION

In sum, there were two major findings of importance in Experiment 1. First, there were large effects of age on working memory for color, spatial location, and temporal order information. The second finding was that for the color and location working memory tests, age effects in working memory were present even when age differences in the MTS condition were controlled. Thus, even when older adults adequately perceived the stimuli, they still had a reduced ability to maintain information during a filled delay interval. At least in these two tests, the differences between younger and older adults under delay conditions appear due to the working memory demands rather than other aspects of the test such as stimulus identification.

Conclusions about temporal order working memory test were less clear. Older adults showed reduced performance regardless of whether testing occurred immediately or after a delay. One possible explanation of this pattern is that encoding of order information requires working memory, even when testing is immediate. Even when there is no delay after presentation of the last stimulus, correct responding involves memory for stimuli viewed across a period of several seconds. Thus, it is possible that older adults performed poorly on the temporal order test under no-delay and delay conditions because both methods of testing involved working memory. Alternatively, learning temporal order is selectively impaired in older adults. This interpretation is consistent with evidence from long-term memory tests that older adults do poorly when required to learn order information, even when they have no difficulty with recognition memory for the items (Dumas & Hartman, 2000; see Moscovitch & Winocur, 1995, for a review).

EXPERIMENT 2

Experiment 1 demonstrated significant age differences on the DMTS tests. This result is consistent with the updating hypothesis, but does not differentiate between the ability to activate information in working memory, maintain activation, and inhibit irrelevant information. Experiment 2 focuses primarily on the second of these. It is possible, for instance, that older adults activate appropriate information in working memory, but lose that information more quickly than younger adults. If this were the case, age differences should become larger as the length of the delay interval increases. In contrast, if age differences were due solely to having less information in working memory and/or failing to suppress inappropriate information, age differences should remain constant regardless of the length of the delay.

Previous research provides little evidence regarding age differences in maintenance of information on the DMTS. Studies using the original version of the task have shown no interactions between age and delay length, but these findings are generally reported in the context of small overall age differences (Oscar-Berman & Bonner, 1985; Oscar-Berman, Hutner, & Bonner, 1992). The Brown-Peterson task offers conflicting data. Of those Brown-Peterson studies that show overall differences between young and old, one shows larger differences at longer delays (Inman & Parkinson, 1983), but two show no change in the effect of age as a function of delay length (Parkin & Walter, 1991; Ryan & Butters, 1980). Unfortunately, multiple differences among the studies preclude resolving the inconsistencies. They varied in stimulus type (words vs. letters), speed of presentation, the length of delays, and type of distraction task. Studies using other types of working memory tests, such as reading span, have not examined this issue. However, long-term memory tests usually show no effects of delay length on age differences (Verhaeghen et al., 1993).

In order to examine rates of forgetting, Experiment 2 compared performance under two different delay intervals, the 6-s delay used in Experiment 1 and a longer delay of 18 s. Only the color test was used. It was predicted that if older adults lose information from working memory more quickly than younger adults, age differences would be larger with the longer delay interval.

METHOD

Participants

Participants included 24 younger adults (16 female and 8 male) and 24 older adults (15 female and 9 male). The young adults had a mean age of 18.7 years (range $= 18-22, SD = 1.2$). Older adults had a mean age of 70.5 years (range $= 60-81, SD = 6.3$) and scored a mean of 29.0 ($SD = 1.1$, range=25–30) on the MMSE. As in Experiment 1, older adults achieved significantly higher scores on the Shipley-Hartford Vocabulary Test (Shipley, 1940; 35.7 vs. 29.6, out of a maximum of $40, p < .05$), but vocabulary level was not significantly correlated with performance on the DMTS test for either age group. No participants from Experiment 1 were included.

Design and Procedure

The experimental design was similar to Experiment 1, with several exceptions. The first was that this experiment utilized only the color task and added a block of trials with an 18-s delay. A second difference was the inclusion of two blocks of the MTS condition instead of one. These were always administered first and last, with the two DMTS conditions administered in between. The order of administration of the two DMTS conditions was counterbalanced across participants. A final difference was that the initial practice for the MTS test was continued until the participant achieved criterion of 2 or fewer errors out of a block of 10 trials.

RESULTS

The mean percentage of errors in the MTS and DMTS conditions for each age group is shown in Table 2. Data analyses examined MTS performance first, then DMTS performance, and the relationship between them. A two-way ANOVA with the two MTS blocks included age as a between-subjects factor and block number (first or last) as a within-subjects factor. It revealed an overall effect of age, $F(1,46) = 15.24, \eta^2 = .25$, an interaction between age and block, $F(1,46) = 4.69, \eta^2 = .09$, but no main effect of block number. Younger adults did better overall. Older adults tended to improve over the course of the session (from 10.8% to 6.9% errors), whereas younger adults showed essentially no change in performance (1.4% and 2.8% errors).

Table 2. Experiment 2: Percentage of Errors on the Matching-to-Sample (MTS) and Delayed Matching-to-Sample (DMTS) Tests.

	MTS	DMTS		
		Delay interval (s)		
		6	18	
Young	2.1	18.6	23.1	*M*
	(2.2)	(14.2)	(17.4)	(*SD*)
Old	8.9	41.9	43.1	*M*
	(8.3)	(12.0)	(16.0)	(*SD*)

Note. Chance performance – 66.7% errors.

A two-way ANOVA on the DMTS data, with age group as a between-subjects factor and length of delay (6 and 18 s) as a within-subjects factor revealed a significant effect of age, $F(1,46) = 36.16, \eta^2 = .44$, indicating better performance for younger adults. There were no effects involving delay length ($Ps > .20$).[3]

This analysis was repeated using the average of the two MTS blocks as a covariate. The only significant effect in this ANCOVA was the effect of age, $F(1,45) = 26.00, \eta^2 = .37$. There were no effects involving the covariate or delay length ($ps > .20$). An additional analysis examining performance for those participants who committed fewer than 2 errors in at least one block of the MTS condition (18 old and 24 young) showed the same pattern of results. Although there was a trend ($p = .10$) towards worse performance with the longer delay, the interaction between age group and delay was not significant.

DISCUSSION

These results are consistent with those of Experiment 1 in showing significant age differences on the DMTS test. Furthermore, extending the length of the delay had no effect on age differences. Older adults made approximately twice as many errors as younger adults at both the 6 and 18 s delays. These findings are similar to those from previous studies of the DMTS paradigm (Oscar-Berman & Bonner, 1985), to some results from the Brown-Peterson task (Parkin & Walter, 1991; Ryan & Butters, 1980), and to studies of long-term memory.

Unlike Experiment 1, older adults in Experiment 2 made more errors than younger adults in the MTS condition, suggesting age differences in perceiving the stimuli. This was not expected, and there is no obvious reason for the difference between experiments; however, as will be noted below, age differences at the MTS were also found in Experiments 3 and 4. The most likely explanation is that age differences in perceptual speed were masked in the first experiment by near-perfect performance levels in the MTS condition. Nevertheless, reduced perceptual ability did not account for the reduced accuracy of older adults under delay conditions. Effect sizes involving age remained large even when controlling for MTS performance.[4]

In sum, the results of Experiment 2 indicate that the locus of age differences is not the ability to maintain information once it is established in working memory. The absence of age differences in rates of forgetting implies that age differences lie in the activation or suppression components of working memory, i.e., either less information enters working memory in older adults or irrelevant information is not inhibited. Experiments 3 and 4 tested the latter possibility.

EXPERIMENT 3

Experiments 3 and 4 tested whether age differences in updating working memory are due to failures to inhibit irrelevant information. Because

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[3] Preliminary analysis of the two DMTS conditions (6 and 18 s) included order of administration as an additional factor. No effects involving order were significant, however, and data were collapsed across this variable in subsequent analyses.

[4] Reanalysis of combined data from identical conditions in Experiments 1 and 2 (i.e., the color test in MTS and 6-s DMTS conditions) confirmed these results. With the larger sample and thus increased statistical power, age differences were significant in the MTS condition, but age differences in the DMTS condition did not disappear after controlling for MTS performance.

the same stimuli are repeated across trials on our version of the DMTS task, there is a high potential for intertrial interference (Fuster, 1989). Therefore, it is important for the test taker to reduce activation of the previous stimuli after each trial is completed in order to prepare for the next trial. If older adults are less able to inhibit information from preceding trials, age differences in working memory may result. The next two experiments test one implication of this hypothesis, namely, that older adults will benefit more than younger adults when the time interval between test trials is increased. When more time transpires between trials, there is more opportunity for inhibiting irrelevant information. Furthermore, inhibition is less important with longer ITIs, because information from the previous trials is less salient and has greater temporal discriminability. In Experiment 3, performance was compared under three ITI conditions: 1, 6, and 12 s. The shortest of these was the same ITI used in Experiment 1.

Previous work with young adults has shown that increasing the ITI boosts performance on the Brown-Peterson task (Wickens & Cammarata, 1986). With regard to age differences, there are mixed results. A study that used the Brown-Peterson task found equal benefits for young and old (Lorsbach, 1990). However, a different pattern was obtained on the reading span task when the ITI was lengthened by inserting unrelated filler tasks between trials (May, Hasher, & Kane, 1999). In one condition older adults benefited more than younger adults; the pattern was reversed in another. The conflicting data in working memory studies of aging are mirrored by studies of attention as well. Older adults are sometimes but not always more susceptible than younger adults to interference. Age differences in interference occur primarily for similar stimuli and when it is difficult to discriminate relevant from irrelevant information (Carlson, Hasher, Connelly, & Zacks, 1995; Hartman, 1995; Plude & Doussard-Roosevelt, 1989).

Although the role of inhibition in age differences on the DMTS has not previously been investigated, Hasher, Zacks, and their colleagues have argued that changes in inhibitory function can account for the reduced performance of older adults on a range of other tasks, including tests of working memory (Hasher & Zacks, 1988). Nevertheless, there is little consensus among researchers. Despite substantial support for the importance of inhibition in explaining age differences (e.g., Hasher, Stoltzfus, Zacks, & Rypma, 1991; McDowd & Oseas-Kreger, 1991), there are conflicting data (e.g., Connelly & Hasher, 1993; Hartman, 1995; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Salthouse & Meinz, 1995; Verhaeghen & DeMeersman, 1998) and disagreement about the interpretation of findings (Burke, 1997; McDowd, 1997). Thus, establishing the role of inhibition on the DMTS may help resolve this debate.

METHOD

Participants

Participants were recruited in the same way as in the previous experiments. They included 24 younger adults (19 female and 5 male) and 24 older adults (15 female and 9 male). Younger adults had a mean age of 20.7 years (range = 18–28, $SD = 2.2$). Older adults had a mean age of 71.5 years (range = 63–78, $SD = 4.2$) and scored a mean of 29.4 on the MMSE (Folstein et al., 1975; range = 27–30, $SD = 0.8$). As in the previous experiments, older adults achieved significantly higher scores on the Shipley-Hartford Vocabulary Test (Shipley, 1940; 37.3 vs. 31.5, out of a maximum of 40, $p < .05$), but vocabulary level was not significantly correlated with performance on the DMTS test for either age group. No participant was included in either of the previous experiments.

Materials and Design

The DMTS test was the same color test used in Experiments 1 and 2. The only difference was the manipulation of ITI length, with lengths of 1, 6, and 12 s. For the two longer ITIs, participants engaged in a simple number reading test between trials in order to maintain attention and motivation. The stimuli for this test consisted of a series of randomly generated 3-digit numbers, presented visually at a rate of one every 2 s, with the message *read* below each number. The last number to appear was marked with the message *last one* followed by a 2-s *get ready* signal. Participants read each number aloud.

Procedure

The procedure was similar to the previous experiments. As in Experiment 2, initial practice on the test

Table 3. Experiment 3: Percentage of Errors on the Matching-to-Sample (MTS) and Delayed Matching-to-Sample (DMTS) Tests.

	Intertrial interval (s)						
	1		6		12		
	MTS	DMTS	MTS	DMTS	MTS	DMTS	
Young	1.1	26.3	0.6	19.0	1.7	14.2	*M*
	(2.5)	(15.3)	(1.9)	(11.8)	(4.5)	(11.3)	(*SD*)
Old	8.9	38.6	5.6	34.0	6.4	28.9	*M*
	(10.9)	(12.8)	(10.5)	(16.9)	(8.5)	(14.7)	(*SD*)

Note. Chance performance – 66.7% errors.

was continued until the participant achieved the criterion of 2 or fewer errors out of a block of 10 trials. Practice was also provided at each ITI length, giving participants an opportunity to become familiar with the number reading task and the overall sequence of events. Each participant completed 6 blocks of trials. There were 2 blocks at each ITI length, one in the MTS and one in the 6-s delay DMTS condition. The order of the ITI lengths was counterbalanced across participants, but both blocks at each ITI length were administered before moving on to another ITI condition. As in the previous experiments, the order of the MTS and DMTS conditions was also counterbalanced across participants. The vocabulary test was administered in the middle of the session rather than at the end, in order to provide a break from the DMTS test.

RESULTS

The mean percentage of errors for both the MTS and DMTS conditions is shown in Table 3.[5] Performance in the MTS condition was examined by means of an ANOVA, with age group as a between-subjects variable and ITI length (short, medium, and long) as a within-subjects variable. It showed a significant effect of age, $F(1,46) = 9.45, \eta^2 = .17$, and a marginal effect of ITI length, $F(2,92) = 2.53, p < .09$. As in Experiment 2, older adults made more errors than young. The absence of a strong effect of ITI length in the MTS condition is not surprising, given the overall high level of performance in this condition.

In the DMTS condition, the ANOVA yielded significant effects of age, $F(1,46) = 17.18$, $\eta^2 = .27$, and ITI length, $F(2,92) = 16.38, \eta^2 = .26$, with no interaction between them ($F < 1$). Older adults made more errors than younger adults, but there was no evidence that they benefited more than younger adults from the ITI manipulation. Nevertheless, the ITI manipulation was effective, and follow-up tests indicated steadily decreasing error rates as the ITI increased in length, with significant differences among all three ITI conditions ($ps < .05$).

In order to check that the advantage for younger adults was not due to the poorer performance of older adults in the MTS condition, additional analyses were conducted separately for each ITI length, covarying performance in the corresponding MTS condition. The results of these ANCOVAs showed significant effects of the covariate on DMTS performance for the short ITI, $F(1,45) = 5.52, \eta^2 = .12$, and medium ITI, $F(1,45) = 8.77$, $\eta^2 = .16$, but not the long ITI. Effects of age remained significant for the medium and long ITI conditions: medium, $F(1,45) = 7.33$, $\eta^2 = .15$; long, $F(1,45) = 10.17$, $\eta^2 = .19$; and approached significance for the short ITI ($p < .09$). Thus, age differences under delayed conditions could not be attributed to worse performance of older adults under no delay. The same pattern of results was obtained when data analysis was restricted to those participants who made

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[5] Preliminary analyses examined effects of order of administration. No effects even approached significance, and data were collapsed across this variable.

fewer than 2 errors in the MTS condition: short ITI, $n = 24$ younger and 15 older adults; medium ITI, $n = 24$ younger and 19 older adults; long ITI, $n = 23$ younger and 19 older adults.

DISCUSSION

As in the previous experiments, the results of Experiment 3 showed significant age differences on the DMTS test. Although age differences also occurred in the MTS condition, they did not account for differences between young and old under delay conditions: Age effects remained even after controlling for errors in the MTS condition. The only exception was in the shortest ITI condition, where controlling for MTS performance left only a trend towards age differences under delay conditions. This appears to be an anomalous finding, however, because it is inconsistent with results for the same condition in Experiments 1 and 2, and as will be seen below, in Experiment 4.

In addition to the overall decrement in performance for older adults, this experiment showed that increasing the time interval between trials improved performance. The effect of ITI length was large, and errors were reduced by approximately one third. Contrary to the prediction, however, the effect of the ITI manipulation was similar for younger and older adults. Age differences at the longest, 12-s ITI were no smaller than at the shortest interval. Thus, there was no evidence that age differences were due to interference from the immediately preceding trial. The next experiment sought to replicate and extend this finding.

EXPERIMENT 4

Experiment 4 extended the range of ITIs used in Experiment 3, to include intervals up to 36 s. One reason for including longer ITIs was to allow for the possibility that older adults need a long period of time to inhibit irrelevant information. A second reason was to reach the point of maximum benefit for each age group. Although performance in Experiment 2 improved with the longer ITIs, it did not reach asymptotic levels of accuracy with the intervals included in that study. It was hoped that an ITI of 36 s would be sufficient to produce optimal performance.

An additional goal of Experiment 4 was to explore the relationship of the DMTS test to a standardized test of working memory and tests of perceptual processing speed. The DMTS test is only one way of measuring working memory, and its relationship to other measures is not known. We were interested in particular in examining its correlation with a measure of working memory that requires manipulation of stored information. We selected the Letter-Number Sequencing Test (Wechsler Memory Scale - III; Wechsler, 1997), a standardized test in which the test taker hears a string of alternating letters and digits and must repeat them back with the numbers first, in ascending sequence, followed by the letters in alphabetical order.

Tests of perceptual speed were included because of evidence for correlations between age differences on other measures of working memory and perceptual speed. A number of studies conducted by Salthouse and his colleagues have reported that the effect of age on working memory tests is greatly reduced after statistically controlling for age differences in perceptual speed (Fristoe, Salthouse, & Woodard, 1997; Salthouse, 1991, 1996). In order to determine whether this relationship also holds for the DMTS test, two widely used tests of perceptual speed were included. These were the Digit Symbol Test from the Wechsler Adult Intelligence Scale (WAIS-R; Wechsler, 1981) and the Pattern and Letter Comparison Test developed by Salthouse (Salthouse, 1993). We planned to examine correlations between the DMTS test and perceptual speed and to test the hypothesis that age differences on the DMTS would be reduced after statistically controlling for speed.

METHOD

Participants

Participants were recruited in the same way as in the previous experiments. They included 48 younger adults (35 female and 13 male) and 48 older adults (31 female and 17 male). Younger adults had a mean age of 18.8 years ($SD = 0.8$). Older adults had a mean age of 71.1 years (range = 62–84, $SD = 5.8$) and scored an average of 29.3 (range = 27–30) on the MMSE (Folstein et al., 1975). Older adults achieved significantly higher scores than younger adults on the Shipley-Hartford Vocabulary Test (Shipley, 1940; 36.9 vs. 30.4, out of a maximum of 40, $p < .05$), but as in the previous experiments, vocabulary level was not significantly correlated with performance on the DMTS test for either age group. No participant was included in any of the previous experiments.

Design

Five ITI intervals were tested: 1, 6, 12, 24, and 36 s. The longest of these were two and three times as long as the longest ITI from Experiment 3. The 1-s ITI was designated as the short ITI, the 6- and 12-s ITIs as medium ITIs, and the 24- and 36-s ITIs as long ITIs.

The MTS condition was administered only with the shortest ITI. In addition, because the large number of conditions would have necessitated an extremely long test session if all of them were administered to each participant, participants in each age group were randomly divided into two subsets. Both subsets took the DMTS test with the short, 1-s ITI, but each subset was given just one of the medium and one of the long ITI conditions. Thus, one subset (subset A) was given the 6- and 36-s ITIs; the other (subset B) was given the 12- and 24-s ITIs. These arrangements resulted in test sessions of approximately equal length for each participant.

Materials

In addition to the DMTS test, the Letter-Number Sequencing Test, Digit Symbol, and Pattern and Letter Comparison Tests were also included in this experiment.

Letter-Number Sequencing Test (Wechsler, 1997).
This test contains 21 items, each consisting of a string of alternating digits and letters read aloud by the examiner at the rate of one per second. The test taker is required to repeat back the numbers first in ascending sequence, followed by the letters in alphabetical order. Items range from 2 to 8 stimuli in length, with 3 trials at each length. The test begins with the shortest sequences, and continues until the test taker misses all trials at a given length. The score consists of the number of correct trials.

Digit Symbol Test (Wechsler, 1981).
This measure of perceptual-motor speed is a paper-and-pencil measure containing 7 rows of empty squares. Each square is paired with a number from 1 to 9. The test taker must determine the appropriate symbol for each empty square, using a key visible at the top of the sheet of paper. The test taker is given 120 s to fill in as many boxes as possible. The score equals the number of correctly filled boxes.

Pattern and Letter Comparison Test (Salthouse, 1993).
This paper-and-pencil test consists of two parts, one with nonverbal and one with verbal stimuli. The nonverbal, Pattern Comparison Test consists of 30 pairs of shapes. Items on the Letter Comparison Test consist of 21 pairs of strings of nonwords. In both cases test takers must write *S* if the two stimuli in a pair are the same, and *D* if they are different. They are given 30 s to work as quickly as possible on each of two pages of each type of stimuli. The score is determined by subtracting the number of incorrect responses from the number correct and dividing by the total number of items.

Procedure

Participants first practiced the MTS test in the short ITI condition, as in previous experiments. They then completed one block of trials in this condition. Three blocks of DMTS trials followed, one in the short condition, one with a medium ITI, and one with a long ITI. The order of these was counterbalanced across participants. The vocabulary test, Letter-Number Sequencing Test, Digit Symbol Test, and the Pattern and Letter Comparison Test were interleaved between blocks of DMTS trials.

RESULTS

The percentage of errors on the MTS and DMTS tests was calculated as in the previous experiments (see Table 4).[6] One older adult was

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[6] Preliminary analyses tested for effects of the order of administration in each delay condition. For the shortest ITI condition, there was a main effect of order, $F(2, 84) = 3.13, \eta^2 = .07$, and a significant interaction between subset and order of administration, $F(2, 84) = 3.22, \eta^2 = .07$. These resulted from an overall increase in performance later in the session, particularly for subset B. For the longer ITI conditions, there were no effects involving order except an interaction between subset and order of administration, $F(2, 84) = 4.63, \eta^2 = .10$, for the longest ITIs. Subset A's performance decreased later in the session, while subset B's improved. No effects involving order interacted with age. Further analyses collapsed across order.

replaced because of difficulty in identifying the colors.

As in the earlier experiments, performance in the MTS condition was analyzed before DMTS condition performance. Data in the MTS condition were subjected to a two-way ANOVA, with age group and subset as between-subjects factors. Results indicated a significantly higher error rate for older adults (8.5% vs. 1.7%), $F(1,92) = 21.63, \eta^2 = .19$; an advantage for subset B, $F(1,92) = 7.58, \eta^2 = .08$; and an interaction between the two, $F(1,92) = 9.81, \eta^2 = .10$. Follow-up tests showed that the interaction was due to poorer performance in older adults assigned to subset B (12.8% vs. 4.2% errors), $F(1,46) = 10.29, \eta^2 = .18$, with no difference in the two subsets of younger adults (1.4% vs. 1.9% errors). The subset effect appears to be the result of chance differences between the subsets of older adults, as participants were randomly assigned to the two subsets.

Prior to analyzing the DMTS conditions, we compared the two medium ITI conditions (6 and 12 s). There was no difference between them ($p > .10$), and thus they were combined to form a single medium ITI condition. The two long ITI (24 and 36 s) conditions also did not differ ($p > .10$) and were combined. In addition, the similarity between the two longest intervals gave us confidence that we had reached asymptotic performance in relation to ITI length. Thus, the main analysis of age differences across short, medium, and long ITIs provided a strong test of the effects of manipulating time between trials.

An ANOVA of the DMTS condition, with age group and subset as between-subjects factors and ITI length (short, medium, and long) as a within-subjects factor, revealed main effects of age, $F(1,92) = 41.05, \eta^2 = .31$, and ITI length, $F(2,184) = 23.71, \eta^2 = .21$, but no effects involving subset, $F < 1$. Older adults did worse than young, all three ITI lengths were significantly different from one another, and there were age differences at each ITI length. No interactions even approached significance. Thus, increasing ITI significantly improved performance, but equally for old and young.

The same results were obtained from an ANCOVA in which performance in the MTS condition was the covariate, except for the additional finding of an effect of subset, $F(1,91) = 4.27$, $\eta^2 = .05$. Performance was better for participants in subset B, but this did not affect the pattern of age differences. When the ANOVA was restricted

Table 4. Experiment 4: Percentage of Errors on the Matching-to-Sample (MTS) and Delayed Matching-to-Sample (DMTS) Tests.

	MTS	DMTS Intertrial interval			
		Short	Medium	Long	
Young	1.7	18.8	13.2	10.1	*M*
	(4.0)	(13.8)	(12.5)	(10.8)	(*SD*)
Subset A	1.4	17.8	11.9	10.3	*M*
	(4.4)	(16.1)	(13.5)	(10.2)	(*SD*)
Subset B	1.9	19.7	14.4	10.0	*M*
	(3.7)	(11.4)	(11.6)	(11.6)	(*SD*)
Old	8.5	34.3	28.6	23.5	*M*
	(10.2)	(15.8)	(14.7)	(14.7)	(*SD*)
Subset A	12.8	30.6	28.3	24.4	*M*
	(10.9)	(15.3)	(15.4)	(15.2)	(*SD*)
Subset B	4.2	38.1	28.9	22.5	*M*
	(7.3)	(15.7)	(14.3)	(14.4)	(*SD*)

Note. Chance performance – 66.7% errors; short intertrial interval (ITI) = 1 s; medium ITI = 6 or 12 s; long ITI = 24 or 36 s.

Table 5. Experiment 4: Standardized Tests of Working Memory and Speed.

	Young	Old	
Letter-Number sequencing	13.0	10.8	*M*
	(2.4)	(2.4)	(*SD*)
Digit Symbol	87.7	62.9	*M*
	(23.2)	(16.1)	(*SD*)
Pattern and Letter Comparison Test[a]			
Patterns	66.5	46.6	*M*
	(9.4)	(10.6)	(*SD*)
Letters	58.2	42.4	*M*
	(11.4)	(9.3)	(*SD*)

[a] These scores represent the percentage of items completed, corrected for errors, i.e., (correct-errors)/total number of items.

to those participants who made fewer than 2 errors in the MTS condition (29 older and 46 younger adults), results matched those from the full ANOVA effects, with main effects of age and ITI length as the only significant findings.

Table 5 presents the results of the Letter-Number Sequencing Test and the perceptual speed tests (Digit Symbol and the Pattern and Letter Comparison Test). Age differences were significant on each of them. *t* tests showed better performance for younger adults on the Letter-Number Sequencing Test, $t(94) = 4.41, \eta^2 = .17$, and the Digit Symbol Test, $t(93) = 6.07, \eta^2 = .28$.[7] A two-way ANOVA (age × type of stimuli) used to examine age differences on the Pattern and Letter Comparison Test yielded significant effects of age, $F(1, 94) = 99.80$, $\eta^2 = .52$, and type of stimuli, $F(1, 94) = 34.17$, $\eta^2 = .27$, and a trend towards an interaction between the two, $p < .06$. Performance was better on the Pattern Comparison Test than on the Letter Comparison Test for both age groups, with slightly greater age differences on the former.

In order to examine the relationship between these tests and the DMTS test, raw scores were converted to z scores. The Pattern and Letter Comparison Test scores were also combined to produce a single score for each participant. A mean DMTS score was calculated for each participant by averaging errors on the three ITI conditions (short, medium, and long).

The Pearson-product correlation between the DMTS Test and Letter-Number Sequencing, calculated with age group partialed out, indicated a significant but moderate correlation ($r = -.29$). A similar analysis of the relationship between the DMTS Test and tests of perceptual speed indicated a significant correlation of $-.22$ with the Pattern and Letter Comparison Test and a nonsignificant correlation with the Digit Symbol Test ($p > .50$). The latter nonsignificant correlation was somewhat surprising but was probably due to the relatively small sample size and the restriction of range in each age group. When age was not partialed out, the expected correlation was obtained ($r = -.31, p < .005$).

In order to determine whether age differences on the DMTS Test were linked to age differences in perceptual speed, two ANCOVAs were conducted on DMTS performance, one with Pattern and Letter Comparison and the other with Digit Symbol as a covariate. These analyses included age and subset as between-subjects variables and ITI condition as a within-subjects variable. The results showed the same pattern as the analyses without these covariates. In both analyses, the effect of age remained significant: Digit Symbol, $F(1, 90) = 26.33, \eta^2 = .23$; and Pattern and Letter Comparison Test, $F(1, 91) = 8.85, \eta^2 = .09$. Nevertheless, the size of the age effects was reduced. For Digit Symbol, η^2 decreased from .31 to .23, and for the Pattern and Letter Comparison Test, it decreased from .31 to .09. The effect of speed was significant only in the Pattern and Letter Comparison Test analysis, $F(1, 91) = 4.78$, $\eta^2 = .05$. In neither case did it interact with any other factor (Fs < 1).

DISCUSSION

The results of Experiment 4 corroborated the conclusions of Experiment 3, and extended the findings to ITI conditions as long as 36 s. Thus,

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[7] Degrees of freedom are equal to 93 instead of 94, because one younger participant did not complete this test.

interference between consecutive trials is a significant factor on the DMTS Test, and increasing the time between trials improves performance. Nevertheless, sensitivity to interference does not explain age differences, as differences between young and old were unaffected by the increase in ITI. Even with an ITI of 36 s, beyond the point at which performance reached maximum benefit from a long ITI, differences between young and old were no smaller than with a very short, 1-s ITI. It seems that age differences are not due to an inability of older adults to avoid interference from preceding trials.[8]

Supplementary analyses supported the validity of the DMTS task as a working memory test sensitive to aging and provided additional data regarding the relationship between perception and working memory on the DMTS. With regard to the former, there was a moderate correlation between the DMTS Test and the Letter-Number Sequencing Test, a standardized test of working memory, which accounted for approximately 10% of the variance in these scores. Although age differences occurred on both tests, they were larger on the DMTS ($\eta^2 = .31$ vs. .17). This is a particularly interesting finding, given that only the Letter-Number Sequencing Test requires simultaneous storage and manipulation of information.

With regard to the role of perception on the DMTS, it was observed first of all that age differences on the DMTS could not be explained by poor perception of the stimuli. Although there were age differences in MTS performance, they were small and differences between young and old on the DMTS test remained significant even after controlling for MTS errors. Second, even though age differences in working memory on the DMTS were not directly due to reduced perception, there was a significant relationship between working memory and perceptual slowing. Thus, the DMTS Test showed moderate correlations with measures of perceptual speed, especially the Pattern and Letter Comparison Test, which accounted for approximately 25% of the variance. In addition, covarying measures of perceptual speed decreased substantially the effect of age on DMTS performance, again with a larger effect for the Pattern and Letter Comparison Test. Thus, we believe that perceptual speed may be important in its effect on the initial encoding of stimuli, but does not directly account for age decrements under delay conditions. This is corroborated by the *post hoc* finding that if one controls for errors in the MTS condition before covarying Pattern and Letter Comparison speed in the analysis of DMTS performance, the perceptual speed covariate is not significant ($p > .25$).

GENERAL DISCUSSION

The goal of the current experiments was to use the DMTS task to test the updating hypothesis as an explanation for age differences in working memory. The DMTS task is a simple one, requiring that relevant information be activated in working memory and then maintained during a delay without rehearsal. We first established the sensitivity of the task to age differences: Substantial performance decrements in older adults were observed in all experiments, regardless of whether the to-be-learned stimuli consisted of colors, spatial locations, or temporal order information. We then focused on two components of the updating hypothesis, the maintenance of information across delay intervals and inhibition of irrelevant information from prior trials.

Maintenance of Information

The presence of a delay had a significant impact on performance, but age differences were equivalent regardless of the length of the delay. Older adults were as able as younger adults to maintain information in the face of distraction once it entered working memory. Thus, age differences appear to occur somewhere before the test taker is engaged in the distracter task. The absence of age differences in maintenance is consistent with some findings with the Brown-Peterson task (Parkin & Walter, 1991; Ryan & Butters,

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[8] Data from Experiments 3 and 4 in the 1-, 6-, and 12-s ITI conditions were also combined and analyzed together in order to increase statistical power. Results supported the conclusion that interference from the immediately preceding trial does not contribute to age differences. In none of the analyses of combined data did age interact with the effect of ITI length.

1980; but see Inman & Parkinson, 1983). Like the DMTS task, the Brown-Peterson task requires the test taker to maintain stimuli in memory in the face of distraction. These findings suggest that older adults have difficulties either activating a reliable representation in working memory or inhibiting irrelevant information.

Inhibition

Experiments 3 and 4 tested for age differences in the inhibition of irrelevant information from previous trials. We experimentally manipulated the ITI, based on the assumption that increasing the time between trials would permit more opportunity to inhibit irrelevant information. Increasing ITI length should also have reduced the necessity of actively inhibiting irrelevant information, because long ITIs would be expected to lead to greater forgetting of the previous trial. If older adults were slower to inhibit, additional time between trials should have helped them compensate. Results, however, indicated that age differences were not affected by this manipulation. When the ITI was lengthened, performance improved equally for young and old. This finding highlighted the role of interference control as an element of working memory, but did not explain age differences on the DMTS Test.

These results are similar to earlier findings with the Brown-Peterson task (Lorsbach, 1990), but inconsistent with the findings of May et al. (1999) involving the reading span task. In the latter study, inserting 90-s unrelated filler tasks between trials had variable effects, depending on the age group and condition. When breaks were administered during an otherwise standard administration of the task, only older adults benefited and age differences were eliminated. In contrast, when the span task was administered beginning with the longest span length and progressing to shorter span lengths, only younger adults showed improvement when filler tasks were added, and age differences increased. The reasons for the inconsistency between conditions in May et al. (1999) and between their study and results in Lorsbach (1990) and the current experiments are not obvious. It is possible that the differences result from the use of cognitively demanding filler tasks in the May et al. (1999) study, although research with younger adults has shown that introducing new stimuli during the ITI has the same effect on release from proactive interference as simple rest does (Wickens & Cammarata, 1986). At any rate, the results of Experiments 2 and 3 are internally consistent, and we can tentatively conclude that intertrial interference is not responsible for age differences on the DMTS. Of course we offer the usual caveat that replication is necessary.

Secondary support for this conclusion comes from a *post hoc* analysis of proactive interference within blocks of trials. Although there were too few observations to conduct such an analysis separately for each experiment, it was possible to use combined data from the 9 delay conditions for the color DMTS tasks in the four experiments. This analysis was done by first calculating the proportion of errors at each of the 15 serial positions and then collapsing the data to form five groupings of three serial positions each (e.g., positions 1-3, 4-6, 7-9, etc.). These were then subjected to an ANOVA, with age as a between-subjects factor and position grouping as a within-subjects factor. This analysis yielded significant effects of age, $F(1, 16) = 18.62$, and position, $F(4, 64) = 4.95$, but no interaction, $F < 1$. Follow-up tests indicated that error rates were lower in the first two groupings, positions 1-6, compared to groupings including positions 7-12. Thus, there was some evidence that proactive interference built up over the first 6 trials in each block, but the pattern was identical for younger and older adults. These give further support for a lack of age differences in inhibition.[9]

Although older adults had no more difficulty inhibiting events from the immediately preceding

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[9] Each experiment provided an additional opportunity to examine the role of interference by testing for the effects of order of administration. If older adults' performance experienced more proactive interference than young, they should have shown a greater decline during the session. The results, however, gave no evidence for this. The performance of older adults did not decline during the course of any experiment. When order of administration did have differential effects on the two age groups (e.g., Experiment 2), the trend was towards improvement in older adults as a function of experience rather than greater proactive interference.

trial than younger adults, it is possible that a different type of inhibition deficit contributed to age differences on the DMTS task. Because the stimuli on each test were drawn from a single category (e.g., colors) and repeated across trials, each stimulus may have come to activate all the others through spreading activation. If this were the case, it would be important to suppress the irrelevant associations when encoding the to-be-remembered stimuli on each trial. Difficulty with this type of inhibitory processing could have produced an age-related reduction in performance across all ITI conditions. Therefore, at present it is premature to draw strong conclusions about age differences in all types of inhibition. Nevertheless, it appears that global difficulties in inhibition do not explain the pattern of findings.

Speed of Perceptual Processing and the Updating Hypothesis

In the current experiments, we took care to ensure that age-related decreases in accuracy after a delay could not be attributed to incomplete identification of the stimuli. Accuracy in the absence of a delay was high, and age effects in the DMTS task remained substantial even after statistically controlling for MTS performance, with η^2 ranging from .14 to .36. (The only exception was the temporal order test in Experiment 1, where age differences disappeared when controlling for MTS performance.) Analyses that restricted the sample to individuals who performed at near-perfect levels of accuracy in the MTS condition showed the same pattern.

Although inadequate perception did not contribute to age differences in working memory, nevertheless there was clear evidence of slowed perceptual processing speed. Speed was indexed indirectly by the MTS condition and more directly in Experiment 4 by independent tests of perceptual speed. In both cases, age differences were observed. Although the differences in the MTS condition were small, they were statistically significant in most of the experiments. Younger adults outperformed older adults on the independent tests of speed as well. Furthermore, Experiment 4 showed significant correlations between measures of perceptual speed and DMTS performance, and controlling for speed reduced the age effects in working memory. These findings are also not surprising. They are consistent with previous reports of reduced perceptual ability (Schneider & Pichora-Fuller, 2000), slowed speed of processing (Cerella, 1985; Myerson, Hale, Wagstaff, Poon, & Smith, 1990; Salthouse, 1996), and the work of Salthouse and colleagues showing that statistically controlling for perceptual speed reduces age differences on other tests of working memory (Salthouse, 1996).

Despite the association between perceptual slowing and reduced working memory, age differences in independent measures of speed did not overlap completely with age differences in working memory. The effects of age remained significant even after controlling for perceptual speed. Furthermore, speed measures were more strongly related to initial perception than to working memory performance on the DMTS test. After controlling for MTS performance, speed was no longer a significant factor in working memory. Overall, age differences in speed appeared more closely linked to perceptual processes than to working memory *per se*, although it remains possible that initial activation of information into working memory may be slowed as well.

Status of the Updating Hypothesis and Use of the DMTS as a Model Task

Overall, age differences on the DMTS indicate a decreased ability of older adults to update the contents of working memory with the products of perceptual processing. Nevertheless, the source of age differences has not yet been clearly identified. It appears that reduced maintenance and interference from preceding trials are not significant factors, but the ability to activate new stimuli in working memory was not tested in the current experiments.

If older adults were less able to activate information in working memory, one would expect the observed pattern of age differences - an overall reduction in accuracy regardless of the length of the study-test delay or ITI. This possibility is consistent with results from several studies using the Brown-Peterson task, which showed that when older adults studied fewer stimuli than young, so that performance was equivalent at 0 delay, age differences on the test were eliminated (Parkinson et al., 1985; Puckett & Lawson, 1989; Puckett & Stockburger, 1988). Reduced activation may be due to a number of causes. For instance, it may result from slowing of working memory. This possibility is supported by computer models that have simulated age differences in complex span measures by reducing the speed with which information is propagated (Byrne, 1998). Of course reduced activation may be due to factors other than reduced speed, e.g., a decreased signal to noise ratio or loss of information as it is transmitted from perceptual mechanisms to working memory.

Although current understanding of age differences in working memory is still incomplete, we believe that the DMTS task will prove to be a useful model task. First of all, it is extremely sensitive to age differences. Values of η^2 for main effects of age were large in all experiments (e.g., ranging from .27 to .44, with values of .12 or greater considered large). These effects were much larger, for instance, than the effect of age on the Letter-Number Sequencing Test ($\eta^2 = .17$). The DMTS task also has the advantage of simplicity, and it presents numerous possibilities for manipulating a single aspect of the task. The experiments reported here manipulated the type of stimulus materials, length of delay interval, and length of the ITI. However, further tests of the components of updating may also be implemented. For instance, activation may be examined by manipulating the method of presentation, the amount of time for study, or the type of instructions. Aspects of inhibition not tested in the current experiments can also be investigated, for example by introducing irrelevant information into each trial or varying the number of unique stimuli used in a session. The DMTS task may also be used to test competing hypotheses. For example, a reduction in the capacity for executive control, necessary for manipulating information or task switching, could be examined in the context of this task.

Implications for the Frontal Lobe Hypothesis of Aging

Overall, the results are consistent with the hypothesis that important age differences in cognition stem from changes in the frontal lobes (e.g., West, 1996). Of course consistency of evidence is not direct proof of a hypothesis, and support for the frontal lobe hypothesis is clearly indirect in the current experiments. Furthermore, the DMTS task has demonstrated sensitivity to both frontal and temporal lobe function in animal studies (e.g., Bachevalier & Mishkin, 1986; Mishkin, 1982; Zola-Morgan & Squire, 1985), and in human neuroimaging studies, although prefrontal cortex is consistently activated, other areas of the brain are involved as well (e.g., D'Esposito, Postle, Jonides, & Smith, 1999; Elliott & Dolan, 1999).

Despite the lack of direct evidence for frontal lobe involvement in age differences on the DMTS task, the version of the task used here, and particularly its memory components, probably do depend primarily on the frontal lobes. Two characteristics of the task are suggestive. The first is the use of distraction during the delay period, because posterior brain areas such as inferior temporal cortex are unable to sustain activation during a delay if there are intervening stimuli (Miller, Erickson, & Desimone, 1996). The second is the repeated use of a small set of stimuli across trials. When unique stimuli are presented on every trial, the test is sensitive primarily to temporal lobe function (e.g., Alvarez et al., 1995; Colombo & Gross, 1994; Wilson et al., 1990), whereas DMTS tasks with small numbers of stimuli have shown significant involvement of prefrontal cortex (Rainer, Assad, & Miller, 1998). In fact, manipulating a DMTS task to include repeated stimuli on consecutive trials increases activation in this part of the brain (Jonides, Smith, Mashuetz, Koeppe, & Reuter-Lorenz, 1998; D'Esposito et al., 1999). Consistent with these findings are results from studies of the spatial version of the DMTS task, which typically use a limited number of locations and also show strong involvement of prefrontal cortex (see Smith & Jonides, 1999, for a recent review).

In sum, although the role of the frontal lobes in age differences on the DMTS warrants validation with direct measures of brain function, the current findings provide plausible support for such an interpretation. In doing so, they complement findings of age differences on other tests of PFC function (Mittenberg, Seidenberg, O'Leary, & Di Giulio, 1989; Spencer & Raz, 1995; Whelihan

& Lesher, 1985), and strengthen the hypothesis that working memory is a critical component of the age-related changes on neuropsychological tests of prefrontal function (e.g., Daigneault, Braun, & Whitaker, 1992; Fristoe et al., 1997; Hartman, Bolton, & Sweeny, 2000; Shimamura & Jurica, 1994; West, 1996).

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