THE ROLE OF REDUCED WORKING MEMORY RESOURCES IN THE ASSOCIATIVE DEFICIT OF OLDER ADULTS

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The undersigned, appointed by the dean of the Graduate School, have examined the dissertation entitled

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presented by Yoko Hara,

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and hereby certify that, in their opinion, it is worthy of acceptance.

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ABSTRACT

Previous research indicates that older adults show problems with remembering associations compared to young adults, yet they remember single pieces of information about as well as young adults do (see Naveh-Benjamin, 2000). The purpose of the present study is to investigate whether reduced working memory (WM) resources affect associative memory and whether such a reduction can account for older adults' associative deficit. Three experiments investigated whether we can simulate an associative deficit in young adults by using secondary tasks that increase their WM loads (either via increasing storage or processing demands of the secondary task) during a primary task in which they were required to learn name-face pairs and then remember the names, the faces, and the name-face associations. Results show that reducing both the storage and the processing resources of WM each produced an associative deficit in young adults. However, further increasing the demands of the secondary task for WM processing resources gradually increased the size of the associative deficit, whereas increasing the demands of the secondary task for WM storage resources did not differentially affect associative memory performance. Furthermore, younger adults with low-WM span or low-online processing showed an associative deficit under full attention conditions compared to young adults with high-WM span or high-online processing. High-WM span/processing individuals also showed an associative deficit when the

processing or storage demands on WM increased. In summary, the present studies showed that one possible reason older adults have an associative deficit is a reduction in their WM resources, especially those related to WM processing.

Introduction

Older adults tend to say that they no longer remember people's names or past events as well as they used to and complain about their poor memories. Research supports their claim that memory abilities decline with age (see Old & Naveh-Benjamin, 2008a, and Spencer & Raz, 1995, for a review). However, aging does not equally impair their memory for different types of information. For example, older adults show intact memory for language (e.g., Thornton & Light, 2006; Zacks & Hasher, 2006) and vocabulary (e.g., Salthouse, 2006), and performance on tests of general knowledge actually improves with age (e.g., Ackerman & Rolfhus, 1999; Beier & Ackerman, 2001). These results suggest that older adults' semantic memory (general knowledge and facts) is relatively preserved.

An Associative Deficit in Older Adults

On the other hand, older adults show an age-related decline in episodic memory compared to young adults (see Old & Naveh-Benjamin, 2008b, for a review). For example, older adults are more likely to forget how they spent their birthday two years ago (an episodic memory) but not the date of their birthday (a semantic memory). Chalfonte and Johnson (1996) suggested that older adults' episodic memory impairment occurs because of their inability to bind contextual features of an event together. In their study, both young and older adults studied colored items placed within an array and then took various memory tests. Results showed that although older adults had intact memory for items and colors when tested separately, they showed memory impairments in item-color associations.

Naveh-Benjamin (2000) extended the suggestion of Chalfonte and Johnson and proposed an associative deficit hypothesis (ADH), stating that the reason we observe age differences in episodic memory is that older adults have problems with associating together different components of an episode at encoding and retrieving these associations when needed. To test this hypothesis, Naveh-Benjamin and his colleagues used different types of studied pairs, different types of instructions, and different types of tests to show that older adults' memory for associations is impaired even though they can remember items as well as young adults. In one of these investigations, Naveh-Benjamin, Guez, Kilb, and Reedy (2004) used name-face pairs in order to provide higher ecological validity to the findings. After studying the pairs, young and older adults could remember individual names and faces equally well. However, a relatively large age difference was found in the name-face associative tests, revealing a possible explanation of why older adults complain about remembering the names of recent acquaintances. Other studies using different stimuli also found results to support the ADH, showing that older adults have a binding deficit (e.g., Bastin & Van der Linden, 2006; Castel & Craik, 2003; Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003; Old & Naveh-Benjamin, 2008b).

Older Adults' Associative Deficit and the Reduced Attentional Resources Hypothesis

Previous studies showed that older adults have an associative deficit, but one question is why they have this problem. One possible explanation for older adults' associative deficit is their reduced attentional resources. Craik's (1982, 1983, 1986) reduced resources hypothesis suggests that age-related memory decline is observed because available resources for processing are reduced in older adults compared to young adults. According to this hypothesis, one could predict that if young adults' resources are reduced by a concurrent secondary task, then their memory performance should become similar to that of older adults. This was investigated by Rabinowitz, Craik, and Ackerman (1982, Experiment 2), and their results showed that young adults behaved like older adults in terms of how they relied more on general semantic cues rather than context-specific cues when their attentional resources were reduced by a concurrent digit monitoring task.

In addition to exploring more ecologically valid designs, Naveh-Benjamin et al. (2004) incorporated a divided attention paradigm to investigate whether older adults' reduction in attentional resources can explain the associative deficit found in older adults. Using the same logic as Rabinowitz et al., they hypothesized that if the reason older adults have binding problems is due to their reduced attentional resources, then this deficit should be simulated in young adults under divided attention (DA). To test this hypothesis, young adults simultaneously studied name-face pairs while they responded to a continuous, auditory three-choice reaction time task. While results showed that the DA task during encoding lowered younger adults' performance overall, they were not more impaired in the associative test than the item test, as predicted. In other words, reducing attentional resources did not create an associative deficit in younger adults. Other studies found similar results (e.g., Craik, Luo, & Sakuta, 2010: Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, Guez, & Marom, 2003; Naveh-Benjamin, Guez, & Shulman, 2004; Naveh-Benjamin et al., 2003; Wang, Dew, & Giovanello, 2010).

Working Memory

The above-mentioned studies using DA paradigms suggest that the reason older adults have an associative deficit may not be due to reduced attentional resources. Thus, the present research is intended to explore another explanation for older adults' binding deficit, namely that it is mediated by a reduction in working memory resources. It has been suggested that age-related declines in cognitive abilities are due to a working memory deficit (e.g., Light & Anderson, 1985; Stine & Wingfield, 1990). According to working memory models, working memory (WM) is a limited mental work place where an individual can hold information in a readily available state for a short period of time and manipulate the activated information in order to carry out the current cognitive task (e.g., Baddeley, 1986; Baddeley & Hitch, 1974; Daneman & Carpenter, 1980; see also Miyake & Shah, 1999). It is unlike short-term memory (STM) which concerns only storage. There are two important components to WM, storage and processing. For example, to solve a mental math problem such as 26 + 8, it is necessary to store the numbers in WM and simultaneously process the calculation.

According to the original multi-component model of WM (Baddeley, 1986; Baddeley & Hitch, 1974; Baddeley & Logie 1999), a limited-attention component called the central executive processes and manipulates information and controls other cognitive functions, including directing two slave systems, the phonological loop and the visuo-spatial sketchpad. However, the central executive itself does not maintain information. Instead, the two subsidiary systems temporarily retain material within a specific domain. The phonological loop stores speech-based information, whereas the visuo-spatial sketchpad is a store for visual/spatial information. In addition to these slave systems, Baddeley (2000) later added another system called the episodic buffer, which links the slave systems as well as sends information to and from long-term memory (LTM).

Just as Baddeley outlined the slave systems for storage and the central executive for processing, Salthouse and Mitchell (1989) suggested that WM has both a structural and operational system. The structural component is measured by the number of items that one can remember at any given moment (similar to Baddeley's storage capacity). The operational component is estimated by the number of processing operations that one can carry out while holding the products of past operations (much like Baddeley's processing resources). For example, the structural capacity is like the number of exams that you can carry in your hands, whereas the operational capacity is like how many exams that you can grade in a limited amount of time.

Baddeley's WM model assumes that these components are separate systems, and dual-task paradigms have often been used to test and provide support for the WM model's assumptions. One assumption is that if two tasks compete for the same resources, one should find detrimental performance in the dual-task condition compared to when the two tasks are performed separately. Duff and Logie (2001) conducted studies using a dual-task paradigm to investigate whether increasing the demands for processing would affect storage capacity, and conversely, whether increasing the demands for storage would affect processing capacity. They predicted that if processing and storage share a single resource, then they should expect to find that dual-task performance is lower than single-task performance. Their participants were asked to complete a processing task, a storage task, and a simultaneous task (processing + storage). They found that increasing the demands for memory storage had no negative effect on processing performance, and a more demanding processing task had only a small effect on storage capacity. Another study conducted by Duff and Logie (1999) found similar results. These studies suggest that there are separate, non-overlapping systems for storage and processing, in agreement with Baddeley's multi-component model of WM.

However, there are other WM models which assume that storage and processing components share a limited pool of WM resources (e.g., Cowan, 1995, 2005; Daneman & Carpenter, 1980; Just & Carpenter, 1992). Thus, by manipulating the demand for both processing and memory load, it is predicted that the trade-off between these two components would affect how much information individuals can retain or process. Morey and Cowan (2004) used a dual-task paradigm described earlier to examine whether two concurrent WM tasks (verbal short-term memory task and visual-array task) would compete for common resources. They manipulated the number of digits that participants were asked to repeat aloud while performing the visual array task developed by Luck and Vogel (1997). There were 3 digit load conditions: no load (0 digits), low load (2 digits), and high load (7 digits). In the visual array task, participants needed to judge whether a second array of colored squares was the same as the preceding one. This task requires the storage of color information and the processing needed to compare two arrays of visual information. When the researchers compared visual array performance of the low memory load condition against the no memory load condition, they found no difference between them. On the other hand, they found that the high memory load condition did reduce visual-array performance, supporting the position that the two concurrent tasks competed for the same common resources.

In summary, WM models assume that there are two components in WM, storage and processing, and that WM has limited resources. However, what limits the capacity of WM (whether storage or processing capacity) is debatable. WM might be limited by the amount and duration of activation (Baddeley, 1986), or limited by time and interference in the activation of LTM and the capacity of focus of attention (Cowan, 1996, 2005), by processing speed (Salthouse, 1996), by inhibitory efficiency (Stoltzfus, Hasher, & Zacks, 1996), by individual differences in storage and processing (Just & Carpenter, 1992), or by individual differences in controlled attention and inhibition (Engle, Kane, & Tuholski, 1999). In addition, whether the two components share the limited WM resources or they have separate limited resources is still unclear. To measure the capacity of WM, reading span and operational span have been used, which requires participants to process information while maintaining items in their WM.

Individual Differences in WM Resources

It has been suggested that individuals vary in their amount of WM resources, and manipulating the demand for processing and storage can allow us to measure these individual differences in overall WM capacity. To accomplish this, the reading span task was created by Daneman and Carpenter (1980). In this task, participants read aloud a series of sentences and are also required to remember the last word of each sentence for recall immediately after all sentences have been read. Unlike traditional measures of STM span, which require only memory storage, the reading span task requires that participants process each sentence and simultaneously store each last word. The reading span score is essentially the maximum number of last words that a participant can correctly recall as the number of sentences is incrementally increased. This WM span task has since been modified to create multiple versions (e.g., Kane & Engle, 2000; Turner & Engle, 1989), but the general purpose of measuring the multiple facets of WM remains the same. Although WM span tasks are used widely, it is still not clear whether span tasks measure the trade-off between processing and storage in a single WM resource or measure the separate WM systems which work coordinately.

A growing body of research (e.g., Conway & Engle, 1996; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003; Unsworth, Schrock, & Engle, 2004) has shown individual differences in performance on different cognitive tasks between high WM span individuals who score relatively well on span tasks (e.g., top 25%) and low WM span individuals who score relatively poorly (e.g., bottom 25%). Rosen and Engle (1997) found that high WM span participants could generate more animal names in a given time compared to low WM span participants. Kane and Engle (2000) found similar results using proactive interference to show a dissociation between high and low WM span individuals, as low span individuals experienced more proactive interference compared to high span individuals. Oberauer (2005, Experiment 2) further suggested a possible link between low WM capacity and the binding deficit. He reported that young adults with low WM capacity behaved like older adults in his study.

Age-Related WM Decline in Older Adults and the Reduced WM Resources Hypothesis

WM has limited resources, and previous studies demonstrated a reduced WM span in older adults (e.g., Light & Anderson, 1985; Norman, Kemper, & Kynette, 1992; Stine & Wingfield, 1990). For example, a reduction of WM capacity in older adults was shown in a life-span study conducted by Park et al. (2002). In their study, participants (ages 20 to 80) took four kinds of WM tasks, each designed to measure WM span, along with other types of memory measurements. WM performance for all WM measures linearly declined as a function of participants' age, showing that older adults have a smaller WM capacity than young adults. Other studies using different methods also found lower WM capacity in older adults compared to young adults (e.g., Foos, 1989; Gick, Craik, & Morris, 1988; Naveh-Benjamin, Cowan, Kilb, & Chen, 2007).

It has been suggested that the age-related decline in WM is primarily due to a deficit in the processing component, or efficiency, of WM processing (e.g., Baddeley, 1986; Morris, Craik, & Gick, 1988; Salthouse & Babcock, 1991; Stine & Wingfield, 1987; Whiting and Smith, 1997), and several studies provide evidence for this. Salthouse (1987) showed participants successive frames of line segments, which were taken from a multi-segment figure. After the presentation of the frames, participants were given a comparison figure and asked to decide whether or not it was the same as the integration of the previously seen frames. The number of frames needed to be integrated (processing component) and the amount of line segments in each frame (storage component) were manipulated.

Salthouse found that increasing the number of integrated operations affected older adults' performance more than that of younger adults when the number of lines that participants needed to remember was held constant. Conversely, the magnitude of age differences was not affected by increasing the amount of information per frame when the number of integration operations was held constant. These results suggest that older adults have less WM processing efficiency but not impaired storage. Using similar stimuli, Salthouse and Mitchell (1989) found no or little difference in accuracy between young and older adults when the total number of segments presented in each frame was varied (structural/storage capacity), while a larger age difference was found when participants needed to integrate relevant information presented in the multiple frames (operational/processing capacity). These results, too, suggest that older adults' processing deficit might be the locus of their WM deficit.

In addition, the prefrontal lobe aging hypothesis postulates that age-related deterioration of the prefrontal lobes contributes to older adults' cognitive impairments (e.g., Dempster, 1992; West, 1996). Anderson et al. (2000) reported decreased frontal lobe activation in older adults compared to young adults at encoding (also Cabeza, Kapur, Craik, & McIntosh, 1997; Stebbins et al., 2002). It was also found that older adults performed like right dorsolateral frontal lobe patients on word list learning and subjective organization, although the patients were relatively younger than older adults (Stuss, Craik, Sayer, Franchi, & Alexander, 1996). In addition, previous studies have shown that older adults displayed lower performance on neuropsychological tests which assess the frontal lobes' functioning, such as Wisconsin Card Sorting Task, which requires inhibition and WM (e.g., Kramer, Humphrey, Larish, & Logan, 1994; Parkin & Lawrence, 1994). The prefrontal cortex is thought to mediate executive control processes along with other cognitive functioning and seems to play an important role in WM such as attentional control and maintenance (e.g., Kane & Engle, 2002). Previous studies also show that the lateral prefrontal cortex is linked to WM (e.g., Baldo & Shimamura, 2000; Chao & Knight, 1996), suggesting that older adults have lower WM efficiency compared to younger adults because of their lower prefrontal lobes' functioning.

More importantly, it has been found that older adults show an associative deficit in WM. In a study conducted by Mitchell, Johnson, Raye, Mather, and D'Esposito (2000), both young and older adults were shown objects individually in an array for a short period of time and were immediately tested over only the objects, only the spatial locations, or both objects and their locations. The results revealed no age difference in the object or location trials. However, older adults had lower memory performance for the object-location combination trials than young adults. Similarly, Hartman and Warren (2005) showed a list of drawn objects which were shown one at a time to both young and old, and participants were then asked to take either an item or temporal memory test. For the item memory test, participants were required to identify which objects appeared in the earlier study phase. In addition, they were asked to decide whether a studied object was presented in a particular position for the temporal memory test. The item test requires the WM storage component more than the WM processing component. However, the temporal test requires participants not only to hold but also to process an association between the object and its position in order to bind two pieces of information. The results showed better performance for the young in the temporal test, but no age difference was found for the item memory test. The results also showed an age difference in an associative WM test which required participants to bind two unrelated pictures. Other researchers showed a binding deficit for older adults using a change-detection task, which again is used to measure WM capacity, as well as a continuous recognition task (Chen & Naveh-Benjamin, 2012; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006).

Just as the WM research mirrors long-term memory in showing an age-related binding deficit, it also shows that this deficit does not seem to be caused by older adults having reduced attentional resources but rather reduced WM processing resources. In a study by Brown and Brockmole (2010, Experiment 1), young and older participants studied and remembered colors, shapes or color-shape associations in a WM task while they performed concurrent tasks that included either repeating digits aloud or counting backwards by threes. Their results showed that repeating digits aloud did not impair associative test performance more than tests of shape or color alone, suggesting that reduced attentional resources is not a likely explanation for older adults' associative deficit in WM. Interestingly, these researchers found that the counting backwards task, which requires more WM processing resources compared to the repetition task, impaired memory for color-shape associations more than memory for items. Allen, Hitch, and Baddeley (2009, Experiment 2 & 3) replicated these results and extended the findings to show that a spatial tapping secondary task (which requires storage but not processing) also did not create an impairment for color-shape associations. On the other hand, a counting backwards task disrupted the binding of color and shapes. These results imply that older adults' associative deficit is caused by a reduction in their WM processing.

The results reported by Cherry and Park (1993) further suggest that reduced WM resources are one reason older adults have an associative deficit in LTM. They investigated the relationship between spatial memory and WM capacity. In a spatial memory task, both young and older participants were instructed to remember objects and their locations. Then after a short delay, they were asked to recall where objects were placed. They also completed three types of WM tasks, of which two required both the storage and processing components of WM. The results indicated that older adults showed poorer spatial memory as well as lower WM span compared to young adults. In addition, the results of hierarchical regression revealed that WM resources measured by three different WM tasks accounted for a substantial proportion of age-related variance in long-term spatial memory, suggesting a relationship between older adults' binding deficit in episodic memory and reduced WM resources. In addition, Bender and Raz (2012) found that an age-related reduction in WM was associated with reduced recognition of word pairs stored in LTM.

Present Research

The studies described so far suggest that one reason older adults have an associative deficit might be related to their reduction in WM resources. Salthouse (1991) suggests that the reason older adults show a WM deficit is that their limited WM capacities are exceeded by simultaneously processing and storing information. Following this claim, one reason older adults show the associative deficit could be that older adults expend most of their WM resources storing and processing each *component* for later recognition. Therefore, when they are tested with item tests, their item memory is close to or equivalent to that of young adults. Meanwhile, storing and processing each component leaves less WM storage, WM processing resources, or both, to store and process associations *between* components, leading to their impaired associative memory. The hypothesis underlying the current research is that experimentally reducing the storage or processing components of WM in young adults at encoding using a dual-task paradigm would create an associative deficit in young adults.

In reviewing various DA tasks, it is clear that sometimes a concurrent task creates an associative deficit in younger adults (e.g., Brown & Brockmole, 2010), and sometimes it does not (e.g., Naveh-Benjamin, Guez, Kilb, et al., 2004). One explanation for this discrepancy is the type of concurrent task being used. Continuous reaction time secondary tasks in DA studies often involve more motor, shallow, perceptional, and monitoring types of processing and require more preexisting memory sets stored in LTM to perform a secondary task– e.g., a tracking task in which participants trace a moving target, a choice-reaction time task requiring the identification of high, medium, and low tones, or a visual task in which participants press a corresponding key to indicate where an asterisk was presented. Especially, those DA studies (e.g., Craik et al., 2010: Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, Guez, Kilb, et al., 2004; Naveh-Benjamin, Guez, et al., 2003; Naveh-Benjamin, Hussain, et al., 2003; Wang et al., 2010) which failed to simulate an associative deficit in young adults did not use the DA tasks that required participants to store new information in WM storage or to engage more elaborative and demanding WM processing such as a math operation. Moreover, these studies did not manipulate WM memory loads like some WM dual-task studies do.

However, concurrent tasks in other paradigms manipulate the different components or subsystems of proposed WM models, including WM storage and processing. Some dual-tasks involve storing information for later use (such as holding a number of items in memory) or require more elaborative or demanding WM processing, such as carrying out math operations. In addition, dual-task paradigms sometimes manipulate the memory loads such as WM storage or processing demands. Thus, concurrent tasks that create binding deficits tend to manipulate WM components and subsystems (very similar to the dual-task paradigms), compared to those that equally impair item and associative recognition tests.

In the present study, we used secondary tasks that require more demands of WM storage or WM processing components, and we manipulated the difficulty of the secondary tasks to reduce the amount of WM storage or WM processing resources available to encode the item and associative information. This is in direct contrast to previous studies that failed to simulate an associative deficit in younger adults (e.g., Craik et al., 2010: Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, Guez, Kilb, et al., 2004; Naveh-Benjamin, Guez, et al., 2003; Naveh-Benjamin, Hussain, et al., 2003; Wang et al., 2010), which have used low-level perceptual-motor secondary tasks. Participants in the present study studied a list of name-face pairs, similar to the study conducted by Naveh-Benjamin, Guez, Kilb, et al. (2004), while performing a concurrent task. The dual-task was used to reduce participants' WM resources by manipulating only one of the WM components while the other component was kept constant. In Experiments 1 and 2, we manipulated the storage component (number of items that participants had to hold in their WM) while the processing component of WM was held constant. In Experiment 3, the difficulty of the dual-task was manipulated by the amount of processing WM resources required when WM storage was held constant. To prevent chance-level performance in the primary task, participants were given forced-choice recognition tests (e.g., Naveh-Benjamin, Guez, Kilb, et al., 2004), which have been shown to be easier than the standard yes-no recognition tests (e.g., Naveh-Benjamin, 2000), while still eliciting an associative deficit in older adults.

One purpose of the current research is to investigate the reduced WM resources hypothesis of an associative deficit in older adults by simulating the associative deficit in young adults. We hypothesized that an associative deficit would emerge in younger adults as the demands of WM storage or processing components are increased. A second purpose is to investigate whether young adults with relatively low WM capacity would show an associative deficit similar to older adults. To examine the effect of individual differences on item and associative memory, the automated operational span task (O-span; Unsworth, Heitz, Schrock, & Engle, 2005) was administrated in which participants remember letters for a later recall test while they are solving math problems. Separate measures of storage and processing were obtained from the O-span task. To measure storage, we examined the maximum number of items that could be recalled (i.e., the O-span score); to measure processing, we examined the on-line math performance (i.e., the math accuracy). This allowed us to split the data according to either high/low WM storage or high/low WM processing ability. Based on previous studies, we expected that if reduced WM resources is the reason older adults have an associative deficit, then young adults whose WM storage or WM processing is low should also display an associative deficit even under full attention (FA) conditions. In addition, we predicted that all individuals would show an associative deficit in the dual-task conditions compared to their own FA performance.

To summarize, in three experiments, we investigated whether older adults' associative deficit could be explained by a reduction in WM resources. In Experiments 1 and 2, we manipulated only the storage component of WM, whereas in Experiment 3, only the processing component was manipulated. In all experiments, we also examined item and associative memory performance as a function of WM storage or processing ability in the O-span task. Our intention was to find out, via simulation in younger adults, whether older adults' LTM associative deficit is related to reduced WM storage capacity, WM processing resources, or both.

Experiment 1: Reducing the Storage Component of WM in Young Adults

To investigate whether we could simulate an associative deficit in young adults by reducing the storage component of WM, participants studied a list of name-face pairs while performing a concurrent N-back task (e.g., Dobbs & Rule, 1989; McElree, 2001). Specifically, we used an inclusive N-back task in which participants listened to a sequential stream of numbers and needed to judge whether a given digit was the same as one of the last few numbers presented. In order to manipulate the task's storage demands while maintaining the demands for processing, the N-back instructions varied between searching for a match only with the previous digit (requiring less storage) and searching for a match with any of the last 2 or 3 digits (requiring more storage). In the dual-task conditions, young adults were asked to concurrently perform the N-back task while studying the name-face pairs. After studying the name-face pairs, participants took forced-choice recognition tests that assessed item and associative memory. Based on the findings of previous studies, we predicted worse performance in both item and associative tests in the dual-task conditions compared to FA conditions. Critically, if a reduction in the storage component of WM is the reason older adults show an associative memory deficit, the N-back task should disrupt performance in associative more than in item tests. Thus, we should expect 3 findings with respect to the N-back manipulation: (1) poorer overall performance in dual-tasks conditions, (2) a larger effect of the N-back task on performance in the associative tests than in the item tests, and (3) lower performance in the associative, relative to the item test, with the increasing storage demands of the N-back task.

In addition to the tasks already described, young adults were asked to perform the O-span task in order to measure their WM span size (Unsworth et al., 2005). This was done so that we could be split the younger adults into high- and low-span groups in terms of WM storage. It was expected that low-span young adults under FA condition in the name-face task would mimic the results of the older adults because, like the older adults, their WM storage resources are reduced. Thus, the low-span group should show an associative deficit relative to the high-span group.

Method

Participants

Seventy-six young adults (26 men, 50 women, M_{age}=19.5 years) participated in this study in exchange for course or extra credits toward their psychology classes. All participants were native English speakers between 18 and 23 years old. Two students did not complete the study, and their data were discarded.

Design

The design of this study was 2 (test: item vs. associative) x 4 (N-back task: FA [no dual-task], 1-back, 2-back and 3-back) x 2 (span: high vs. low). Span size was the only between-groups variable.

Materials

Name-face memory task**.** Four name-face study lists were constructed. Each list contained 44 names and 44 faces (see Figure 1). The first two and last two name-face pairs served as buffers to absorb primacy and recency effects. In Experiment 1, each photo was taken from one of four age groups: young adults (ages 18-29), young-middle-aged adults (ages 30-49), older-middle-aged adults (ages 50-69), and older adults (ages 70-94). Half of the faces were males, and the other half were females. In addition, all first and last names presented in the lists were common names in the U.S. and first and last names were randomly combined as full names. Then, these names were randomly assigned to gender appropriate faces. There were four types of forced-choice memory tests that accompanied each study list (see Figure 2). Each forced-choice face test contained 16 studied faces with 16 new faces, and each forced-choice name test contained 16 studied names with 16 new names. Each studied and new face pair was matched for age, gender, and ethnicity; each studied and new name pair was matched for gender. The studied items and new items were counterbalanced such that target faces for some participants were distractor faces for other participants. In each forced-choice face-name associative test, each studied face appeared with two studied names. Thus, each face-name test contained 8 studied faces with 16 names (names were matched for gender). In the forced-choice name-face associative tests, each studied name appeared with two studied faces. Each name-face test contained 8 studied names with 16 faces (faces were matched for gender, age, and ethnicity). The order of the study lists and order of the 4 memory tests were counterbalanced. In addition, the spatial location of the target stimuli was counterbalanced at test such that targets appeared on both the left and right sides of the computer screen equally often. Also, two practice study-test blocks were constructed.

Inclusive N-back task. Participants listened to a sequence of single digits (1-9) over headphones. Each digit was presented every 1.5 seconds. In the 1-back condition, they were instructed to decide whether the current digit was the same or different from the digit presented previously. In the 2-back condition, they were asked to decide whether the current digit was the same or different from any of the last two digits they heard. In the 3-back condition, they decided whether the current digit was the same or different from any of the previous three digits they heard. Participants pressed “v” for “same” responses, and “n” for “different” responses. Half of the correct answers were “same” and half were “different”.

Automated operational span task (O-span). The O-span task was developed by Unsworth et al. (2005) and used in order to measure participants’ WM. In the O-span task, participants saw a math problem on a computer screen. Once they solved this problem, they clicked the computer mouse and moved onto the next screen. Then they saw an answer for the math problem and decided whether the answer provided was true or not by clicking the appropriate box on the screen. Once they clicked one of the choices, they saw a letter to be remembered on the screen displayed for 800 ms. Then the letter was replaced by a new math problem. These steps were repeated until they saw a recall screen. At the recall screen, twelve letters were presented with boxes next to each of them, and participants were asked to recall the letters in order by sequentially clicking boxes corresponding to each letter. Once they finished recalling, the next trial began. For the O-span task, participants were instructed to maintain above 85% accuracy for the math operations at all times.

The experimental trials for the O-span task consisted of 3 blocks of each set size ranging from 3 to 7. There were a total of 75 math operations and 75 letters to be recalled in the experimental trials for the entire task.

Procedure

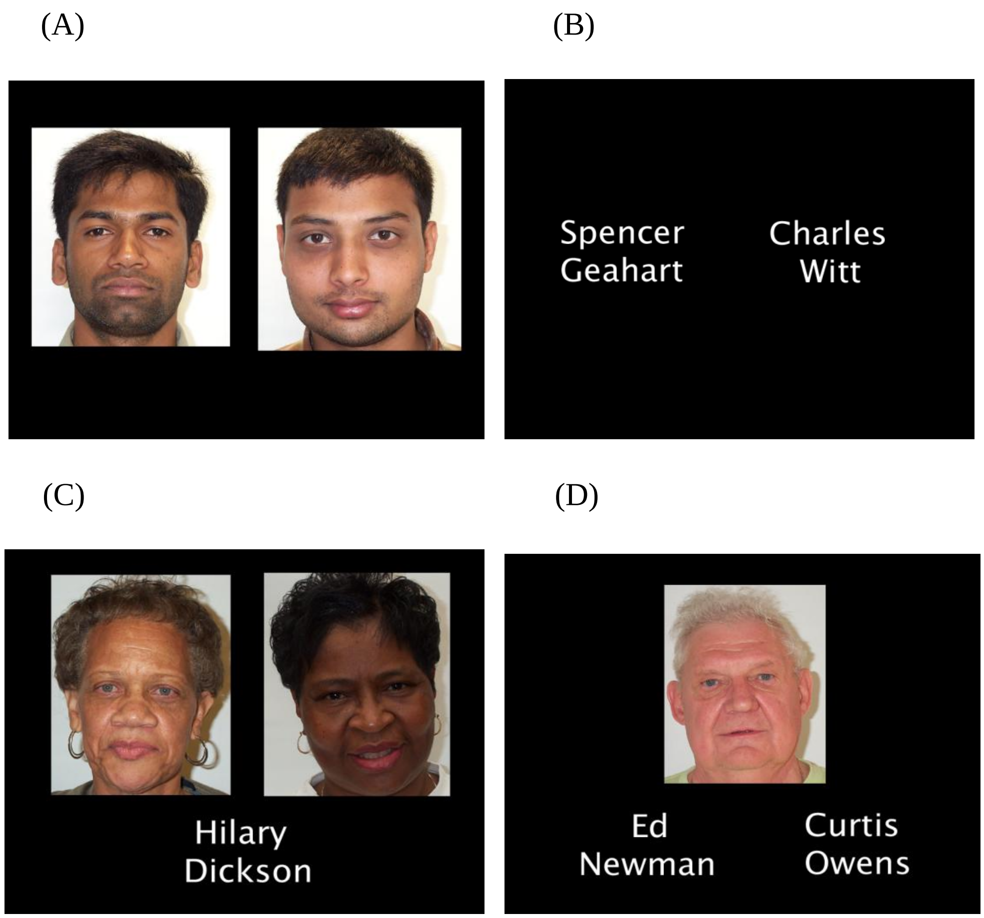
There were 3 practice trials before the first experimental trial. For the first practice set, participants performed each inclusive N-back task (1-back, 2-back, and 3-back, in that order). In the second practice set, participants completed a name-face block in the FA condition. This included the study phase and four different forced-choice memory tests. For the third practice set, they performed one of the dual-task conditions. Specifically, participants were asked to study a list of name-face pairs while performing the 2-back task. Prior to the dual-task condition, they were asked to pay equal attention to each task. After each practice set, participants were asked whether they had any questions.

Each participant completed 4 experimental name-face blocks. Each face appeared against a black background with a name shown in white text (see Figure 1). Each face appeared above the name, and each pair was presented for 6 seconds. Participants were asked to study the names and faces as well as which face appeared with each name. There were four dual-task conditions: FA, 1-back, 2-back, and 3-back. The order of the dual-task conditions was counterbalanced. In the FA condition, participants studied a list of name-face pairs without a concurrent N-back task. In the dual-task conditions, they performed one of the N-back tasks while they were studying the name-face pairs. Each N-back task was performed alone once immediately before it was performed under its respective dual-task condition. This single-task condition served as a baseline, which was performed for the same length as the duration for the study phase (4 minutes and 24 seconds).

Figure 1. Example of a Studied Name-Face Pair.

After each study phase, participants were asked to count backward by 3's from a number provided for a minute. Following this interpolated activity, they completed the four forced-choice tests under FA (see Figure 2). For each forced-choice face test, participants saw two faces presented side by side and their task was to decide which face appeared in the study phase. In the name test, they saw two names side by side and decided which name appeared in the study phase. For the forced-choice face-name associative test, participants saw a studied face with two studied names presented on the bottom of the screen side by side, and they were asked to decide which name appeared with the face. For the forced-choice name-face associative test, they saw two studied faces side by side with one studied name and decided which face appeared with the name. Participants were asked to press the "M" key (relabeled as "R") when recognizing the stimulus appearing to the right and to press the "B" key (relabeled as "L") when recognizing a stimulus on the left. After finishing all 4 experimental name-face blocks, participants took the O-span task.

Figure 2. Examples of a Forced Choice Face Test (A), a Forced Choice Name Test (B), a Forced Choice Name-Face Associative Test (C), and a Forced Choice Face-Name Associative Test (D).

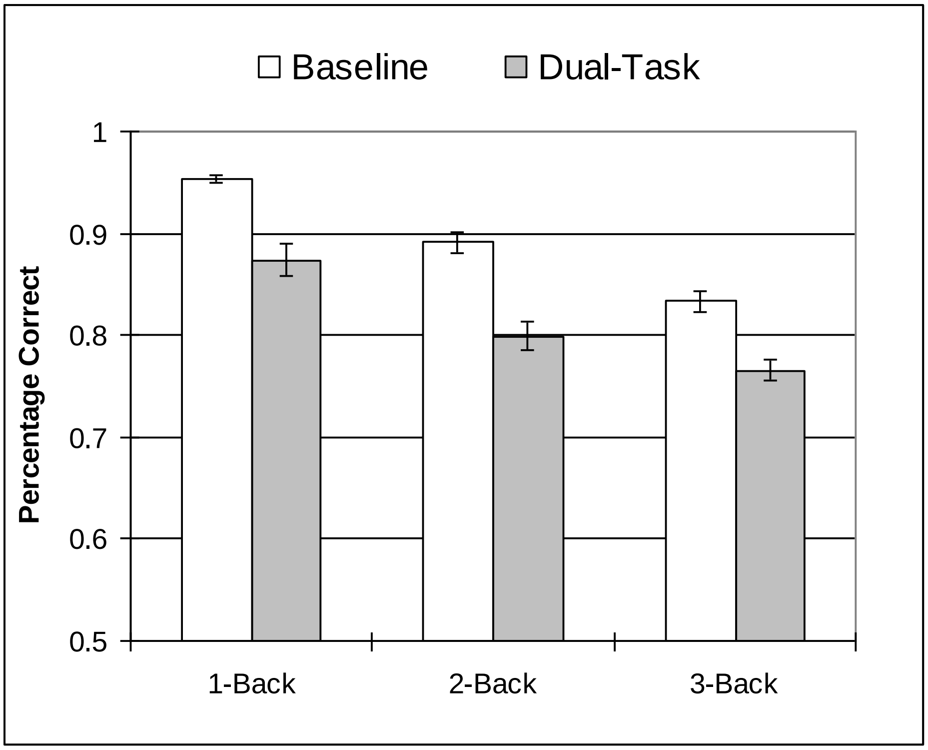


Results

N-back Task Performance

Secondary task performance was measured by the percentage of correct responses for each condition, calculated for each individual (see Appendix A, Table A1, for the means and SD).

Figure 3. Mean N-Back Task Performance (with Standard Error Bars) in Experiment 1.



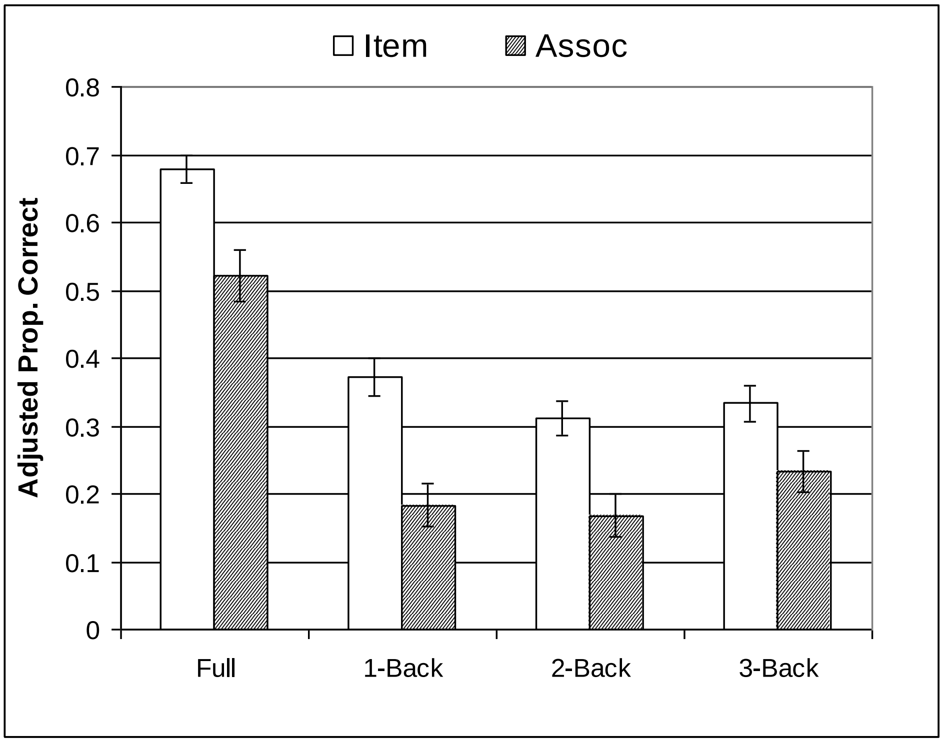
A 2 (dual-task: baseline, dual-task) x 3 (N-back condition: 1-back, 2-back, 3-back) ANOVA was conducted. Performance for baseline conditions (*M*=.89, *SD*=.05) was significantly better than for dual-task conditions (*M*=.81, *SD*=.09), F (1, 73) = 101.10, p<.001, η_p^2=.58 (see Figure 3). In addition, when the three N-back conditions were compared, performance declined as the storage demands of the N-back task increased, F (2, 146) = 50.21, p<.001, η_p^2=.41. Follow-up t-tests indicated that performance for 1-back (*M*=.91, *SD*=.07) was significantly better than 2-back (*M*=.84, *SD*=.10), t (73) = 5.51, p<.001, and 2-back performance was significantly better than 3-back performance (*M*=.80, *SD*=.08), t (73) = 3.92, p<.001. The ANOVA indicated that the interaction of dual-task and N-back condition was not significant, F (2, 146) = 1.35, p>.05, η_p^2=.02.

Memory Performance

Next, the memory performance in the name-face task was examined. Since all tests were forced-choice, the dependent measure was adjusted proportion correct in which chance level performance was 0.0 instead of 0.5 (calculated as (hit-0.5)/0.5). The data were collapsed across the two different forced-choice item tests to provide a measure of item memory and across the two different forced-choice associative tests to provide a measure of associative memory for each condition (see Appendix A, Table A2, for the means and SD).

A 2 (test: item, associative) x 4 (N-back task: FA, 1-back, 2-back, 3-back) ANOVA was performed. The main effect of N-back task was significant, F (3, 219) = 70.03, p<.001, η_p^2=.49 (see Figure 4). Follow-up t-tests indicated that performance in the FA condition (M=.60, SD=.20) was higher compared to the 1-back condition (M=.28, SD=.21), t (73) = 12.6, p<.001, the 2-back condition (M=.24, SD=.19), t (1, 73) = 13.37, p<.001, and the 3-back condition (M=.28, SD=.18), t (73) = 11.50, p<.001. However, there were no significant differences among the dual-task conditions, all ts < 1.6, ps>.05. These findings support our first hypothesis, claiming that adding a concurrent task will impair overall memory performance.

Figure 4. Memory Performance for Items and Associations as a Function of N-Back Condition (with Standard Error Bars) in Experiment 1.



The main effect of test was also significant, F (1, 73) = 53.62, p<.001, η_p^2=.42, indicating that performance in the item tests (M=.42, SD=.13) was significantly higher than performance in the associative tests (M=.28, SD=.17). To investigate our second hypothesis, that the N-back task will impair the associative test more than the item test, we looked for an interaction between test and N-back task. However, the two-way interaction was not significant, F (3, 219) = 1.08, p>.05, η_p^2=.02, indicating that the N-back task equally affected item and associative tests. The lack of an interaction also reflects the fact that the 3-back task did not differentially impair associative over item memory performance more than the 1-back task, which fails to support our third hypothesis.

High-Span vs. Low-Span Participants

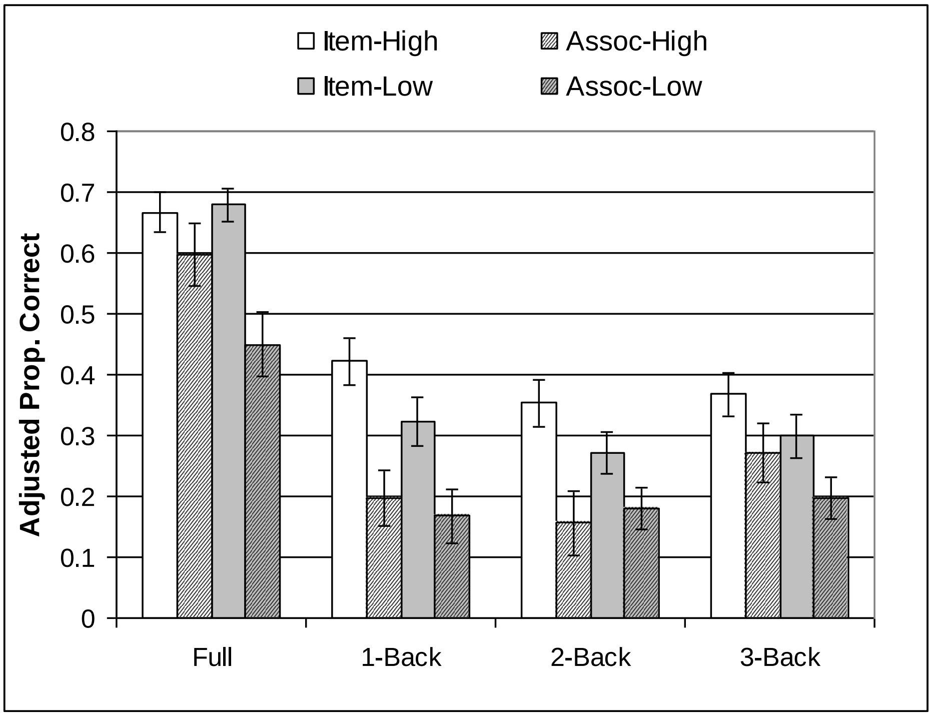
Next, the data were divided into two groups based on participants' memory accuracy on the O-span task (based on only the storage component of WM, i.e., how well they recalled letters in a correct order). Specifically, 36 participants who performed above the median O-span score (44) were deemed "high-spans" (*M*span=55.7, span range: 45-75), and 38 participants who performed below the median were deemed "low-spans" (*M*span=28.1, span range: 9-44[1]). To determine whether high- and low-span individuals were differentially affected by dual-task (see Figure 5), a 2 (test) x 4 (N-back task) x 2 (span) ANOVA was performed.

The three-way interaction among test, N-back task, and O-span was significant, F (3, 216) = 2.95, p=.03, η_p^2=.04. To examine whether low-spans display an associative deficit when compared to high-span individuals, a 2 (test) x 2 (span) ANOVA based only on the FA condition was performed, which produced a significant interaction, F (1, 72) = 4.65, p=.03, η_p^2=.06. Follow-up comparisons revealed that there was a significant difference between item (*M*=.69, *SD*=.15) and associative memory performance (*M*=.45, *SD*=.33) in the low-span group, F (1, 37) = 22.62, p=.001, η_p^2=.38. However, there was no significant difference between the item (*M*=.67, *SD*=.20) and associative test (*M*=.60, *SD*=.31) in the high-span group, F (1, 35) = 1.43, p>.05, η_p^2=.04. These results support the prediction that low-span individuals should show an associative deficit relative to high-span individuals in the FA condition if one reason older adults show an associative deficit is a reduction in their reduced WM storage resources. However, we did not find

[1] Unsworth et al. (2009) found that participants who processed information more successfully remembered items better than those who processed information less successfully. Their results showed that there was no trade-off between processing and storage, meaning that participants do not use a strategy to sacrifice their on-line math performance for better storage performance or vice versa. Thus they suggest that excluding data for participants who scored below 85% on O-span math accuracy is not necessary. Based on their finding, we kept those who scored lower than 85% on O-span math accuracy in our data for further analyses.

significant interactions of test and span in any of the N-back conditions, all *F*s<.25, *p*s>.05, suggesting no differences between the two span groups in the N-back conditions.

Figure 5. Memory Performance for High- vs. Low-O-span Based on the Storage Component of the O-Span Task (with Standard Error Bars) in Experiment 1.



In order to further investigate the relationship between the WM span size and an associative deficit, we computed each participant's associative deficit in the FA condition by calculating the difference between item and associative memory performance. Then, we calculated the correlation between the O-span score and the associative deficit in the FA condition and found a negative relationship between them, r (72) = -.19, p=.05, one tailed. This result indicates that the higher the span size is, the smaller the associative deficit tends to be. Together, these results suggest that one potential reason older adults show an associative deficit is their reduced storage component of WM.

To examine whether high-span and low-span individuals' associative deficits were affected differently by the N-back task, planned interaction comparisons were performed. For high-span individuals, a 2 (test) x 2 (N-back task: FA vs.1-back) ANOVA comparison resulted in a significant interaction, F (1, 35) = 5.20, p=.03, η_p^2=.13, indicating that high-span individuals in the 1-back condition showed an associative deficit compared to their own performance in the FA condition (see Figure 5 and Appendix A, Table A3, for the means and SD). Next, a 2 (test) x 2 (N-back task: FA vs. 2-back) ANOVA comparison revealed a marginally significant interaction, F (1, 35) = 3.54, p=.07, η_p^2=.09. However, we did not find an interaction between span and N-back task when only the FA and 3-back conditions were included, F (1, 35) = .11, p>.07, η_p^2=.00.

On the other hand, a 2 (test) x 2 (N-back task: FA vs. 1-back) for the low-span group did not show a significant interaction, F (1, 37) = 1.57, p>.05, η_p^2=.04. However, there was a significant interaction when the same ANOVA was performed using the FA and 2-back conditions, F (1, 37) = 4.56, p=.04, η_p^2=.11, showing that the item test was more impaired by the N-back task than the associative test – the direct opposite of our predictions. The interaction of span and N-back task was also significant when the FA and 3-back conditions were included, F (1, 37) = 4.38, p=.04, η_p^2=.11, again reflecting a smaller associative deficit in the concurrent task condition. These unexpected results may be due to a floor effect for low-span individuals in the dual-task conditions.

In order to examine whether low-spans are experiencing a floor effect, we excluded participants who scored below .4 on the associative test in the FA condition, leaving 19 participants in the low-span group. Then we re-conducted a 2 (test) x 2 (N-back task: FA vs. 1-back) for the low-span group and found a significant interaction, F (1, 18) = 17.99, p<.001, η_p^2=.50, showing a larger decline in associative memory compared to item memory. Although a two-way interaction of test and dual-task between FA and 2-back was not significant, F (1, 18) = .83, p>.05, η_p^2=.04, a 2 (test) x 2 (N-back task: FA vs. 3-back) was also significant, F (1, 18) = 5.96, p=.03, η_p^2=.25, showing a larger associative deficit in the 3-back condition compared to the FA condition. Thus, these results suggest that one potential reason for the lack of a larger associative deficit in the N-back conditions in the low-span group is their relative low level of performance in the associative test in the FA condition, which did not leave much room for a substantial decline in this test in the N-back conditions.

Discussion

The results of the secondary N-back task performance indicated that manipulating the storage demands of the N-back task made the task more difficult. As the storage demands increased, participants' baseline performance declined. Also, performance declined when they performed the two tasks concurrently compared to their baseline performance.

Before dividing participants into high- and low-span individuals, the results showed no associative deficit in young adults in any one of dual-task conditions. Only the effect of dual-task was observed, indicating that participants showed lower memory performance for all tests in the dual-task conditions compared to the FA condition. This result is consistent with Naveh-Benjamin, Guez, Kilb, et al. (2004), which used a secondary task that was not designed to tap into WM resources. Thus, reducing the storage component of WM did not simulate an associative deficit in young adults. These results indicated that the reason older adults show an associative deficit may not be due to their reduced storage component of WM.

Interestingly, when the data were split into the two span groups, it was found that high-span and low-span individuals behaved differently. For the low-span individuals, associative performance was significantly worse than item performance in the FA condition, but there was no such effect for the high-span individuals. In addition, the negative correlation between the span size and the associative deficit in the FA condition suggests that the larger the WM span is, the smaller the associative deficit is. Thus, these results support our prediction that low-span young adults would behave like older adults in the FA condition, suggesting that reduced WM storage capacity could be one reason older adults show an associative deficit.

Consistent with the predictions, high-span individuals in the 1-back condition showed an associative deficit compared to their own FA condition, and this result partially supports our prediction; however, the remaining patterns are less clear. Although low-span individuals showed an associative deficit in the FA condition, their deficit did not increase in any of the N-back condition. In addition, high-span participants were more affected by the dual task than low-span participants. These results point to two possibilities as to why high-span and low-span individuals performed differently under FA and dual-task conditions. One is that high-span individuals are generally more affected by secondary tasks than low-span individuals. This is in line with previous studies (e.g., Kane & Engle, 2000; Rosen & Engle, 1997).

According to Kane and Engle (2000), low-span adults have less attentional control and cannot inhibit irrelevant information, meaning their attention is already saturated in FA conditions by the primary task and irrelevant distractions. Therefore, their cognitive performance under FA conditions should be lower than that of high-span individuals. Previous studies found that high-span individuals outperformed low-span individuals in a variety of cognitive tasks in which individuals' attention control is required (e.g., Kane & Engle, 2000, 2003; Rosen & Engle, 1997; Unsworth et al., 2004). According to Kane and Engle (2000), adding a concurrent task may not affect low-span individuals as much as it does for high-span individuals because their attention consumed by irrelevant distractions under FA is now used to perform a concurrent task. In comparison, high-span individuals are more affected by a secondary task because the secondary task interferes with their ability to control their attention and inhibition. A second possibility for the differential effect of dual-task on high- and low-span individuals is a floor effect found in the low-span individuals. Low-span young adults showed a smaller associative deficit in the dual-task conditions relative to the FA condition, and it is possible that they could not show a larger associative deficit because their performance in the associative test was already low in the FA condition. This explanation was examined by further analysis that showed that when individuals who scored lower than .4 on the associative test were excluded from the analysis, the low-span group showed an associative deficit in the 1-back condition, similar to the high-span group. Thus, the results suggest that the reason high- and low-span individuals behaved differently under the dual-task conditions was possibly due to a floor effect.

In summary, the associative deficit was only partially accounted for by a reduction in the WM storage component in Experiment 1. We failed to simulate an associative deficit in all young adults by reducing the storage component of WM, though we did observe it in high-span individuals. We also found an associative deficit in low-span individuals compared to high-spans in the FA condition.

Experiment 2: Further Investigation of Reduction of the Storage Component of WM in Young Adults

The overall results of Experiment 1 did not consistently simulate an associative deficit in young adults under the dual-task conditions, and when associative deficits were observed, they did not become larger when the demands of the N-back task increased. One potential reason we did not simulate an associative deficit is that a reduction in WM storage capacity is not the reason older adults have an associative deficit. However, we did observe that low-span individuals display an associative deficit when compared to high-span individuals. In order to reconcile these contrasting results, one might claim that floor effects prevented greater impairments in the associative test. Specifically, participants' memory performance for the associative test was already low (around .20) when they performed the easiest version of the concurrent task (i.e., 1-back). Thus, it is possible that such a low level of performance did not allow enough sensitivity to display an effect of the storage manipulation.

Also, in Experiment 1, participants heard a series of single digits, and they needed to make their response every 1.5 seconds. That is, every 1.5 seconds, the N-back task in Experiment 1 required participants to store digits, but it also required them to process these digits to decide whether the current digit was the same as the last one, last two, or last three digits. Thus, every 1.5 seconds, the N-back task required not only WM storage but potentially also WM processing to engage in this task. Therefore, the 1-back task may have already been too demanding for participants, preventing us from seeing the expected effects of our manipulation. If so, then we should be able to simulate the associative deficit in young adults when both a primary task and a concurrent secondary task were made easier to boost participants' overall primary memory performance.

In order to reduce the potential floor effect in Experiment 2, shorter lists of name-face pairs were used. The second change we made was to use a different secondary WM storage task. In Experiment 2, the number of letters participants needed to remember/store in the WM task was manipulated to reduce participants' WM storage. The advantage of the new storage task over the N-back task used in Experiment 1 was that there was more emphasis on the storage component of WM with fewer processing demands. In the new storage task, participants heard a series of letters, one at a time, and were asked to remember letters presented by a female speaker. Once they heard a letter presented by a male speaker (a probe), they were instructed to respond whether that letter was presented by the female speaker since the last probe. A break of 1.5 seconds followed each probe. Participants heard either 2, 3, or 4 letters before they heard a probe. In other words, they only needed to make a response after every 3, 4 or 5 letters that were presented (or every 4.5, 6, or 7.5 seconds).

In order to make sure that increasing the number of to-be-remembered letters increased the demands for the WM storage capacity, two different storage conditions were utilized. The only difference between the two conditions was the type of letters used. One storage task used letters that were all phonologically similar, and the other storage task used letters that all sound distinct from each other. The reason for using the two different storage conditions in Experiment 2 was related to the *phonological similarity effect*. Previous studies found that when participants were asked to remember information that was phonologically dissimilar such as “K, M, F, and I”, their memory performance was higher than when they were asked to remember phonologically similar information such as “V, D, Z, and B” (e.g., Baddeley, 1966; Conrad, 1964; Conrad & Hull, 1964). Again, the purpose of using the new storage task was to reduce participants’ WM storage, but if we have only presented a series of phonologically dissimilar letters, it may not be taxing enough to affect the storage capacity of WM. Hence, we attempted to use a task that creates a heavier load on WM storage.

It was expected that we would find a phonological similarity effect in the secondary task performance. The phonologically dissimilar storage task would elicit higher performance compared to the phonologically similar storage task. Also, we would expect to find a smaller difference between dual-task conditions in the dissimilar storage task condition compared to the similar storage task. As for the name-face memory performance, we would expect to see that increasing the demands of WM storage capacity in the similar storage task would result in the greatest decline in the name-face task in the dual-task conditions.

To summarize, the primary task used in this study was similar to the one used in first experiment except that the number of name-face pairs that participants needed to study was reduced in order to eliminate potential floor effects. Thus, we would expect higher memory performance for the primary task in all conditions compared to the first experiment. Even more importantly, if a reduction in the WM storage component is the reason older adults have an associative deficit, we would expect that using and manipulating a secondary task that mainly requires WM storage, will result in an associative memory deficit that increases as the WM storage demands in the secondary task increase. As before, we expected to find different patterns in high-span and low-span individuals when we divided the data into two span groups based on the O-span score. On the other hand, if the reason we did not simulate the associative deficit in Experiment 1 was not due to a floor effect or to the quality of the storage manipulation, then in Experiment 2, we would expect to replicate the results of Experiment 1.

Method

Participants

Sixty-eight young adults (35 men, 33 women, *M*age=19), different than those used in Experiment 1, participated in this study. They were recruited from an introductory psychology class in exchange for course credit. One participant did not complete the experiment and was discarded from the analyses.

Design

The design of this study was a 2 (test: item vs. associative) x 7 (letter task: FA, similar 2 letter [S2L], similar 3 letter [S3L], similar 4 letter [S4L], dissimilar 2 letter [D2L], dissimilar 3 letter [D3L], and dissimilar 4 letter [D4L]) x 2 (span: high vs. low) factorial design. Span size was the only between-groups comparison.

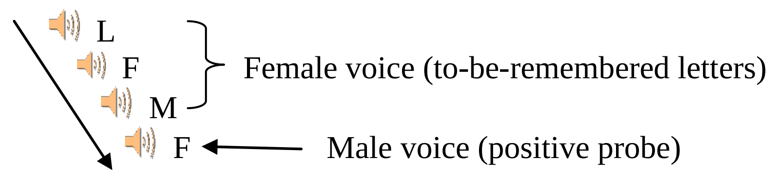
Materials.

<u>Name-face memory task:</u> Seven name-face study lists were constructed. Each list contained 30 name-face pairs. Six name-face pairs were used as buffers for the catch trials (discussed later), and they were not re-presented in any of the memory tests. A total of 24 name-face pairs were used for the four memory tests. Unlike Experiment 1, to create more study lists, half of the photos used were younger adults (ages 18-49) and the other half were older adults (ages 60-94). Also, half of the faces were males, and the

other half were females. Each forced-choice item test contained 6 studied items with 6 new items. Each forced-choice associative tests contained 6 triplets (either 1 face and 2 names or 2 faces and 1 name). The method of counterbalancing was similar to that of Experiment 1.

Secondary storage task. In the similar storage task condition (S), the eight letters used in the storage task were phonologically similar to each other and included B, C, D, G, P, T, V, and Z. In the dissimilar storage task condition (D), the eight letters used in the storage task sounded dissimilar and included F, H, K, L, M, Q, R, and S. In both storage task conditions, participants were asked to remember a series of letters (between 2 and 4) presented by a female speaker (see Figure 6). Each letter was presented every 1.5 seconds. Once participants heard a letter presented by a male speaker (a probe), they were asked to decide whether the probe was presented in the series of letters they have just heard since the last probe (see Figure 6). Participants pressed “v” for “yes” responses and “n” for “no” responses and had 1.5 seconds to make their response. The time length of this task was the same as the duration of the study phase (180 seconds). Half of the responses were “yes” and half were “no”. For each storage task condition, there were three letter tasks that participants needed to perform, the 2 letter (2L) task, 3 letter (3L) task, and 4 letter (4L) task. For the 2L task, participants heard a series of 2 letters before the presentation of a probe, for the 3L task, participants heard a series of 3 letters before a probe was presented, and for the 4L task, they were presented with a series of 4 letters before a probe was presented. Prior to each letter task, participants were told by the experimenter how many letters to expect before hearing the probe. For the positive probes (in which the correct answer was “yes”), the mean retention interval of letters which were re-presented as probes was the same across the three letter tasks (approximately 1.5 seconds) so that any differences in performance among the letter conditions cannot be attributed to the differences in the retention intervals.

Figure 6. Example of the Dissimilar 3L Storage Task in Experiment 2.



However, keeping the mean retention interval across the three letter conditions created a potential problem. Specifically, the letters re-presented as the positive probes always reappeared 1.5 seconds after their initial presentation for the 2L task. To make participants think that the probe could be from any of the ordinal positions in the series, several catch trials were inserted. The catch trials consisted of probes that would either skew the mean retention interval to be larger than 1.5 seconds (i.e., the first letter in an L4 series) or shorter than 1.5 seconds (i.e., the second letter in an L2 series). The responses for these catch trials were always made during the 1st, 2nd, 8th, 14th, 21th, and 29th positions of each name-face study list and were not included in the analysis of the secondary task performance.

<u>O-span task.</u> Was the same as in Experiment 1.

Procedure

There were four practice blocks. In the first practice block, each participant was asked to complete each secondary task starting with the three letter tasks with the similar letters (S2L, S3L and S4L, in that order) followed by the three letter tasks with the dissimilar letters (D2L, D3L and D4L, in that order). In the second practice block, they were asked to study 9 name-face pairs under FA with each pair presented for 6 seconds. After the study phase, participants were asked to perform the same distractor task as in Experiment 1 for one minute, and then they took four practice tests, two forced-choice item tests and two forced-choice associative tests. In the third practice block, participants were asked to practice studying a list of name-face pairs while performing the S3L task in order to practice dividing their attention between the two tasks. They were instructed to pay equal attention to both tasks at encoding. At retrieval, they completed the four forced-choice tests under FA. In the fourth practice block, participants were asked to study a list of name-face pairs while performing the D3L task, after which they again took four practice tests under FA.

There were 7 experimental blocks, and each block—except for the FA block—contained a baseline secondary task, a dual-task study phase, a distractor phase, and a test phase. In the FA block, participants studied a list of name-face pairs without a secondary task and took four memory tests after a distractor task. For each study phase, participants studied a list of 30 name-face pairs with each name-face pair presented for 6 seconds. Participants were asked to study names and faces as well as to study which face appeared with a particular name. There were three dual-task conditions: FA, similar storage task condition (S), and dissimilar storage task condition (D). The order of these conditions was counterbalanced. In each of the two storage secondary task conditions, there were 3 blocks of letter tasks: 2L, 3L, and 4L. Within a storage task condition, the order of the three letter tasks was counterbalanced. Participants performed each baseline secondary task for the same length of time as the duration of the name-face study phase (3 minutes).

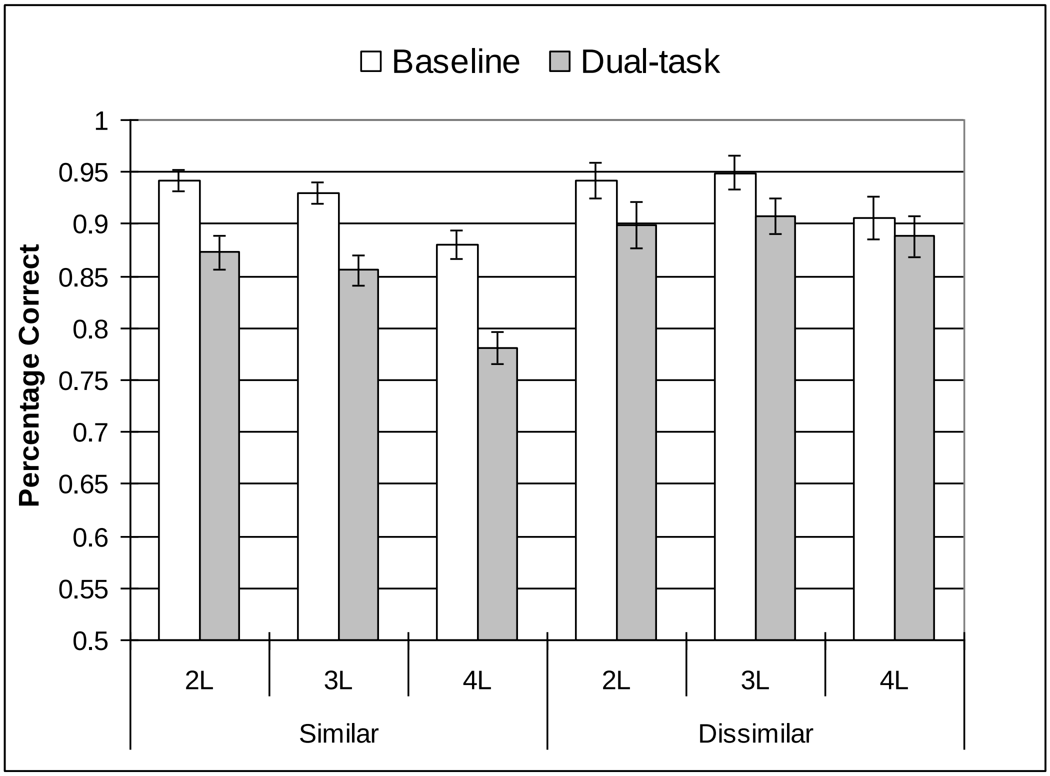
At the end of the experiment, participants took the O-span task, which was the same as in Experiment 1.

Results

Letter Task Performance

Secondary task performance was measured by the percentage of correct responses as a function of dual-task and letter condition, calculated for each individual (see Figure 7 and Appendix B, Table B1, for the means and SD). A 2 (dual-task: baseline, dual-task) x 2 (storage task: S, D) x 3 (letter condition: 2L, 3L, 4L) ANOVA was conducted. Baseline performance (*M*=.92, *SD*=.08) was significantly better than the dual-task performance (*M*=.87, *SD*=.08), *F* (1, 66) = 76.19, *p*<.001, η_p^2=.54 (see Figure 7). As expected, the dissimilar storage task (*M*=.92, *SD*=.08) was performed significantly better than the similar storage task (*M*=.88, *SD*=.08), *F* (1, 66) = 5.66, *p*=.02, η_p^2=.79. This result supports our prediction that phonologically similar letters are remembered less well than phonologically dissimilar letters. The main effect of letter condition was also significant, *F* (2, 132) = 22.04, *p*<.001, η_p^2=.25. The follow-up t-tests revealed that both the 2L (*M*=.91, *SD*=.10) and 3L (*M*=.89, *SD*=.08) conditions were performed significantly better than 4L (*M*=.86, *SD*= .11), *t* (66) = 6.90, *p*<.001 and *t* (66) = 5.02, *p*<.001, respectively. However, there was no significant difference between the 2L and 3L conditions, *t* (66) = .36, *p*>.05.

Figure 7. Secondary Task Performance for Baseline and Dual-Task Conditions as a Function of Storage Task and Letter Condition (with Standard Error Bars) in Experiment 2.



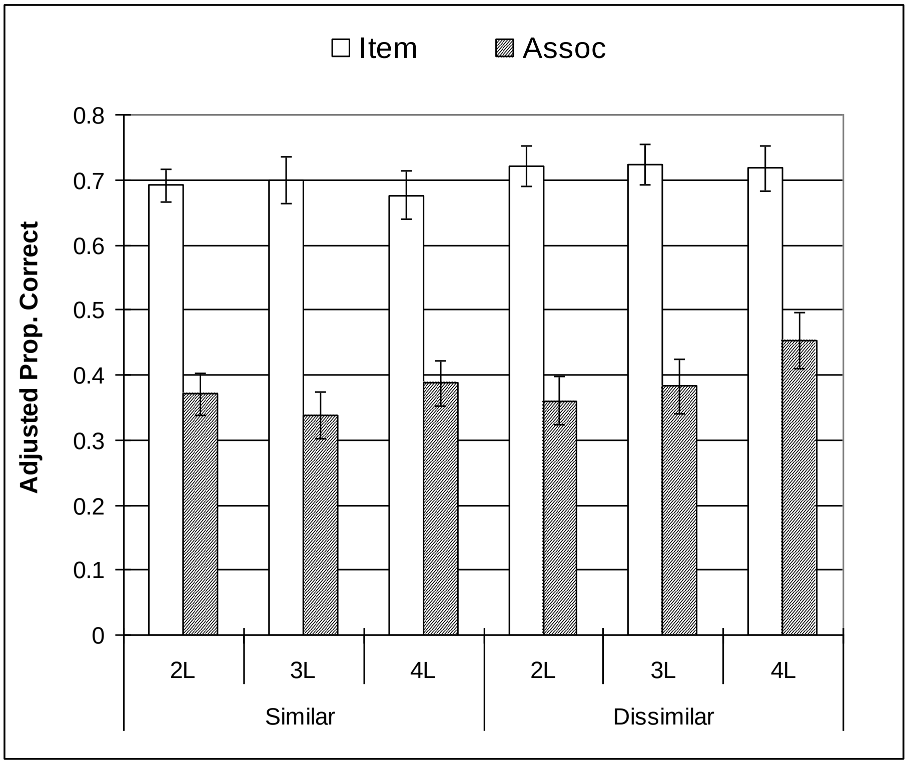
In addition, a three-way interaction among dual-task, storage task, and letter condition was marginally significant, F (2, 132) = 2.92, p=.06, η_p^2=.04. Also, a two-way interaction of storage task and letter condition was significant, F (2, 132) = 5.22, p=.01, η_p^2=.07. Follow-up tests revealed significant differences among the letter conditions in the similar letter condition, F (2, 132) = 31.73, p<.001, η_p^2=.33, but less so in the dissimilar letter condition, F (2, 132) = 3.11, p=.05, η_p^2=.05. Follow-up t-tests for the similar condition revealed that lower performance was seen in the S4L task (M=.83, SD=.10) compared to both the S2L task (M=.91, SD=.10), t (66) = 7.00, p<.001, and the S3L task (M=.89, SD=.08), t (66) = 6.02, p<.001 (there was no significant difference between the S2L and S3L conditions, t (66) = 1.46, p>.05). Thus, it seems that the S4L task was harder for participants compared to the S2L and S3L tasks. Follow-up tests for the dissimilar condition showed the same pattern as the similar condition. Lower performance was recorded in the D4L task (M=.90, SD=.16) compared to both the D2L task (M=.92, SD=.16), t (66) = 2.82, p=.01, and the D3L task (M=.93, SD=.13), t (66) = 1.94, p=.06. The D2L and D3L conditions did not differ, t (66) = -.54, p>.05. In sum, although we found a stronger effect of the letter task in the similar storage task condition, the same patterns were obtained in the similar and the dissimilar conditions.

Finally, the two-way interaction of dual-task and storage task was significant, F (1, 66) = 14.18, p<.001, η_p^2=.18. The follow-up tests revealed that dual-task performance was better in the dissimilar (M=.90, SD=.14) than the similar storage task condition (M=.84, SD=.10), F (1, 66) = 11.84, p=.001, η_p^2=.15. However, there was no significant difference between the baselines in the similar (M=.92, SD=.07) and dissimilar storage task condition (M=.93, SD=.14), F (1, 66) = .78, p>.05, η_p^2=.01. This demonstrates that the similar storage task requires more WM storage resources than the dissimilar task, as expected.

Memory Performance

Next, memory performance in the name-face task was examined. The adjusted proportion correct was calculated as described in Experiment 1 (see Appendix B, Table B2, for the means and SD). Again, the data were collapsed across the two different forced-choice item tests and across the two different forced-choice associative tests.

Figure 8. Memory Performance for Items and Associations as a Function of Storage Task and Number of Letters (with Standard Error Bars) in Experiment 2.



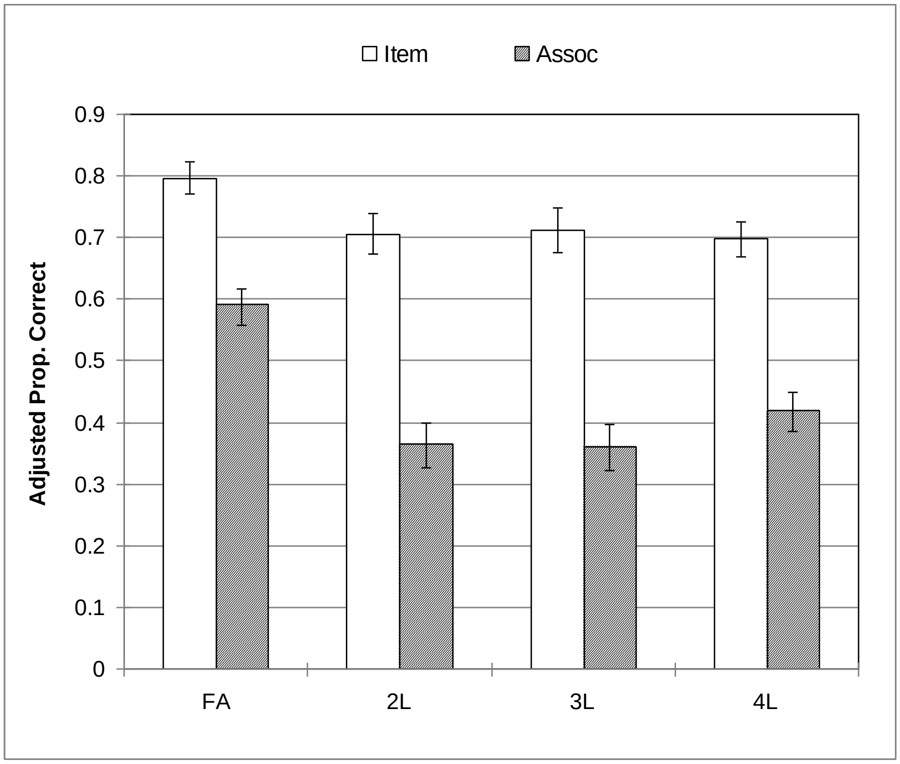
First, in order to examine whether there was any difference between the similar and dissimilar storage task conditions (see Figure 8), the data were analyzed in a 2 (storage task: similar, dissimilar) x 3 (letter condition: 2L, 3L, 4L) x 2 (test: item, associative) ANOVA. Only the main effect of test was significant, F (1, 66) = 250.80, p<.001, η_p^2=.79, indicating that the item test (M=.71, SD=.02) elicited better performance than the associative test (M=.38, SD=.03). There was no effect of letter condition, F (2, 132) = .45, p>.05, η_p^2=.01. In contrast to the predictions, there was no main effect of storage task, F (1, 66) = 1.78, p>.05, η_p^2=.03, and storage task did not interact with any of the variables (test x storage task x letter condition, F (2, 132) = .58, p>.05 η_p^2=.01; storage task x letter condition, F (2, 132) = .43, p>.05, η_p^2=.01; storage task x test, F (1, 66) = .00, p>.05, η_p^2=.00; test x letter condition, F (2, 132) = 1.79, p>.05, η_p^2=.03).

Based on these results, the data were collapsed across the two storage task conditions before including the FA condition for comparison (see Appendix B, Table B3, for the means and SD).

Next, a 4 (dual-task: FA, 2L, 3L, 4L) x 2 (test: item, associative) ANOVA was conducted (see Figure 9). A main effect was observed for test, F (1, 66) = 318.81, p<.001, η_p^2=.83, showing that performance was higher in the item test (M=.73, SD=.14) than in the associative test (M=.43, SD=.18). Also, the main effect of dual-task was significant, F (3, 198) =17.59, p<.001, η_p^2=.21. The follow-up t-tests showed that performance in the FA condition (M=.69, SD=.19) was significantly better than in the 2L (M=.53, SD=.22), t (66) = 5.87, p<.001, the 3L (M=.53, SD=.22), t (66) = 5.01, p<.001, and the 4L condition (M=.56, SD=.17), t (66) = 5.58, p<.001. There were no significant differences among the three dual-task conditions, all ts <1.3, ps>.05.

The two-way interaction of test and dual-task was also significant, F (3, 201) = 4.22, p=.01, η_p^2=.06 (see Figure 9). The follow-up one-way ANOVA for the item test was significant, F (3, 198) = 3.61, p=.01, η_p^2 =.05, and follow-up t-tests showed that the FA condition (M=.80, SD=.21) elicited higher performance than the 2L condition (M=.71, SD=.22), t (66) = 2.69, p=.01, the 3L condition (M=.71, SD=.25), t (66) = 2.13, p=.04, and the 4L condition (M=.70, SD=.18), t (66) = 2.94, p=.01. There were no differences among the three letter conditions, all ts<.35, ps>.05.

Figure 9. Memory Performance for Items and Associations as a Function of Number of Letters (with Standard Error Bars) in Experiment 2.



The follow-up one-way ANOVA on associative test performance was also significant, *F* (3, 198) = 18.30, *p*<.001, η_p^2=.22. The follow-up t-tests revealed that participants performed better in the FA condition (*M*=.59, *SD*=.27) compared to the 2L condition (*M*=.36, *SD*=.26), *t* (66) = 5.14, p<.001, the 3L condition (*M*=.36, *SD*=.27), *t* (66) = 5.64, *p*<.001, and the 4L condition (*M*=.42, *SD*=.23), *t* (66) = 4.69, *p*<.001. There were no differences in the associative memory performance among the three letter conditions, all *t*s< 1.9, *p*s>.05. These results indicated that there was an effect of dual task on memory, meaning that participants could not remember name-face information well when they were asked to perform a concurrent secondary task compared to when they performed no concurrent secondary task.

The follow-up tests on the two-way interaction of test and dual-task found that item memory performance (M=.80, SD=.21 for FA, M=.71, SD=.22 for 2L, M=.71, SD=.25 for 3L, M=.70, SD=.18 for 4L) was significantly better than associative memory performance (M=.59, SD=.27 for FA, M=.36, SD=.26 for 2L, M=.36, SD=.27 for 3L, M=.42, SD=.23 for 4L) for the FA condition (F (1, 66) = 28.84, p<.001, η_p^2=.30), the 2L condition (F (1, 66) = 112.85, p<.001, η_p^2=.63), the 3L condition (F (1, 66) = 120.70, p<.001, η_p^2=.65), and the 4L condition (F (1, 66) = 96.52, p<.001, η_p^2=.59). Thus, these results indicated that it was easier for participants to remember individual names and individual faces than name-face pairs.

Given our prediction that reducing the storage component of WM (via the letter task) would elicit an associative deficit, we performed several planned pairwise interaction contrasts. A 2 (test) x 2 (dual-task: FA vs. 2L) showed a significant interaction, F (1, 66) = 6.18, p=.02, η_p^2=.09, such that there was a significant difference between FA and 2L in item memory performance, F (1, 66) = 7.24, p=.01, η_p^2=.10, but a substantially larger difference in associative memory performance, F(1, 66) = 26.41, p<.001, η_p^2=.29. Next, a two-way ANOVA including only FA and 3L as the dual-task conditions also found a significant interaction, F (1, 66) = 8.87, p=.01, η_p^2=.12. Again, the follow-up tests revealed that there was a significant difference between FA and 3L in item memory, F (1, 66) = 4.55, p=.04, η_p^2=.06, and this difference increased for associative memory, F (1, 66) = 31.80, p<.001, η_p^2=.33. These significant two-way interactions indicate that the associative deficit gets larger in the 2L and the 3L conditions compared to the FA condition. These results support our hypothesis that reducing WM storage resources will impair associative memory more than item memory, thus showing a larger associative deficit in the dual-task conditions. However, a two-way interaction was not significant when only the FA and 4L conditions were included, F (1, 66) = 2.52, p>.05, η_p^2=.04, suggesting that the item and associative tests were equally affected by the 4L manipulation. This result along with other results support our hypothesis that adding a secondary task will impair overall memory performance, but this specific result fails to support the prediction that reducing WM storage resources elicits an associative deficit. In addition, there were no other significant 2 (test) x 2 (dual-task: 2L vs. 3L, 2L vs. 4L, and 3L vs. 4L) interactions, all Fs <3.5, ps>.05.

High-Span vs. Low-Span Participants

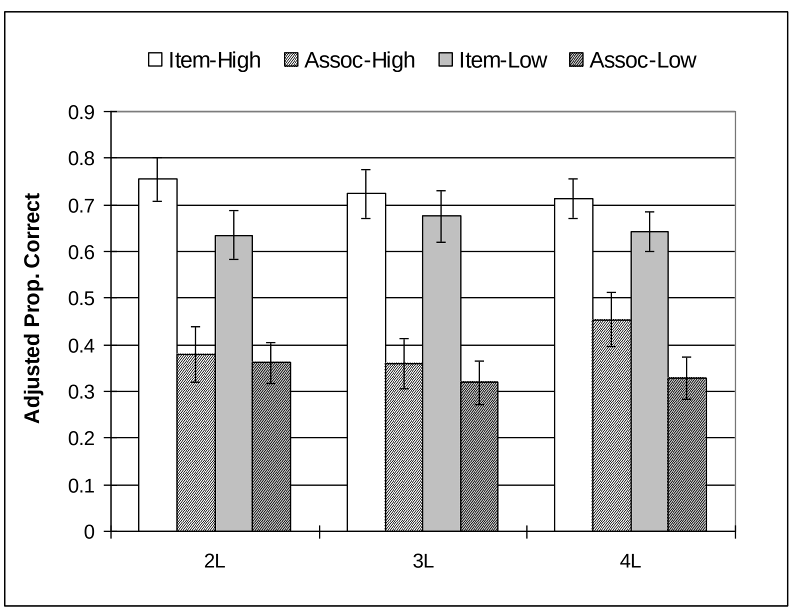
Data were divided into two groups based on participants' performance on the O-span task. Thirty-two participants who performed above the median O-span score (42) were categorized as "high-span" (*M*span=53.6, span range: 43-75), and 35 participants who scored below 42 were categorized as "low-span" (*M*span=28.3, span range: 0-42).

First, we investigated whether the high- and the low-span groups behaved differently in the similar and dissimilar storage task conditions (see Figure 10). A 2 (storage task: similar, dissimilar) x 3 (dual-task: 2L, 3L, 4L) x 2 (test: item, associative) x 2 (O-span: high-span, low-span) ANOVA was performed. Only the main effect of test was significant, F (1, 65) = 260.23, p<.001, η_p^2=.80, revealing that participants performed better on the item test (M=.71, SD=.16) than the associative test (M=.38, SD=.21). Other than a marginally significant interaction of test and O-span, F (2, 132) = 2.97, p=.09, η_p^2=.04, no other effects reached statistical significance (letter task, F (2, 130) = .81, p>.05, η_p^2=.01; storage task, F (1, 65) = 1.64, p<.05, η_p^2=.03; quadruple interaction, F (2, 130) = .23, p>.05, η_p^2=.00; storage task x letter task x test, F (2, 130) = .56, p>.05,

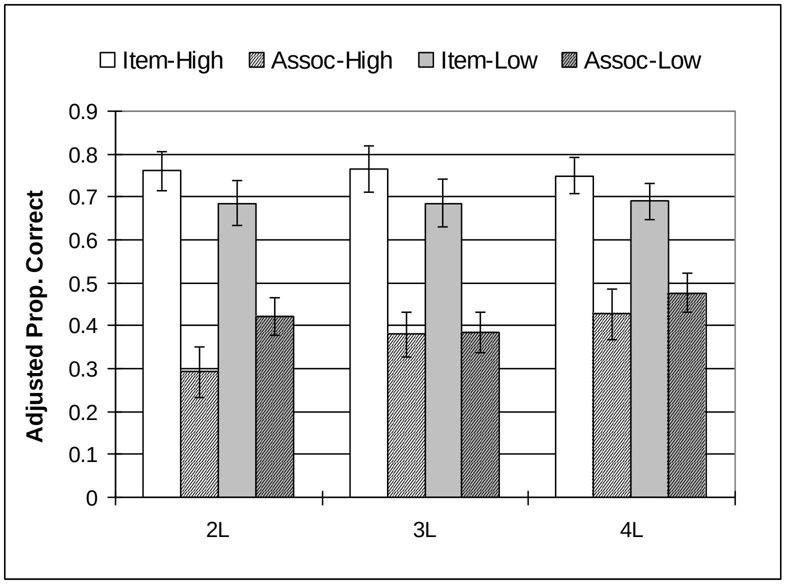
η_p^2=.01; letter x test x O-span, F (2, 130) = 1.46, p>.05, η_p^2=.02; storage task x test x O-span, F (2, 130) = 2.21, p>.05, η_p^2=.03; storage task x letter task x O-span, F (2, 130) = .90, p>.05, η_p^2=.01; storage task x O-span, F (1, 65) = 1.84, p>.05, η_p^2=.00; test x O-span, F (1, 65) = .13, p>.05, η_p^2=.00). These results suggest that there were no differences between the similar and dissimilar storage tasks, even when looking separately at high-span and low-span participants. Such results are consistent with the analyses conducted earlier, though they were unexpected. As a result, data for the similar storage task and the dissimilar storage task were collapsed for further investigation.

Figure 10. **(A)** Memory Performance in Experiment 2 for Items and Associations for High- and Low-Span Participants as a Function of Number of Letters in the Similar Storage Task Condition (with Standard Error Bars), and **(B)** Memory Performance for Items and Associations for High- and Low-Span Participants as a Function of Number of Letters in the Dissimilar Storage Task Condition (with Standard Error Bars).

(A)

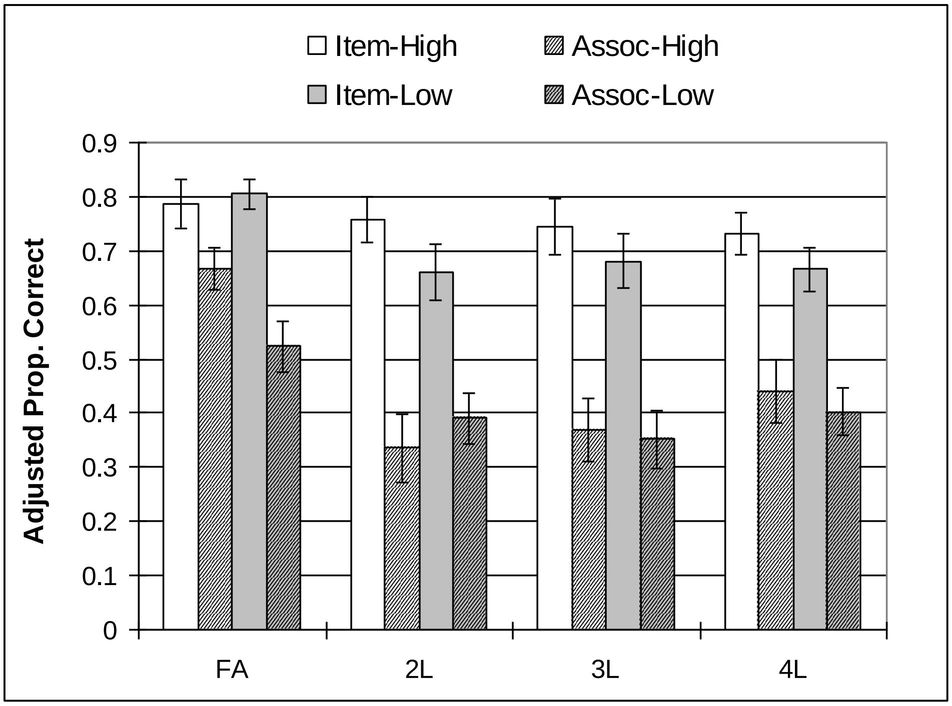


(B)



The collapsed data (see Figure 11) were analyzed with a 4 (dual-task: FA, 2L, 3L, 4L) x 2 (test: item, associative) x 2 (O-span: high-span, low-span) ANOVA (see Appendix B, Table B4, for the means and SD). Again, the main effect of test revealed that participants performed better in the item test (M=.73, SD=.14) than in the associative one (M=.44, SD=.18), F (1, 65) = 314. 57, p<.001, η_p^2=.83. The main effect of dual-task was also significant, F (2, 195) = 17. 50, p<.001, η_p^2=.21. Follow-up t-tests showed that performance in the FA (M=.69, SD=.19) condition was significantly better than in any one of the letter task conditions (M=.53, SD=.21 for 2L, M=.53, SD=.22 for 3L, and M=.56, SD=.17 for 4L), all ts >5, ps<.001. There were no differences among the dual-task conditions, all ts <1.3, ps>.05.

Figure 11. Memory Performance for Items and Associations as a Function of Dual-Task Condition in High- and Low-Span Participants (with Standard Error Bars) in Experiment 2.



Next, we wanted to replicate the pattern of findings observed in Experiment 1, showing that low-span participants showed an associative deficit compared to high-span participants in the FA condition. A 2 (test) x 2 (O-span) ANOVA for the FA condition was conducted and indicated that there was indeed an interaction, F (1, 65) = 4.75, p=.03, η_p^2=.07. Further investigation revealed that there was no significant difference between the high-span (M=.79, SD=.26) and low-span groups (M=.80, SD=.16) in their item memory performance, F (1, 65) = .07, p>.05, η_p^2=.00, whereas there was a significant difference in their associative memory performance (M=.67, SD=.22 for high-span, and M=.52, SD=.29 for low-span), F (1, 65) = 5.41, p=.02, η_p^2=.08. These results show that low-span participants had an associative deficit compared to high-span individuals in the FA condition, replicating the results of Experiment 1.

Similar to Experiment 1, we computed a difference score between item and associative memory performance to further investigate the relationship between WM span and an associative deficit. Unlike Experiment 1, the correlation between O-span score and the associative deficit in the FA condition did not reach significance, r (68) = -.17, p>.05, one tailed (but see Appendix E for some further analyses).

More importantly, whether the dual-task affected high-span and low-span individuals' item and associative memory differently was examined by looking at the three-way interaction of dual task, test, and O-span (see Figure 11). We found the triple interaction to be significant, F (3, 195) = 3.98, p<.001, η_p^2=.06. The follow-up 4 (dual-task) x 2 (test) ANOVA for high-span individuals was found to be significant, F (3, 93) = 8.61, p<.001, η_p^2=.22. Follow-up one-way ANOVAs examining the effect of dual-task were performed separately for the item and the associative tests. It was found that high-span participants' item memory was not affected by the dual-task, F (3, 93) = .50, p>.05, η_p^2=.02. On the other hand, their associative memory was affected by the dual-task, F (3, 93) = 14.94, p<.001, η_p^2=.33. Follow-up t-tests confirmed that the high-span's associative memory in the dual-task conditions (M=.34, SD=.32 for 2L, M=.37, SD=.30 for 3L, and M=.44, SD=.25 for 4L) was worse than their memory in the FA condition (M=.67, SD=.22), all ts >4, ps<.001. However, the two-way interaction of dual-task and test for the low-span individuals was not significant, F (3, 102) = .37, p>.05, η_p^2=.01. These results indicate that high-span individuals showed an associative deficit in the dual-task condition compared to the FA condition. As seen in Experiment 1, low-span individuals did not show this pattern.

Discussion

The results of the secondary task showed that performance was better when participants performed the secondary task alone compared to when they performed it simultaneously with the name-face task. It was also found that participants' secondary task performance in the dissimilar storage task was higher than their performance in the similar storage task. Thus, as predicted, we found a phonological similarity effect in the secondary task performance. Even though we found evidence for the phonological similarity effect in the secondary task, this was not the case in the name-face task -- under dual-task conditions, there were no observable differences between the similar and dissimilar storage tasks when examining item and associative memory performance. One possible explanation for the lack of a similarity effect in the primary task is that the WM storage manipulation was not strong enough; however, the same manipulation was strong enough to elicit an effect in the secondary task performance. Another possibility is that participants prioritized the name-face task once the secondary task became harder and it cost them in lowering their secondary in the task performance.

The results of the primary task revealed that the strategies used in Experiment 2 to eliminate potential floor effects observed in the associative test in Experiment 1, were successful. Compared to Experiment 1, the mean item performance in the dual-task conditions increased from .32 to .73, and the mean associative performance increased from .28 to .43. This may explain why dual-task conditions elicited an associative deficit in Experiment 2 but not Experiment 1, as in Experiment 1 it may not have been possible for associative memory performance to decrease any further. The fact that the secondary letter task produced an associative deficit in Experiment 2 is consistent with the notion that the associative deficit is a result of reduced resources related to WM storage.

On the other hand, the associative deficit did not become larger as the secondary task demands increased (e.g., an associative deficit was observed to the same degree in the 2L and 3L, but not in the 4L condition). Specifically, we did not find the differential effect of the number of letters that had to be stored on item and associative memory performance. This result is similar to the one obtained in Experiment 1 in which we did not see the differential effect of the N-back tasks on item and associative memory. Taken together, it suggests that increasing the demands for WM storage in younger adults has no differential effect on item and associative memory, as age does.

However, another possible explanation for this pattern in Experiment 2 is that participants were able to chunk letters into one group and hold them as one piece of information rather than separate letters. Thus, it is possible that our manipulation of reducing WM storage component was not strong enough and that increasing the number of letters that participants need to hold beyond 4, might result in the observing of the differential effect of the letter tasks on the primary memory. However, if it is not the case, then the task would not involve only WM mechanism as the capacity of WM is about 4 items (Cowan, 1988, 1999).

When the data were separated into high- and low-span groups, we found similar results to those reported in Experiment 1. In the FA condition, low-span participants showed an associative deficit compared to the high-span group. Thus, low-span individuals behaved like older adults in the FA condition. However, in the dual-task conditions, it was only the high-span group that showed an associative deficit compared to their own FA performance, revealing that high-span individuals were more affected by the dual-task. These results are in line with previous studies (e.g., Kane & Engle, 2000; Rosen & Engle, 1997).

In summary, unlike Experiment 1, we successfully simulated the associative deficit in young adults by adding a concurrent letter task, intended to reduce their WM storage capacity. However, we did not find the expected differential effect of number of letters on item or associative memory as the secondary task demands were incrementally increased. As in Experiment 1, we found that low-span individuals showed an associative deficit relative to high-spans in the FA condition. However, only high-span participants showed an associative deficit in the dual-task conditions compared to their performance in the FA condition. These findings provide only partial support for the suggestion that the associative deficit is a product of deficient WM storage.

Experiment 3: Reducing the Processing Component of WM in Young Adults

The results obtained from Experiments 1 and 2 suggest that reduced WM storage resources in older adults may be part of the reason older adults show an associative deficit. However, not all of the predictions were supported. As mentioned in the introduction, there are two important components of WM (storage and processing), and it may be the case that the reason older adults have an associative deficit is because of the reduced processing component of WM rather than the storage one. Unsworth, Redick, Heitz, Broadway, and Engle (2009) found that young participants who were fast and accurate in the online math operations remembered more items during final recall in WM span tasks than those who had poor math performance. In other words, it is possible that superior processing ability increases the ease of storing new information in WM. Thus, it is possible that a reduction in WM processing resources makes people slower to articulate and rehearse items, leaving fewer WM resources for binding information. As discussed earlier, some studies show that the secondary tasks requiring more WM processing, such as counting backwards, disrupted memory for associative information more than tasks presumed to require fewer processing resources (Allen et al., 2009, Experiment 2 & 3; Brown & Brockmole, 2010, Experiment 1). Such results lead to the question of whether reducing the processing component of WM would mimic older adults' associative deficit in young adults. We tested this question in the third experiment, where young adults studied the same lists of name-face pairs as Experiments 1, but performed a different concurrent task, which involved manipulating the difficulty of a math operation task to reduce WM processing resources. Participants were asked to perform either addition, subtraction, or division math operations as a concurrent task, with division requiring the most processing resources, while keeping constant the amount of WM storage required in each of the conditions. If the reduced processing component of WM is the reason for the associative deficit in older adults, it is expected that an associative deficit would be observed when the demands for processing resources by the concurrent task are increased.

As in Experiments 1 and 2, the data were also split between high- and low-performing groups in the O-span task; however, groups were categorized according to math accuracy as opposed to O-span score. Those who performed well on the math problems were grouped as "high-processing" and those who scored low on the math problems were grouped as "low-processing." The data were split in this way in Experiment 3 because math accuracy in the O-span is a measurement of online math processing. When looking separately at the results of the high- and low-processing groups, it was expected that the low-processing group would show an associative deficit in the FA condition relative to the high-processing group, if indeed, WM processing resources are important for encoding associations.

Method

Participants

Seventy-nine young adults (33 men, 46 women, M_{age}=19.5 years) participated in this study in exchange for course or extra credits toward their psychology classes. All participants in this experiment were native English speakers between 18 and 28 years old who did not participate in Experiments 1 or 2. Two participants did not complete the study, and their data were discarded.

Design

The design of this study was a 2 (test: item vs. associative) x 4 (math operation: FA, addition, subtraction, and division) x 2 (O-span math accuracy: high vs. low) factorial design. O-span math accuracy was the only between-groups comparison.

Materials

Name-face memory task. The study lists and test lists were identical to those used in Experiment 1.

Math operation secondary task. For the math operation task (addition, subtraction, and division), each stimulus was presented every 1.5 seconds. The math operation conditions were blocked so that participants were informed of which math operation task that they were going to perform. In each math operation task, participants first heard a two-digit number. Then, depending on the condition, they heard a math operation, either "plus," "minus," or "divided by." Then they heard a single digit followed by one of the following: "equal," "greater than," or "less than." Finally, they heard a digit as an answer and were asked to decide whether the answer provided was "true" or "false." For example, they might have heard "48 plus 2 equal 50" (true trial). In order to make the three tasks similar, correct answers were always whole numbers, meaning that there were no fractional numbers used as correct answers. In addition, to make sure that the division condition was sufficiently difficult, most division problems included digits greater than 10. For example, participants might have heard "48 divided by 2 greater than 26" (false trial). In this case, they cannot simply use their knowledge of multiplication tables to solve the problem. Also, for the false trials, participants heard a digit which was only 1 to 3 digits higher or lower than the correct answer. Participants had 1.5 seconds to press "v" for "true" responses or press "n" for "false" responses. Each block contained 30 mathematical strings, and there were equal numbers of true and false trials as well as equal numbers of equal, greater than, and less than trials. The order of addition, subtraction, and division blocks was counterbalanced.

O-span task. Was the same as in Experiments 1 and 2.

Procedure

There were 3 practice blocks. For the first practice block, participants practiced each math operation as a baseline – addition, subtraction and division, in that order. Then, they practiced the name-face task under FA. In the third practice set, they studied name-face pairs while performing a concurrent subtraction task.

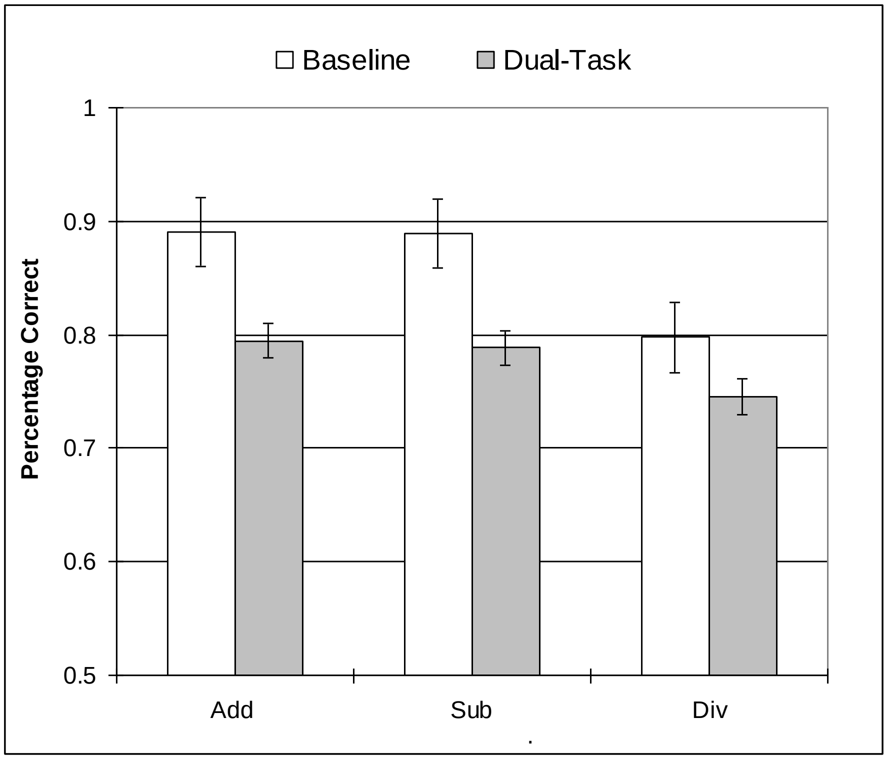
Next, they completed the 4 experimental blocks. Each participant studied the same lists of name-face pairs as in Experiment 1. Each math task was performed without studying name-face pairs as the baseline for the same duration as the study phase (4 minutes and 24 seconds). After the baseline measurement, participants were asked to perform the same math operation task while studying name-face pairs. After the study phase, participants performed the interpolated activity, and took the four forced-choice memory tests. At the end of the experiment, participants performed the O-span task.

Results

Math task performance

Math task performance was calculated as the percentage of correct responses made in each condition (see Appendix C, Table C1, for the means and SD). A 2 (dual task: baseline, dual-task) x 3 (math operation; addition, subtraction, division) ANOVA was conducted. The main effect of dual task was significant, F (1, 76) = 95.51, $p<.001$, $\eta_p^2=.56$ (see Figure 12). Thus, participants' math task performance was significantly better when they paid full attention to the math task compared to when they were asked to study name-face pairs simultaneously (M=.86, SD=.06 for baseline, and M=.78, SD=.09 for dual-task). Also, the main effect of math operation was significant, F (2, 152) = 29.43, $p<.001$, $\eta_p^2=.28$. Follow-up pairwise comparisons indicated that participants performed significantly worse on the division task (M=.77, SD=.07) compared to both the addition (M=.84, SD=.08) and the subtraction tasks (M=.84, SD=.10), t (76) = 7.44, $p<.001$ and t (76) =6.82, $p<.001$ respectively. However, there was no significant difference between the addition and the subtraction tasks, t (76) = .32, $p>.05$.

Figure 12. Math Operation Task Performance (with Standard Error Bars) in Experiment 3.



The two-way interaction of dual-task and math operation was significant, F (2, 152) = 4.84, p=.01, η_p^2=.06. The follow-up one-way ANOVAs of dual-task at each math operation condition indicated that participants performed the secondary task significantly worse when they were concurrently studying name-face pairs (M=.79, SD=.12 for addition, M=.79, SD=.13 for subtraction, and M=.75, SD=.10 for division) compared to their baseline secondary task performance in addition (M=.89, SD=.07), subtraction (M=.89, SD=.09), and division (M=.80, SD=.09), F (1, 76) = 53.52, p<.001, η_p^2=.41, F (1, 76) = 55.94, p<.001, η_p^2=.42, F (1, 76) = 17.53, p<.001, η_p^2=.19 respectively. These results showed the effect of performing two tasks simultaneously and suggested a reduction in their secondary task performance was the cost to studying name-face pairs.

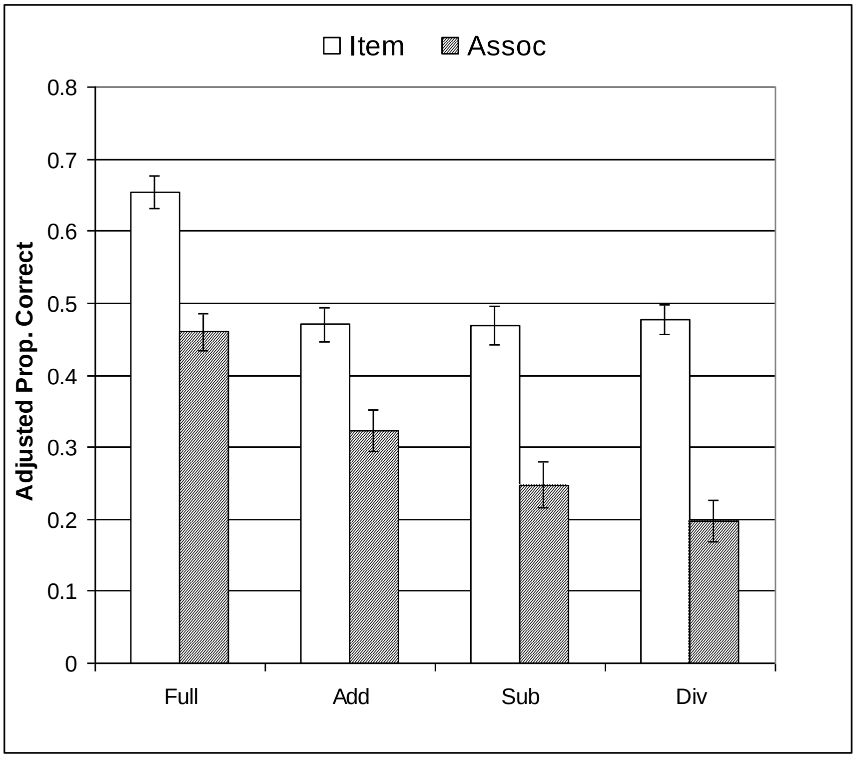
In addition, the follow-up one-way ANOVAs examining the effect of math operation for each dual-task condition indicated a significant difference among the three math operation conditions in the baseline condition, F (2, 152) = 40.76, p<.001, η_p^2=.35, but less so in the dual-task condition, F (2, 152) = 6.40, p=.002, η_p^2=.08. The follow-up t-tests revealed that participants' baseline secondary task performance in the division condition was worse than the addition and subtraction conditions, all *t*s>7, *p*s<.001, though there were no differences between addition and subtraction, t (76) = .10, p>.05. In the dual-task conditions, participants also performed worse in division than both addition and subtraction, all *t*s >3.5, *p*s<.001, with no difference between addition and subtraction, t (76) = .36, p>.05.

Memory Performance

The scoring and data collapsing were the same as in Experiment 1 (see Appendix C, Table C2, for the means and SD). To examine memory performance, a 2 (test: item, associative) x 4 (dual-task: FA, addition, subtraction, division) ANOVA was conducted. The main effect of dual-task was significant, F (3, 228) = 30.98, p<.001, η_p^2=.29, as was the main effect of test, F (1, 76) = 202.77, p<.001, η_p^2=.73 (see Figure 13), suggesting that the item test (*M*=.52, *SD*=.12), was performed better than the associative test (*M*=.31, *SD*=.14). Follow-up t-tests on the main effect of dual-task revealed that the FA condition (*M*=.56, *SD*=.17) elicited better memory performance compared to any one of the math operation conditions (*M*=.40, *SD*=.17 for addition; *M*=.36, *SD*=.21 for subtraction; *M*=.34, *SD*=.18 for division), all *t*s>7.5, *p*s<.001. Among the math operation conditions, a significant difference was found between the addition and division conditions, t (76) =

2.52, *p*=.01, but not between the addition and subtraction or between the subtraction and the division conditions, all *t*s<1.7, *p*s>.05.

Figure 13. Memory Performance as a Function of Math Operation Condition (with Standard Error Bars) in Experiment 3.



Importantly, the ANOVA also showed that the two-way interaction of test and dual-task was significant, F (3, 228) = 2.73, p=.05 η_p^2=.04. Follow-up one-way ANOVAs indicated that there was a significant difference among the dual-task conditions in the associative test, F (3, 228) = 18.91, p<.001 η_p^2=.20, as well as in the item test, F (3, 228) = 17.14, p<.001 η_p^2=.18. Follow-up t-tests showed that the item performance in the FA condition (*M*=.67, *SD*=.19) was significantly higher than the addition, subtraction, and division conditions (*M*=.47, *SD*=.21, *M*=.47, *SD*=.24, and *M*=.48, *SD*=.19, respectively), all *t*s >6.5, *p*s<.001. However, there were no significant differences among the math operation conditions (addition, subtraction, and division), in this test, all *t*s<1, *p*s>.05. These results indicate that item memory performance was affected by having a concurrent task, but the type of concurrent task did not matter.

However, associative memory performance showed a different pattern. Pairwise comparisons for the associative test revealed that the performance in the FA condition (*M*=.46, *SD*=.23) was significantly better than in the addition, subtraction, and division conditions (*M*=.33, *SD*=.25 for addition, *M*=.25, *SD*=.28 for subtraction, *M*=.20, *SD*=.26 for division), all *t*s>4, *p*s<.001. More importantly, associative memory performance in the addition condition was significantly better than the subtraction, t (76) = 1.99, p=.05, and division conditions, t (76) = 3.15, p=.01. The difference between the subtraction and division conditions did not reach statistical significance, t (76) = 1.23, p>.05. These results indicate that associative memory was most affected by the subtraction and division tasks.

In addition, because we were interested in whether an associative deficit emerged as the demands of the processing task increased, planned pairwise interaction contrasts were conducted. There were no significant two-way interactions between test and dual-task when FA and addition were compared, F (1, 76) = 1.30, p>.05 η_p^2=.02, or when FA and subtraction were compared, F (1, 76) = .230, p>.05 η_p^2=.00. However, the two-way interaction between test and the FA and the division conditions approached significance, F (1, 76) = 3.62, p=.06 η_p^2=.05, indicating an associative deficit in the division condition compared to the FA condition.

High-Online Processing vs. Low-Online Processing

Since we were interested in how individuals' processing ability would affect their memory performance for the item and associative tests, we used a median split (.94) to create high- and low-online math processing groups (see Figure 14; Appendix C, Table C3, for the means and SD). Thirty-eight participants were grouped as "high-processing" (M_{acc}=.96, accuracy range: .95-1), whereas 39 participants were categorized as "low-processing" (M_{acc} =.89, accuracy range; .79-.94)[2].

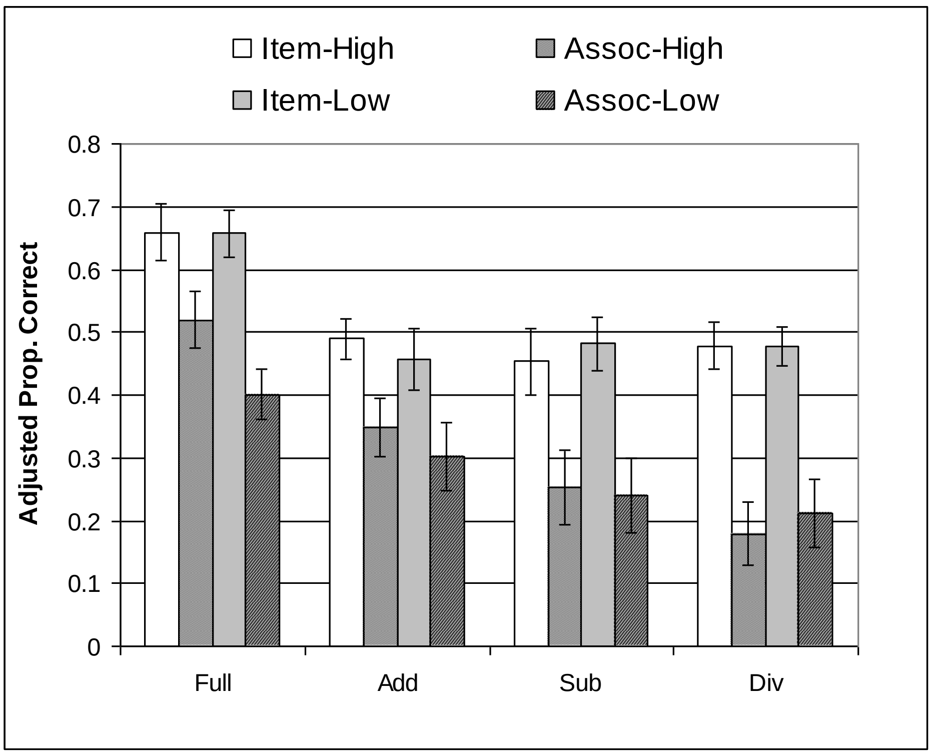
A 4 (dual-task: FA, addition, subtraction, division) x 2 (test: item, associative) x 2 (online processing: high, low) ANOVA was performed to locate any differential patterns between the processing groups. Consistent with the previous analyses, there was an interaction of dual-task and test, F (3, 225) = 2.74, p=.04, η_p^2=04, but the other two-way interactions and the three-way interaction were not significant, all Fs<1.4, ps>.05. These results suggest that there was no differential pattern between high- and low-processing groups and that both groups showed that dual-tasks affected associative memory more than item memory.

However, we were more interested in whether low-processing individuals would demonstrate an associative deficit relative to their high-processing counterparts in the FA condition. To assess this, we conducted a planned interaction comparison within the FA condition, and a 2 (processing) x 2 (test) ANOVA produced a significant interaction, F (1, 75) = 4.45, p=.04, η_p^2=.06. Follow-up one-way ANOVAs found that item memory performance was not significantly different between the two groups (M=.66, SD=.18 for

[2] In the WM literature, participants that score below .85 on O-span math accuracy are typically excluded from the analyses. However, we were not concerned about the validity of the standard "O-span score" measuring stored items in Experiment 3. Instead, we used math accuracy as a tool for investigating item and associative performance in the name-face task, which is why we included all participants in the analyses.

high-processing, M=.66, SD=.21 for low-processing), F (1, 75) = .00, p>.05 η_p^2=.00, whereas the high-processing group (M=.52, SD=.22) outperformed the low-processing group (M=.40, SD=.22) in associative memory performance, F (1, 75) = 5.57, p=.02 η_p^2=.07. Thus, in the FA condition, the low-online processing group showed an associative deficit relative to the high-online processing group.

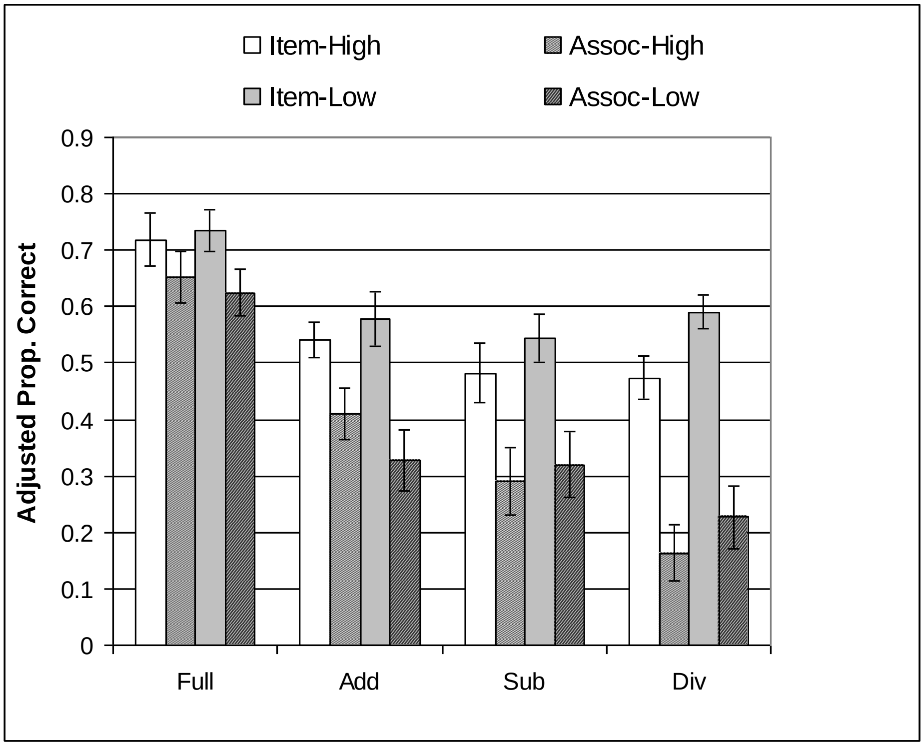
Figure 14. Memory Performance for High- vs. Low-Online Math Accuracy Individuals (with Standard Error Bars) in Experiment 3.



To investigate the relationship between math processing and the associative deficit, we computed difference scores between item and associative memory for each individual and found a marginally negative relationship between them, r (77) = -.17, p=.07, one-tailed. Thus, it seems that low-processing individuals tend to have an associative deficit compared to high-processing individuals.

Furthermore, a 2 (test) x 2 (dual-task: FA vs. division) ANOVA revealed that the high-processing group showed a significant two-way interaction of test and dual-task, $F(1, 75) = 9.37$, $p=.01$, $\eta_p^2=.20$, indicating that the associative deficit emerged in the division condition compared to the FA condition, but this was not the case when FA was compared to addition or subtraction, all *F*s $<.8$, *p*s$>.05$. On the other hand, the low-processing group did not show significant interactions in any of the same comparisons, all *F*s <2, *p*s$>.05$. One possible reason we did not observe any interactions in the low-processing group is that they already had an associative deficit in the FA condition and floor effects prevented their associative deficit from increasing under dual-task conditions. In order to examine this possibility, we excluded participants who scored below .4 on the associative test in the FA condition, leaving 24 high-processing and 16 low-processing individuals in the analysis (see Figure 15).

Figure 15. Memory Performance for High- vs. Low-Online Math Accuracy Individuals Who Performed Over .4 on the Associative Test in the FA Condition (with Standard Error Bars) in Experiment 3.



A second 2 (test) x 4 (dual) x 2 (processing) ANOVA was conducted using the modified sample. The triple interaction was not significant, F (3, 114) = .25, p>.05, η_p^2=.01, but the two-way interaction of dual-task and test was, F (3, 114) = 6.61, p<.001, η_p^2=.15. Further comparisons revealed that all individuals indeed showed an associative deficit in the division condition compared to the FA condition, F (1, 39) = 22.23, p<.001, η_p^2=.36. Thus, this result suggests that the reason the low-processing group did not show an associative deficit in any of dual-task conditions was potentially due to a floor effect.

Discussion

The results for the secondary task showed that performance in the baseline condition of the math task was better than in the dual-task conditions. However, participants' addition and subtraction performance were not significantly different. Apparently, although we assumed that the addition task would be significantly easier than subtraction task, this was not the case.

Similar to Experiment 2, in which we simulated an associative deficit in young adults by reducing the storage WM component, we successfully simulated an increased associative deficit in young adults by manipulating the processing demands of the secondary task. Unlike Experiments 1 and 2, however, the results of Experiment 3 showed that increasing the processing demands of the math task especially hurt associative test performance compared to the item test, thus indicating a larger associative deficit as a function of processing demands. This result suggests that a reduction in the processing component of WM could be one reason for older adults' binding deficit.

Splitting the young adults into high- and low-processing groups, based on their online math performance in the WM span task, showed that young adults who performed poorly in the online processing component of the O-Span task also showed an associative deficit in the FA condition compared to those who performed well in the math task. Moreover, as in Experiments 1 and 2, the high-processing group showed larger associative deficits in the dual-task conditions as the concurrent task became more demanding, while the low-processing group did not. However, when we examined only participants who performed above .4 on the associative test in the FA condition, we found similar patterns in both processing groups, where both groups' associative memory declined as the demands of WM processing increased. Thus, together these results suggest that older adults' reduction in the processing component of WM may be one reason for their associative deficit.

General Discussion

Older adults have an associative deficit compared to younger adults, characterized by greater age differences in an associative, relative to an item recognition test (e.g., Bastin & Van der Linden, 2006; Castel & Craik, 2003; Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, Guez, Kilb, et al., 2004; Naveh-Benjamin, Hussain, et al., 2003; Old & Naveh-Benjamin, 2008b). The purpose of the present study was to investigate whether reducing WM resources (either storage, processing, or both) is one reason older adults have an associative deficit. In order to test our hypothesis, we tested young adults to examine whether we can simulate an associative deficit using dual-task paradigms. In the following sections, we discuss our major findings.

Overall Primary Task Memory Performance

In Experiment 1, we were not successful in simulating an associative deficit in young adults by using a secondary N-back task (as a WM storage manipulation). We found that the difference between item and associative tests remained the same across the N-back conditions. In Experiment 2, we modified the procedure to eliminate potential floor effects by using shorter study lists as well as employing a different secondary task (still designed to consume WM storage resources). As a result, young participants in Experiment 2 showed an associative deficit in the dual-task conditions compared to the FA condition. Finally, in Experiment 3, we were also able to simulate an associative deficit in young adults by manipulating the amount of WM processing resources. Furthermore, their associative deficit increased as the secondary task required more WM processing resources. Hence, we successfully simulated the associative deficit in young adults, using a dual-task paradigm.

This result is different from previous studies which failed to simulate an associative deficit in young adults using DA paradigms (e.g., Craik et al., 2010: Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, Guez, Kilb, et al., 2004; Naveh-Benjamin, Guez, et al., 2003; Wang et al., 2010). As discussed earlier, the difference between the present study and the previous DA studies that manipulated attentional resources is the type of the secondary tasks used. The DA tasks that did not simulate an associative deficit in young adults did not require participants to store information in their WM or to engage elaborative WM processing. In addition, those DA studies did not manipulate the difficulty of a secondary task in terms of how demanding the secondary task was. In contrast, the secondary tasks used in the current study require WM, tapping incrementally into either storage or processing resources. Thus, our results indicate that what kinds of secondary task are used is important in order to simulate an associative deficit in young adults under the dual-task condition.

Although we successfully simulated an associative deficit in young adults in Experiments 2 and 3, we found similarities and differences between the two experiments. In both studies, item memory performance dropped once the dual-task was administrated but stayed the same across the dual-task conditions. Additionally, there was only a relatively small decline in item memory from FA to dual-task conditions, which is in line with other results that typically show smaller age differences item memory than associative memory performance (e.g., Craik et al., 2010: Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, Guez, Kilb, et al., 2004; Naveh-Benjamin, Guez, et al., 2003; Naveh-Benjamin, Hussain, et al., 2003; Wang et al., 2010). Such findings may indicate that both older adults and younger adults undergoing dual-task conditions requiring WM resources still have enough resources to encode and process each component even though their WM resources are reduced.

We also observed some interesting differences between Experiments 2 and 3. Although we found a similar overall pattern in item memory, the processing task decreased item memory by about 20% in Experiment 3 but the storage task decreased item memory by about 5% in Experiment 2. The results suggest that the storage of distracting information has a small effect on people's ability to remember studied items, but *processing* distracting information affects item memory much more. Thus, reducing the WM processing component could be more detrimental to memory performance overall, compared to reducing the WM storage component. However, it is possible that the differences between the two tasks in item memory were found because the storage task was easier than the processing task used in the present studies.

The most interesting difference between Experiments 2 and 3 emerged once the demands of the secondary tasks were incrementally increased. In Experiment 2, the manipulation of WM storage resources did not differentially affect associative (relative to item) memory performance, whether this was done by increasing the number of letters to be remembered or by manipulating the similarity of those letters. On the other hand, in Experiment 3, we found a differential effect of math operations on participants' associative memory. In particular, as the demands for processing WM capacity increased, participants' associative memory declined. Thus, increasing the demands of the WM processing component affected associative memory, whereas increasing the demands of the WM storage component had no incremental effect on associative memory. These results suggest that distracting information disrupts associative memory. However, while the amount of distracting information does not seem to have an impact on associative memory performance, increasing the processing demands of distracting information incrementally impairs associative memory.

Comparing Experiments 2 and 3 revealed that a reduction of WM resources, both storage and processing, impairs associative memory more than item memory. These results are in line with WM studies that found an associative deficit in young adults in WM/STM (Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Hartman & Warren, 2005; Mitchell et al., 2000). Our results suggest that older adults' associative deficit could be due to their reduced WM capacity. More specifically, a reduction in WM processing disrupts associative memory more than a reduction in WM storage, suggesting that older adults' associative deficit may be best explained by their reduced WM processing. These results are in line with previous research (e.g., Baddeley, 1986; Morris et al., 1988; Salthouse 1987; Salthouse & Babcock, 1991; Stine & Wingfield, 1987; Whiting & Smith,1997).

Another possible reason we found an effect of task difficulty in Experiment 3 (but not Experiment 2) is that there were greater differences among the time requirements for the various secondary task conditions in Experiments 2 and 3. According to the time-based resource-sharing hypothesis (e.g., Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007), increasing the time demands of a secondary task decreases memory performance for the primary task because there is less total time available to process primary task information. In Experiment 2, the 2L and 3L tasks elicited an associative deficit, whereas the 4L task did not. Based on the time-based resource-sharing hypothesis, could this be due to the 2L and 3L tasks requiring more processing time than the 4L condition, leaving participants with less time available to encode name-face pairs and resulting in a tradeoff between secondary task time and associative memory performance? Likewise, could it be that the larger effect of dual-task on the associative test in Experiment 3 in the division task than in the addition and subtractions ones, was due to the former requiring more time than the latter tasks, preventing participants from spending the necessary time to encode each name-face pair? These explanations were examined with additional analyses (see Appendix D), but the results do not support the time-based resource-sharing hypothesis as an explanation for these differential effects.

In sum, the present study was the first to examine whether older adults' associative deficit can be explained by a reduction in WM storage or processing resources by simulating an associative deficit in young adults. We successfully simulated an associative deficit in young adults using a dual-task paradigm, unlike the previous DA studies that failed to do so. Moreover, we found that reducing the WM processing component disrupted associative memory more than reducing the WM storage component. The results indicate that older adults' associative deficit can be due to a reduction in WM resources -- especially the reduced WM processing component.

High- vs. Low-Span/Processing Groups

Since at least one previous study (Oberauer, 2005, Experiment 2) showed that low-span young adults behave like older adults in a binding task, we were also interested in whether the low-performing groups in the O-span task would show an associative deficit. To examine this hypothesis, the data were split into high- and low-span groups in Experiments 1 and 2, based on their O-span score. In Experiment 3, we split our data into high-processing and low-processing groups based on how well participants solved the math operations task in the O-span. As hypothesized, low-performing participants (whether low-span or low-processing) showed an associative deficit relative to their high-performing counterparts under FA conditions, suggesting that reduced WM resources can be one reason older adults have a binding deficit.

Even though we could not find a larger associative deficit in any of the dual-task conditions for the low-processing group (possibly due to a floor effect, which is discussed later) in Experiment 3, both the high- and low-processing groups showed a similar pattern in which only associative memory was disrupted by dual-task conditions. Thus, these results provide additional support for the hypothesis that older adults' associative deficit is due to a reduction in WM processing.

To further investigate whether a reduction in WM resources disrupts associative memory more than item memory, we conducted additional analyses by combining the data from all three experiments (see Appendix E). When we collapsed across high-span and high-processing groups to create a high-WM group (and the same for the low-WM group), we again found that the low-WM group had an associative deficit relative to the high-WM group in the FA condition, providing further evidence that a reduction in WM resources may be one reason older adults have an associative deficit.

Unlike the FA condition, the high-span individuals were more affected by the dual-task compared to the low-span individuals in Experiments 1 and 2. However, the high-span groups did not show an increase in their associative deficits as the demands of WM storage component increased in Experiment 1 and 2. These results were inconsistent with our prediction in which we expected to keep observing increased associative deficit in both high- and low-span groups in the dual-task conditions if a reduction in WM storage disrupts associative memory. These results look puzzling, but they are actually consistent with the overall results (before splitting the data into high- and low-groups).

In Experiment 2, we found that increasing WM storage demands did not have any additive effect on participants' associative deficit, which is consistent with the finding that there was no additive effect of the dual-task on the low-span group's associative deficit because their associative deficit was already reduced under FA. On the other hand, the high-span group's associative deficit became larger once the dual-task was administrated because their WM storage resources were reduced by the dual-task, which is consistent with the result that adding the letter task impaired associative memory. However, increasing WM storage demands did not have any incremental effect on the high-span's associative memory, which is again consistent with the finding that increasing the number of letters had no incremental effect on associative memory. Thus, high- and low-span individuals are mimicking the patterns we found in the overall results in Experiment 2.

In contrast to Experiments 1 and 2, we found that both the high- and low-processing groups were impaired in the dual-task conditions in Experiment 3 when the concurrent task involved WM processing. Although the low-processing group showed a similar pattern to the high-processing group in associative memory (which declined as the demands of the WM processing task increased), this group's associative deficit did not increase in the dual-task conditions compared to their own FA condition. One potential reason for this pattern is a floor effect; since the low-processing participants already showed an associative deficit in the FA condition, this deficit could not increase as much as the associative deficit of high-processing participants could. To examine this possibility, we excluded those individuals who scored poorly (below .4) on the associative test in the FA condition and, as we expected, both high- and low-processing individuals showed a larger associative deficit in the division condition compared to their own FA condition. This indicates that if we eliminate floor effects by such as using a shorter study list like we used in Experiment 2, it is likely that we would see associative deficits for all participants in the dual-task conditions in Experiment 3.

A second possible explanation for why the low-performing individuals did not show a larger associative deficit in any one of the dual-task conditions is that they are less affected by a secondary task. Previous studies that investigated individual differences in storage capacity showed that low-span individuals were less susceptible to the effect of dual-task compared to high-span individuals (e.g., Kane & Engle, 2000; Rosen & Engle, 1997). This seems to fit with the results obtained in Experiments 1 and 2, in which the high-span group was more affected by the dual-task. However, as described earlier, the dual-task impaired memory performance in both the high- and low-processing groups in Experiment 3. Thus, this explanation cannot fully explain the current results.

Lastly, the present research is the first to examine individual differences on item and associative memory using scores obtained by the O-span task. Although the O-span task provides three different measures of performance -- storage capacity (based on the O-span score), processing speed (based on the RT for the math task), and processing accuracy (based on math accuracy) -- the O-span score is most often used in the WM literature to split the data into high- and low-span groups. This practice has been adopted since scores in math accuracy tend to be very high (above 85%) and are assumed to have less variability among participants compared to the O-span score, which varies from 0 to 75 (Conway et al., 2005). However, the present research shows that math accuracy can be useful for splitting the data into high- and low-processing groups and observing group differences in other cognitive tasks.

Additional analyses showed a strong positive relationship between the O-span score and math accuracy (see Appendix E). The results show that individuals who are more accurate in solving math problems in the O-span tend to remember more letters. This result is consistent with the previous studies (e.g., Engle, Cantor, & Carullo, 1992; Salthouse, Pink, & Tucker-Drob, 2008; Shah & Miyake, 1996; Unsworth et al., 2009; Waters & Caplan, 1996) and indicates that there are no processing and storage trade-offs, contrary to the hypothesis proposed by Carpenter and Just (1989), suggesting that these components work coordinately in the O-span task.

In conclusion, when we categorized individuals into high- and low-performance groups based on the O-span score or math accuracy, we found that low-performing participants showed an associative deficit compared to high-performing participants under FA. As opposed to our hypothesis, the low-performing groups did not show a larger associative deficit in the dual-task conditions, whereas the high-performing groups did show greater impairment in the associative test than the item test when WM storage resources were manipulated in Experiments 1 and 2. However, in Experiment 3, both high- and low-processing groups showed the same pattern in which the associative deficit increased as the dual-task demands increased. Taken together, these data indicate that reduced WM resources disrupt associative memory.

Why Do Older Adults Have an Associative Deficit?

The present study demonstrates that young adults will display an associative deficit under conditions in which their WM resources are reduced. In addition, low span/processing participants showed a larger associative deficit compared to their counterparts in the FA condition. Thus, the present research suggests that one reason older adults have an associative deficit is due to a reduction in their WM memory resources, especially their WM processing components. The results obtained by the present research are in line with our hypothesis that older adults consume most of their WM resources by encoding and processing each component, leading to relatively intact component memory but also leaving them with fewer WM resources to bind components into associations.

The present research also provides mixed results in terms of whether gradually increasing the WM demands of the secondary task has an impact on the size of the associative deficit. In Experiment 1, an associative deficit was not observed for the dual-task condition. In Experiment 2, the dual-task led to an associative deficit, which did not worsen with the increased storage demands of the secondary task. This is in line with a study conducted by Morris et al. (1988) in which they investigated whether increasing a memory load would have a differential effect on young and older adults in a sentence verification task. They found that increasing the memory load equally affected each age group, but it had no incremental effect on verification errors. Similar to this result, we found that adding a letter task impaired memory performance, but increasing the memory load had no incremental effect on memory in Experiments 1 and 2. On the other hand, Morris et al. found that increasing the sentence complexity (a processing manipulation) affected older adults more than young adults. This result is consistent with our results from Experiment 3, in which the WM processing manipulation had especially deleterious effects on associative memory and increasing the difficulty of the processing task had an incremental effect on associative memory.

Our results indicate that remembering associations requires the WM processing component more than the WM storage component. Morris et al. (1988) suggested the possibility that aging does not affect older adults' ability to store information, but it does affect their ability to process information. Taken together, we suspect that that aging affects both the storage and processing components of WM, but it might have a stronger effect on the processing component, leading to an associative deficit in older adults.

As mentioned earlier, the prefrontal deficit hypothesis (e.g., Dempster, 1992; West, 1996) postulates that aging affects older adults' frontal lobe functioning, and the changes in the frontal lobes may be the cause of older adults' cognitive decline. The frontal lobes have been linked to many cognitive abilities, including WM (see Baldo & Shimamura, 2002; Kane & Engle, 2002). Although we did not measure frontal lobe functioning in young adults, our findings may be interpreted by the prefrontal deficit hypothesis. For instance, it might be possible that aging impairs older adults' frontal lobe functioning, leading to reduced WM processing, which then contributes to their associative deficit. In addition, the frontal lobes are involved in executive processes that include the inhibition of irrelevant information (e.g., Chao & Knight, 1997; Knight, Stains, Swick, & Chao,1999). McNab and Klingberg (2008) showed that the prefrontal cortex and the basal ganglia are responsible for filtering out irrelevant information. Thus, reduced inhibition could be another mediator such that declining frontal lobes efficiency leads to reduced WM processing, which in turn leads to a reduction in inhibition and attention control, resulting in older adults' associative deficit. In addition, Kane and Engle (2002) reported a link between individual differences in WM and dorso-lateral prefrontal cortex (dPFC) functioning. They discussed that both low-WM individuals under FA and high-WM individuals under DA show similar patterns of cognitive functioning to patients with dPFC damage.

As discussed earlier, Kane and Engle (2000) argue that low-span individuals have less attentional control and are less efficient in controlling their attention and inhibiting irrelevant information compared to high-span individuals (see also Conway & Engle, 1996; Engle & Kane, 2003; Kane et al., 2001; Unsworth et al, 2004). In addition, Vogel, McCollough, and Machizawa (2005) showed that the low-WM capacity individuals were less efficient filtering out irrelevant information compared to the high-WM capacity individuals by measuring their brain waves. Therefore, high-performing groups would be expected to outperform low-performing groups in the FA condition, and this was found in all three experiments of the current study. However, high-performing groups tended to be more affected by the secondary task than low-performing groups, to the point that their performance became similar to the low-performing groups. As mentioned in Experiment 1, Engle and his colleagues (e.g., Kane & Engle, 2000; Rosen & Engle, 1997) have suggested that adding a concurrent task may not impair low-span individuals as much as it does for high-span individuals because the secondary task consumes the attention of low-spans that was formerly occupied by irrelevant distractions under FA. In contrast, high-span individuals who are able to inhibit irrelevant information under FA conditions suffer more from a concurrent task because they are forced to allocate some of their resources to it, preventing them from paying as much attention to the primary task. This explanation is in line with the current results. Furthermore, the fact that the high-performing participants' impairments were primarily seen in the associative test suggests that inhibition also has a role in older adults' associative deficit.

The current results are also consistent with the inhibition deficit theory proposed by Hasher and Zacks (1988), stating that older adults have less inhibitory efficiency compared to younger adults, and previous studies found results to support their theory (e.g., Hasher, Stoltzfus, Zacks, & Rypma, 1991). Ryan, Leung, Turk-Browne, and Hasher (2007) also reported that older adults have both inhibition and associative deficits by contrasting their eye movements during encoding to young adults. Moreover, Lustig, Hasher, and Zacks (2007) argue that reduced WM resources in older adults are actually the product of deficient inhibitory ability rather than inhibition being the result of reduced WM resources. Though the current results cannot determine the causal relationship between WM resources and inhibition, our results may suggest a link between the reduced WM resources and inhibition in associative memory.

To summarize, we found evidence that reduced WM resources in younger adults contributes to impaired associative memory but relatively intact item memory, which characterizes the associative deficit of older adults. However, further research is needed to investigate whether a reduction in WM resources is the reason older adults have an associative deficit or if other mediators (e.g., frontal lobe functioning and/or inhibitory efficiency) are also involved.

Future Directions

Since the present research was the first to examine the role of WM resources in associative memory by trying to simulate the associative deficit in young adults, these results should be replicated using different methods. It is also important to investigate why associative memory was disrupted even more by gradually increasing WM processing demands of the secondary task (Experiment 3) but not by gradually increasing its WM storage demands (Experiments 1 and 2). It is possible that if a more difficult storage task is used (e.g., a larger number of letters in the letter task or words instead of letters), we would see a larger associative deficit as the secondary task becomes more difficult. This is also true if participants use chunking to remember letters, as increasing the amount of to-be-remembered letters will also increase the number of chunks, which may lead to an increased associative deficit in the dual-task condition. This point is relevant, considering that secondary task performance for the letter task in Experiment 2 was substantially higher than the math task in Experiment 3.

In addition, many previous studies investigating an associative deficit in older adults use a yes-no recognition test rather than the forced-choice version used in the current studies (e.g., Kilb & Naveh-Benjamin, 2007; Naveh-Benjamin, Guez, et al., 2003; Naveh-Benjamin, Hussain, et al., 2003). Although studies have consistently shown an associative deficit using both test types, incorporating yes-no recognition tests would allow us to examine hits and false alarms separately. Previous studies (e.g., Kilb & Naveh-Benjamin, 2008, 2011; Naveh-Benjamin et al., 2009) found that older adults tend to have more false alarms compared to young adults, whereas the groups show equivalent hit rates. In addition, Castel and Craik (2003) reported that young adults under DA had reduced hit rates but slightly increased false-alarm rates on an associative recognition test, whereas older adults had an increased false-alarm rate and a reduced hit rate, compared to younger adults under FA even though the two age groups showed equivalent overall associative memory performance. An interesting question is whether similar patterns for hits and false alarms will be observed when WM resources are reduced as well as when the data are split into high- and low-WM groups. The low-WM group as well as young adults performing dual-tasks should show similar specific patterns to older adults.

Our results do not rule out the possibility that the reason older adults have an associative deficit is due to reduced attentional resources (Craik, 1982, 1983, 1986). The difference between the DA tasks used in the previous studies and the dual-tasks in the present experiments are not only in how much WM resources are required but also how often participants need to make their responses during the dual-task condition. DA tasks require participants' constant responses, such as responding to a series of tones one by one, indicating the location of an asterisk appearing in one of the four locations on a computer screen, or tracing the path of a moving target. Although the dual-tasks used in the present set of experiments required constant vigilance, they did not require participants to respond to every stimulus (except in Experiment 1). Interestingly, when we used the N-back task, which required participants to respond to every stimulus, we failed to simulate an associative deficit in young adults, similar to the previous DA studies. On the other hand, when we used the dual-task that did not require participants to respond to every stimulus, we successfully simulated an associative deficit in young adults. It is possible that the continuous reaction time secondary task is too demanding and impaired both item and associative memory. Interestingly, when a relatively easier and less demanding DA task was used (easier because participants did not respond to every stimulus), young adults under DA behaved similarly to older adults (Castel & Craik, 2003). Thus, if the number of required responses to the DA task is decreased, it may be possible to observe an associative deficit in young adults even for secondary tasks that do not tap into WM resources.

The present research used the dual-task only at encoding, but it is important to also examine the effect of dual-task at retrieval. Some previous DA studies have reported that the DA task disrupts memory performance minimally when the DA task is administrated at retrieval compared to when it is performed during the encoding of information (e.g., Baddeley, Lewis, Eldridge, & Thompson, 1984; Castel & Craik, 2003; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Naveh-Benjamin, Craik, Guez, & Dori, 1998; Naveh-Benjamin, Kilb, & Fisher, 2006), which is why we added the concurrent task at encoding only in the present research. However, it may be informative to manipulate WM resources at both encoding and retrieval since older adults presumably have reduced WM resources at both. As mentioned earlier, previous DA studies show that manipulating attention at retrieval had minimal effects on memory performance compared to when attention was manipulated at encoding. Park, Smith, Dudley, and

Lafronza (1989) also reported that the effect of DA was very small during retrieval and that the effect was similar for young and older adults. Thus, according to previous DA studies, we would expect a reduction in WM resources at retrieval to have only a small effect on memory performance. However, since older adults have reduced WM resources not only at encoding but also at retrieval, it is possible that a reduction in WM resources at retrieval has an additive effect in addition to a reduction in WM resources at encoding, especially when WM processing resources are reduced.

In summary, the present set of experiments show that young adults exhibited an associative deficit like older adults when the amount of WM resources available at encoding was manipulated. Furthermore, the present study also showed a difference between high- and low-WM span/processing young individuals' associative memory. These results support our hypothesis that reduced WM resources is one reason older adults have an associative deficit. However, the present results also suggest the possibility that a reduction in WM resources may cause older adults to lose their ability to inhibit irrelevant information and this might lead to a decline in their ability to remember associations. More research is needed to examine this hypothesis.

References

Ackerman, P. L., & Rolfhus, E. L. (1999). The locus of adult intelligence: Knowledge, abilities, and nonability traits. *Psychology and Aging, 14*(2), 314-330. doi: 10.1037/0882-7974.14.2.314

Allen, R. J., Hitch, G. J., & Baddeley, A. D. (2009). Cross-modal binding and working memory. *Visual Cognition, 17*(1-2), 83-102. doi: 10.1080/13506280802281386

Anderson, N. D., Iidaka, T., Cabeza, R., Kapur, S., McIntosh, A. R., & Craik, F. I. M. (2000). The effects of divided attention on encoding- and retrieval-related brain activity: A PET study of younger and older adults. *Journal of Cognitive Neuroscience, 12*(5), 775-792. doi: 10.1162/089892900562598

Baddeley, A. D. (1966). The influence of acoustic and semantic similarity on long-term memory for word sequences. *The Quarterly Journal of Experimental Psychology, 18*(4), 302-309. doi: 10.1080/14640746608400047

Baddeley, A. (1986). *Working memory*. New York, NY US: Clarendon Press/Oxford University Press.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4*(11), 417-423. doi: 10.1016/s1364-6613(00)01538-2

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed). The psychology of learning and motivation: Advances in research and theory. (pp. 47-89). New York: Academic Press.

Baddeley, A., Lewis, V., Eldridge, M., & Thomson, N. (1984). Attention and retrieval from long-term memory. *Journal of Experimental Psychology: General, 113*(4), 518-540. doi: 10.1037/0096-3445.113.4.518

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

Baldo, J. V., & Shimamura, A. P. (2000). Spatial and color working memory in patients with lateral prefrontal cortex lesions. *Psychobiology, 28*(2), 156-167.

Baldo, J. V., & Shimamura, A. P. (2002). Frontal lobes and memory. In A. D. Baddeley, M. D. Kopelman, & B. A. Wilson (Eds.), *The Handbook of Memory Disorders* (2nd Second Edition), Wiley & Sons, Inc.: London

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time Constraints and Resource Sharing in Adults' Working Memory Spans. *Journal of Experimental Psychology: General*, *133*(1), 83-100. doi: 10.1037/0096-3445.133.1.83

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(3), 570-585. doi: 10.1037/0278-7393.33.3.570

Bastin, C., & Van der Linden, M. (2006). The effects of aging on the recognition of different types of associations. *Experimental Aging Research, 32*(1), 61-77. doi: 10.1080/03610730500326291

Beier, M. E., & Ackerman, P. L. (2001). Current-events knowledge in adults: An investigation of age, intelligence, and nonability determinants. *Psychology and Aging, 16*(4), 615-628. doi: 10.1037/0882-7974.16.4.615

Bender, A. R., & Raz, N. (2012). Age-related differences in recognition memory for items and associations: Contribution of individual differences in working memory and metamemory. *Psychology and Aging*. doi: 10.1037/a0026714

Brown, L. A., & Brockmole, J. R. (2010). The role of attention in binding visual features in working memory: Evidence from cognitive ageing. *The Quarterly Journal of Experimental Psychology, 63*(10), 2067-2079. doi: 10.1080/17470211003721675

Cabeza, R., Kapur, S., Craik, F. I. M., & McIntosh, A. R. (1997). Functional neuroanatomy of recall and recognition: A PET study of episodic memory. *Journal of Cognitive Neuroscience, 9*(2), 254-265. doi: 10.1162/jocn.1997.9.2.254

Castel, A. D., & Craik, F. I. M. (2003). The Effects of Aging and Divided Attention on Memory for Item and Associative Information. *Psychology and Aging, 18*(4), 873-885. doi: 10.1037/0882-7974.18.4.873

Chalfonte, B. L., & Johnson, M. K. (1996). Feature memory and binding in young and older adults. *Memory & Cognition*, *24*(4), 403-416. doi: 10.3758/bf03200930

Chao, L. L., & Knight, R. T. (1996). Prefrontal and posterior cortical activation during auditory working memory. *Cognitive Brain Research*, *4*(1), 27-37. doi: 10.1016/0926-6410(95)00043-7

Chao, L. L., & Knight, R. T. (1997). Prefrontal deficits in attention and inhibitory control with aging. *Cerebral Cortex, 7*(1), 63-69. doi: 10.1093/cercor/7.1.63

Chen, T., & Naveh-Benjamin, M. (2012). Assessing the associative deficit of older adults in long-term and short-term/working memory. *Psychology and Aging*. doi: 10.1037/a0026943

Cherry, K. E., & Park, D. C. (1993). Individual difference and contextual variables influence spatial memory in younger and older adults. *Psychology and Aging, 8*(4), 517-526. doi: 10.1037/0882-7974.8.4.517

Conrad, R. (1964). Acoustic confusions in immediate memory. *British Journal of Psychology, 55*(1), 75-84. doi: 10.1111/j.2044-8295.1964.tb00899.x

Conrad, R., & Hull, A. J. (1964). Information, acoustic confusion and memory span. *British Journal of Psychology*, *55*(4), 429-432. doi: 10.1111/j.2044-8295.1964.tb00928.x

Conway, A. R. A., & Engle, R. W. (1996). Individual Differences in Working Memory Capacity: More Evidence for a General Capacity Theory. *Memory, 4*(6), 577-590. doi: 10.1080/741940997

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review*, *12*(5), 769-786. doi: 10.3758/bf03196772

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104*(2), 163-191. doi: 10.1037/0033-2909.104.2.163

Cowan, N. (1995). *Attention and memory: An integrated framework*. New York, NY US: Oxford University Press.

Cowan, N. (1996). Short-term memory, working memory, and their importance in language processing. *Topics in Language Disorders, 17*(1), 1-18. doi: 10.1097/00011363-199611000-00003

Cowan, N. (1999). An Embedded-Processes Model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control.* (pp. 62-101). New York, NY US: Cambridge University Press.

Cowan, N. (2005). *Working memory capacity*. New York, NY US: Psychology Press.

Cowan, N., Naveh-Benjamin, M., Kilb, A., & Saults, J. S. (2006). Life-span development of visual working memory: When is feature binding difficult? *Developmental Psychology, 42*(6), 1089-1102. doi: 10.1037/0012-1649.42.6.1089

Craik, F. I. M. (1982). Selective changes in encoding as a function of reduced processing capacity. In F. Klix, J. Hoffman, & E. van der Meer (Eds.), *Cognitive Research in Psychology* (pp.152-161). Berlin: Deutscher Verlag der Wissenschaffen.

Craik, F. I. M. (1983). On the transfer of information from temporary to permanent memory. *Philosophical Transaction of the Royal Society of London, Series B, 302,* 341-359.

Craik, F. I. M. (1986). A functional account of age differences in memory. In F. Klix & H. Hagendorf (Eds.), *Human Memory and Cognitive Capabilities, Mechanisms and Performance* (pp.409-422). Amsterdam: North-Holland and Elsevier.

Craik, F. I. M., Govoni, R., Naveh-Benjamin, M., & Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology: General, 125*(2), 159-180. doi: 10.1037/0096-3445.125.2.159

Craik, F. I. M., Luo, L., & Sakuta, Y. (2010). Effects of aging and divided attention on memory for items and their contexts. *Psychology and Aging, 25*(4), 968-979. doi: 10.1037/a0020276

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning & Verbal Behavior, 19*(4), 450-466. doi: 10.1016/s0022-5371(80)90312-6

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review, 12*(1), 45-75. doi: 10.1016/0273-2297(92)90003-k

Dobbs, A. R., & Rule, B. G. (1989). Adult age differences in working memory. *Psychology and Aging, 4*(4), 500-503. doi: 10.1037/0882-7974.4.4.500

Duff, S. C., & Logie, R. H. (1999). Storage and processing in visuo-spatial working memory. *Scandinavian Journal of Psychology, 40*(4), 251-259. doi: 10.1111/1467-9450.404124

Duff, S. C., & Logie, R. H. (2001). Processing and storage in working memory span. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 54A*(1), 31-48. doi: 10.1080/02724980042000011

Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*(5), 972-992. doi: 10.1037/0278-7393.18.5.972

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

Foos, P. W. (1989). Adult age differences in working memory. *Psychology and Aging, 4*(3), 269-275. doi: 10.1037/0882-7974.4.3.269

Gick, M. L., Craik, F. I., & Morris, R. G. (1988). Task complexity and age differences in working memory. *Memory & Cognition, 16*(4), 353-361. doi: 10.3758/bf03197046

Hartman, M., & Warren, L. H. (2005). Explaining age differences in temporal working memory. *Psychology and Aging, 20*(4), 645-656. doi: 10.1037/0882-7974.20.4.645

Hasher, L., Stoltzfus, E. R., Zacks, R. T., & Rypma, B. (1991). Age and inhibition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17*(1), 163-169. doi: 10.1037/0278-7393.17.1.163

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99*(1), 122-149. doi: 10.1037/0033-295x.99.1.122

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General, 130*(2), 169-183. doi: 10.1037/0096-3445.130.2.169

Kane, M. J., & Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*(2), 336-358. doi: 10.1037/0278-7393.26.2.336

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review, 9*(4), 637-671. doi: 10.3758/bf03196323

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General, 132*(1), 47-70. doi: 10.1037/0096-3445.132.1.47

Kilb, A., & Naveh-Benjamin, M. (2007). Paying attention to binding: Further studies assessing the role of reduced attentional resources in the associative deficit of older adults. *Memory & Cognition*, *35*(5), 1162-1174. doi: 10.3758/bf03193486

Kilb, A., & Naveh-Benjamin, M. (2011). The effects of pure pair repetition on younger and older adults' associative memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(3), 706-719. doi: 10.1037/a0022525

Knight, R. T., Staines, W. R., Swick, D., & Chao, L. L. (1999). Prefrontal cortex regulates inhibition and excitation in distributed neural networks. *Acta Psychologica*, *101*(2–3), 159-178. doi: 10.1016/s0001-6918(99)00004-9

Kramer, A. F., Humphrey, D. G., Larish, J. F., & Logan, G. D. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9*(4), 491-512. doi: 10.1037/0882-7974.9.4.491

Light, L. L., & Anderson, P. A. (1985). Working-memory capacity, age, and memory for discourse. *Journal of Gerontology, 40*(6), 737-747. doi: 10.1093/geronj/40.6.737

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, 390, 279-281. doi:10.1038/36846

Lustig, C., Hasher, L., & Zacks, R. T. (2007). Inhibitory deficit theory: Recent developments in a 'new view'. In D. S. Gorfein & C. M. MacLeod (Eds.), *Inhibition in cognition.* (pp. 145-162). Washington, DC US: American Psychological Association.

McElree, B. (2001). Working memory and focal attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*(3), 817-835. doi: 10.1037/0278-7393.27.3.817

McNab, F., & Klingberg, T. (2008). Prefrontal cortex and basal ganglia control access to working memory. *Nature Neuroscience*, *11*(1), 103-107. doi: 10.1038/nn2024

Mitchell, K. J., Johnson, M. K., Raye, C. L., Mather, M., & D'Esposito, M. (2000). Aging and reflective processes of working memory: Binding and test load deficits. *Psychology and Aging, 15*(3), 527-541. doi: 10.1037/0882-7974.15.3.527

Miyake, A., & Shah, P. (1999). *Models of working memory: Mechanisms of active maintenance and executive control*. New York, NY US: Cambridge University Press.

Morey, C. C., & Cowan, N. (2004). When visual and verbal memories compete: Evidence of cross-domain limits in working memory. *Psychonomic Bulletin & Review, 11*(2), 296-301. doi: 10.3758/bf03196573

Morris, R. G., Gick, M. L., & Craik, F. I. (1988). Processing resources and age differences in working memory. *Memory & Cognition, 16*(4), 362-366. doi: 10.3758/bf03197047

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: Tests of an associative deficit hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*(5), 1170-1187. doi: 10.1037/0278-7393.26.5.1170

Naveh-Benjamin, M., Cowan, N., Kilb, A., & Chen, Z. (2007). Age-related differences in immediate serial recall: Dissociating chunk formation and capacity. *Memory & Cognition, 35*(4), 724-737. doi: 10.3758/bf03193310

Naveh-Benjamin, M., Craik, F. I. M., Guez, J., & Dori, H. (1998). Effects of divided attention on encoding and retrieval processes in human memory: Further support for an asymmetry. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*(5), 1091-1104. doi: 10.1037/0278-7393.24.5.1091

Naveh-Benjamin, M., Guez, J., Kilb, A., & Reedy, S. (2004). The Associative Memory Deficit of Older Adults: Further Support Using Face-Name Associations. *Psychology and Aging, 19*(3), 541-546. doi: 10.1037/0882-7974.19.3.541

Naveh-Benjamin, M., Guez, J., & Marom, M. (2003). The effects of divided attention at encoding on item and associative memory. *Memory & Cognition, 31*(7), 1021-1035. doi: 10.3758/bf03196123

Naveh-Benjamin, M., Guez, J., & Shulman, S. (2004). Older adults' associative deficit in episodic memory: Assessing the role of decline in attentional resources. *Psychonomic Bulletin & Review, 11*(6), 1067-1073. doi: 10.3758/bf03196738

Naveh-Benjamin, M., Hussain, Z., Guez, J., & Bar-On, M. (2003). Adult age differences in episodic memory: Further support for an associative-deficit hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*(5), 826-837. doi: 10.1037/0278-7393.29.5.826

Naveh-Benjamin, M., Kilb, A., & Fisher, T. (2006). Concurrent task effects on memory encoding and retrieval: Further support for an asymmetry. *Memory & Cognition, 34*(1), 90-101. doi: 10.3758/bf03193389

Naveh-Benjamin, M., Shing, Y. L., Kilb, A., Werkle-Bergner, M., Lindenberger, U., & Li, S.-C. (2009). Adult age differences in memory for name-face associations: The effects of intentional and incidental learning. *Memory, 17*(2), 220-232. doi: 10.1080/09658210802222183

Norman, S., Kemper, S., & Kynette, D. (1992). Adults' reading comprehension: Effects of syntactic complexity and working memory. *Journals of Gerontology, 47*(4), 258-265. doi: 10.1093/geronj/47.4.P258

Oberauer, K. (2005). Binding and Inhibition in Working Memory: Individual and Age Differences in Short-Term Recognition. *Journal of Experimental Psychology: General, 134*(3), 368-387. doi: 10.1037/0096-3445.134.3.368

Old, S. R., & Naveh-Benjamin, M. (2008a). Age-related changes in memory: Experimental approaches. In S. M. Hofer & D. F. Alwin (Eds.), *Handbook of cognitive aging: Interdisciplinary perspectives.* (pp. 151-167). Thousand Oaks, CA US: Sage Publications, Inc.

Old, S. R., & Naveh-Benjamin, M. (2008b). Differential effects of age on item and associative measures of memory: A meta-analysis. *Psychology and Aging, 23*(1), 104-118. doi: 10.1037/0882-7974.23.1.104

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging, 17*(2), 299-320. doi: 10.1037/0882-7974.17.2.299

Park, D. C., Smith, A. D., Dudley, W. N., & Lafronza, V. N. (1989). Effects of age and a divided attention task presented during encoding and retrieval on memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*(6), 1185-1191. doi: 10.1037/0278-7393.15.6.1185

Parkin, A. J., & Lawrence, A. (1994). A dissociation in the relation between memory tasks and frontal lobe tests in the normal elderly. *Neuropsychologia, 32*(12), 1523-1532. doi: 10.1016/0028-3932(94)90124-4

Rabinowitz, J. C., Craik, F. I., & Ackerman, B. P. (1982). A processing resource account of age differences in recall. *Canadian Journal of Psychology/Revue canadienne de psychologie, 36*(2), 325-344. doi: 10.1037/h0080643

Rosen, V. M., & Engle, R. W. (1997). The role of working memory capacity in retrieval. *Journal of Experimental Psychology: General, 126*(3), 211-227. doi: 10.1037/0096-3445.126.3.211

Ryan, J. D., Leung, G., Turk-Browne, N. B., & Hasher, L. (2007). Assessment of age-related changes in inhibition and binding using eye movement monitoring. *Psychology and Aging, 22*(2), 239-250. doi: 10.1037/0882-7974.22.2.239

Salthouse, T. A. (1987). Adult age differences in integrative spatial ability. *Psychology and Aging, 2*(3), 254-260. doi: 10.1037/0882-7974.2.3.254

Salthouse, T. A. (1991). *Theoretical perspectives on cognitive aging.* Hillsdale, NJ US: Lawrence Eribaum Associates.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*(3), 403-428. doi: 10.1037/0033-295x.103.3.403

Salthouse, T. A. (2006). Mental exercise and mental aging. *Perspectives on Psychological Science, 1*(1), 68-87. doi: 10.1111/j.1745-6916.2006.00005.x

Salthouse, T. A., & Babcock, R. L. (1991). Decomposing adult age differences in working memory. *Developmental Psychology, 27*(5), 763-776. doi: 10.1037/0012-1649.27.5.763

Salthouse, T. A., & Mitchell, D. R. (1989). Structural operational capacities in integrative spatial ability. *Psychology and Aging, 4*(1), 18-25. doi: 10.1037/0882-7974.4.1.18

Salthouse, T. A., Pink, J. E., & Tucker-Drob, E. M. (2008). Contextual analysis of fluid intelligence. *Intelligence, 36*(5), 464-486. doi: 10.1016/j.intell.2007.10.003

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General, 125*(1), 4-27. doi: 10.1037/0096-3445.125.1.4

Spencer, W. D., & Raz, N. (1995). Differential effects of aging on memory for content and context: A meta-analysis. *Psychology and Aging, 10*(4), 527-539. doi: 10.1037/0882-7974.10.4.527

Stebbins, G. T., Carrillo, M. C., Dorfman, J., Dirksen, C., Desmond, J. E., Turner, D. A., . . . Gabrieli, J. D. E. (2002). Aging effects on memory encoding in the frontal lobes. *Psychology and Aging, 17*(1), 44-55. doi: 10.1037/0882-7974.17.1.44

Stine, E. L., & Wingfield, A. (1987). Process and strategy in memory for speech among younger and older adults. *Psychology and Aging, 2*(3), 272-279. doi: 10.1037/0882-7974.2.3.272

Stine, E. A., & Wingfield, A. (1990). How much do working memory deficits contribute to age differences in discourse memory? *European Journal of Cognitive Psychology, 2*(3), 289-304. doi: 10.1080/09541449008406209

Stoltzfus, E. R., Hasher, L., & Zacks, R. T. (1996). Working memory and aging: Current status of the inhibitory view. In J. T. E. Richardson, R. W. Engle, L. Hasher, R. H. Logie, E. R. Stoltzfus, & R. T. Zacks (Eds.), *Working memory and human cognition* (pp.66-88). New York: Oxford University Press.

Stuss, D. T., Craik, F. I. M., Sayer, L., Franchi, D., & Alexander, M. P. (1996). Comparison of older people and patients with frontal lesions: Evidence from word list learning. *Psychology and Aging, 11*(3), 387-395. doi: 10.1037/0882-7974.11.3.387

Thornton, R., & Light, L. L. (2006). Language Comprehension and Production in Normal Aging. In J. E. Birren & K.W. Schaire (Eds.), *Handbook of the psychology of aging (6th ed.).* (pp. 261-287). Amsterdam Netherlands: Elsevier.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28*(2), 127-154. doi: 10.1016/0749-596x(89)90040-5

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*(3), 498-505. doi: 10.3758/bf03192720

Unsworth, N., Redick, T. S., Heitz, R. P., Broadway, J. M., & Engle, R. W. (2009). Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage. *Memory, 17*(6), 635-654. doi: 10.1080/09658210902998047

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working Memory Capacity and the Antisaccade Task: Individual Differences in Voluntary Saccade Control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*(6), 1302-1321. doi: 10.1037/0278-7393.30.6.1302

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature,* 438, 500-503. doi:10.1038/04171

Wang, W.-c., Dew, I. T. Z., & Giovanello, K. S. (2010). Effects of aging and prospective memory on recognition of item and associative information. *Psychology and Aging, 25*(2), 486-491. doi: 10.1037/a0017264

Waters, G. S., & Caplan, D. (1996). The measurement of verbal working memory capacity and its relation to reading comprehension. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 49A*(1), 51-79. doi: 10.1080/027249896392801

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120*(2), 272-292. doi: 10.1037/0033-2909.120.2.272

Whiting, W. L. I. V., & Smith, A. D. (1997). Differential age-related processing limitations in recall and recognition tasks. *Psychology and Aging, 12*(2), 216-224. doi: 10.1037/0882-7974.12.2.216

Zacks, R. T., & Hasher, L. (2006). Aging and Long-Term Memory: Deficits Are Not Inevitable. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change.* (pp.162-177). New York, NY US: Oxford University Press.

Appendix A: Tables of Secondary Task Performance and Memory Performance in Experiment 1

Table A1

Secondary Task Performance as a Function of N-Back and Dual-Task Condition in Experiment 1

	N-Back		
	1-BacK	**2-Back**	**3-Back**
Baseline	.95 (.03)	.88 (.14)	.83 (.09)
Dual-Task	.87 (.13)	.79 (.15)	.77 (.09)

Note. Standard deviations are in parentheses.

Table A2

Memory Performance as a Function of Test and Dual-Task Condition in Experiment 1

	Test			
	Face	**Name**	**Item**	**Associative**
FA	.75 (.22)	.60 (.26)	.68 (.18)	.52 (.33)
1-Back	.44 (.29)	.31(.34)	.37 (.24)	.18 (.27)
2-Back	.38 (.31)	.26 (.29)	.31 (.23)	.17 (.27)
3-Back	.40 (.30)	.28 (.33)	.33 (.22)	.23 (.25)

Note. Standard deviations are in parentheses. FA=Full Attention

Table A3

Memory Performance as a Function of Test, Dual-Task, and O-Span Group in Experiment 1

		Test			
		Face	**Name**	**Item**	**Associative**
High-Span					
	FA	.72 (.25)	.61 (.28)	.67 (.20)	.60 (.31)
	1-Back	.47 (.27)	.37(.35)	.42 (.23)	.20 (.28)
	2-Back	.39 (.32)	.33 (.26)	.35 (.24)	.16 (.31)
	3-Back	.41 (.32)	.36 (.30)	.37 (.22)	.27 (.29)
Low-Span					
	FA	.79 (.18)	.59 (.24)	.69 (.15)	.45 (.33)
	1-Back	.41 (.30)	.25(.32)	.32 (.25)	.17 (.27)
	2-Back	.37 (.31)	.20 (.30)	.27 (.21)	.18 (.22)
	3-Back	.39 (.29)	.20 (.35)	.30 (.22)	.20 (.21)

Note. Standard deviations are in parentheses. FA=Full Attention

Appendix B: Tables of Secondary Task Performance and Primary Memory Performance in Experiment 2

Table B1

Secondary Task Performance as a Function of Storage Task and Dual-Task Condition in Experiment 2

	Storage Task					
	Similar			**Dissimilar**		
	2L	**3L**	**4L**	**2L**	**3L**	**4L**
Baseline	.94 (.08)	.93 (.08)	.88 (.11)	.94 (.15)	.95 (.14)	.91 (.18)
Dual-Task	.87 (.14)	.86 (.12)	.78 (.13)	.90 (.18)	.91 (.14)	.89 (.17)

Note. Standard deviations are in parentheses.

Table B2

Memory Performance as a Function of Test and Dual-Task Condition in Experiment 2

		Test			
		Face	**Name**	**Item**	**Associative**
	FA	.81 (.29)	.78 (.26)	.79 (.21)	.59 (.27)
Similar					
	2L	.72 (.36)	.66 (.36)	.69 (.30)	.37 (.30)
	3L	.69 (.41)	.72 (.39)	.70 (.31)	.34 (.29)
	4L	.69 (.33)	.67 (.32)	.68 (.25)	.39 (.31)
Dissimilar					
	2L	.77 (.30)	.67 (.41)	.72 (.26)	.36 (.35)
	3L	.71 (.37)	.73 (.36)	.72 (.29)	.38 (.35)
	4L	.75 (.32)	.69 (.29)	.72 (.23)	.45 (.28)

Note. Standard deviations are in parentheses. FA=Full Attention

Table B3

Memory Performance as a Function of Test and Dual-Task Condition in Experiment 2 after Collapsing the Storage Task Condition

	Test			
	Face	**Name**	**Item**	**Associative**
FA	.81 (.29)	.78 (.26)	.80 (.21)	.59 (.27)
2L	.75 (.27)	.66(.29)	.71 (.22)	.36 (.26)
3L	.70 (.32)	.72 (.29)	.71 (.25)	.36 (.27)
4L	.72 (.24)	.68 (.24)	.70 (.18)	.42 (.23)

Note. Standard deviations are in parentheses. FA=Full Attention

Table B4

Memory Performance as a Function of Test, Dual-Task, and O-Span Group in Experiment 2

		Test			
		Face	**Name**	**Item**	**Associative**
High-Span					
	FA	.80 (.35)	.77 (.27)	.79 (.26)	.67 (.22)
	2L	.78 (.22)	.73 (.25)	.76 (.18)	.34 (.32)
	3L	.73 (.31)	.76 (.32)	.74 (.26)	.37 (.30)
	4L	.74 (.22)	.72 (.19)	.73 (.16)	.44 (.25)
Low-Span					
	FA	.81 (.23)	.79 (.24)	.80 (.16)	.52 (.29)
	2L	.71 (.30)	.60 (.31)	.66 (.25)	.38 (.20)
	3L	.66 (.33)	.70 (.26)	.68 (.24)	.35 (.23)
	4L	.70 (.25)	.64 (.27)	.67 (.19)	.40 (.21)

Note. Standard deviations are in parentheses. FA=Full Attention

Appendix C: Tables of Secondary Task Performance and Memory Performance in Experiment 3

Table C1

Secondary Task Performance as a Function of Math Operation and Dual-Task Condition in Experiment 3

	Math Operation		
	Addition	**Subtraction**	**Division**
Baseline	.89 (.07)	.89 (.09)	.80 (.09)
Dual-Task	.79 (.12)	.79 (.13)	.75 (.10)

Note. Standard deviations are in parentheses. FA=Full Attention

Table C2

Memory Performance as a Function of Test and Dual-Task Condition in Experiment 3

	Test			
	Face	**Name**	**Item**	**Associative**
FA	.72 (.23)	.59 (.27)	.67 (.19)	.46 (.23)
Addition	.54 (.26)	.40(.29)	.47 (.21)	.33 (.25)
Subtraction	.49 (.32)	.45 (.28)	.47 (.24)	.25 (.28)
Division	.54 (.28)	.42 (.19)	.48 (.19)	.20 (.26)

Note. Standard deviations are in parentheses. FA=Full Attention

Table C3

Memory Performance as a Function of Test, Dual-Task, and Math Processing Group in Experiment 3

		Test		
	Face	**Name**	**Item**	**Associative**
High-Processing				
FA	.72 (.23)	.60 (.26)	.66 (.18)	.52 (.22)
Addition	.56 (.25)	.42(.29)	.49 (.20)	.35 (.23)
Subtraction	.46 (.31)	.45 (.28)	.45 (.21)	.25 (.25)
Division	.54 (.29)	.42 (.22)	.48 (.18)	.18 (.29)
Low-Processing				
FA	.73 (.23)	.58 (.28)	.66 (.21)	.40 (.22)
Addition	.53 (.27)	.39(.30)	.46 (.22)	.30 (.27)
Subtraction	.52 (.32)	.45 (.29)	.48 (.26)	.24 (.31)
Division	.54 (.27)	.42 (.25)	.48 (.20)	.21 (.24)

Note. Standard deviations are in parentheses. FA=Full Attention

Appendix D: Examination of the Time-Based Resource-Sharing Hypothesis Explanation

In Experiments 2 and 3, we found that young adults showed a larger associative deficit in the dual-task conditions compared to their own FA condition. However, we found an incremental effect of WM processing task on associative memory only in Experiment 3. One possible reason we found a difference between these two experiments is that the durations of storing and processing distracting information was different among the dual-task conditions in Experiments 2 and 3.

According to the time-based resource-sharing hypothesis (Barrouillet et al., 2004; Barrouillet et al., 2007), one pool of limited resources is used for both the processing and storage of information, so that only one can be completed at a time. For example, assume that encoding a name-face pair and performing a concurrent task require the same resources. If the total time to encode a name-face pair is 6 seconds, and participants spend 3 of those seconds performing the concurrent task, then they have only 3 seconds left to learn the name-face pair. If another concurrent task can be completed in only 2 seconds, then the participant would have 4 seconds to allocate towards learning names and faces. We should then expect to find a negative linear relationship between the total time needed to complete the secondary task and primary memory performance. Specifically, according to this model, we expect that the more time participants devote to storing and processing the secondary task, the lower their item and associative memory performance should be.

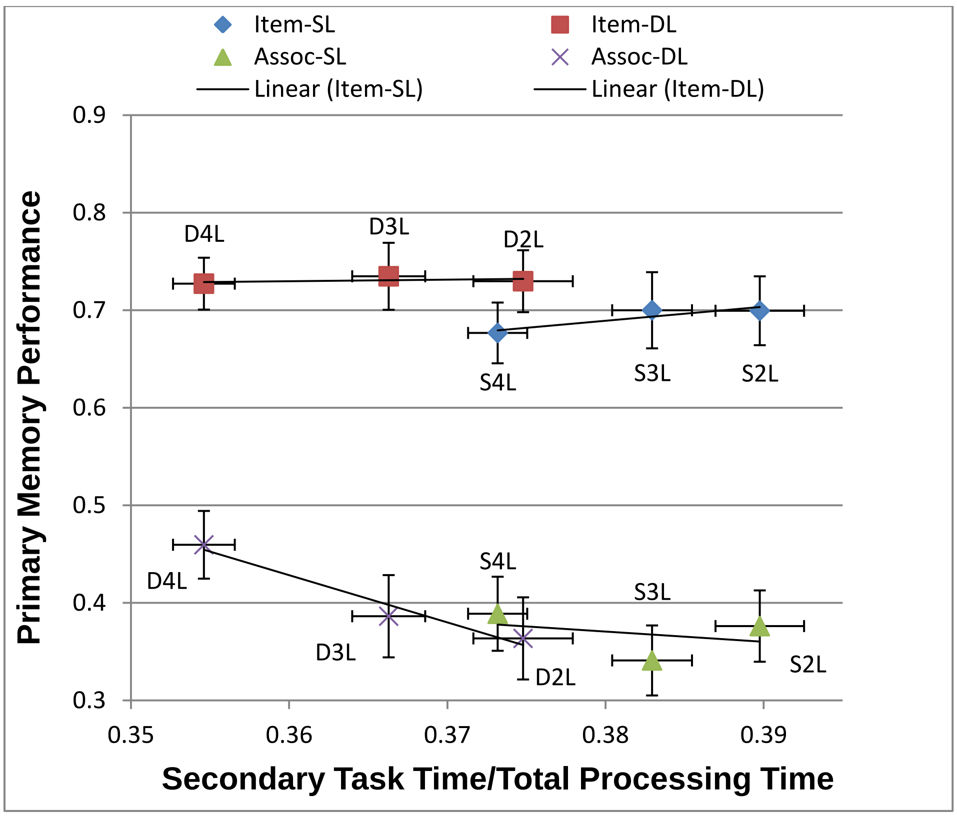
In Experiment 2, we did not find a larger disruption to associative memory as the secondary task demands increased. Participants demonstrated a larger associative deficit in the 2L and 3L conditions than the 4L condition, contrary to our predictions. One possible explanation is that since participants had to make more responses (processing) in the 2L and 3L tasks than in the 4L task, the 2L and 3L tasks required less WM storage but required more WM processing. Thus, we expected that the total time participants devoted to the 2L and 3L tasks was longer than the 4L task. Also, since we did not find a difference in the primary memory performance between the 2L and 3L conditions, it is possible that there is also no difference in the processing time between them. According to the time-based resource-sharing hypothesis, we should find a negative linear relationship between the total time participants spent on the letter task and their memory performance. Contrary to Experiment 2, we found a differential effect of math task on associative memory in Experiment 3 in the expected direction; however, this result may also be explained in terms of time. If so, we should again see a negative linear relationship between secondary task time and memory performance in Experiment 3.

In order to examine these possibilities, we conducted further analyses for Experiments 2 and 3. First, we calculated the time participants devoted to completing each secondary task by adding the time they listened to each stimulus and their response reaction times (RT). This number was calculated for each individual. Each participant's total time devoted to the secondary performance was then divided by the total time participants were allowed to study the name-face pairs. After calculating the proportion of time that each participant devoted to the secondary task for each dual-task condition, we regressed item and associative memory performance on the mean proportion of time spent completing the secondary task for each condition (see Figure 16).

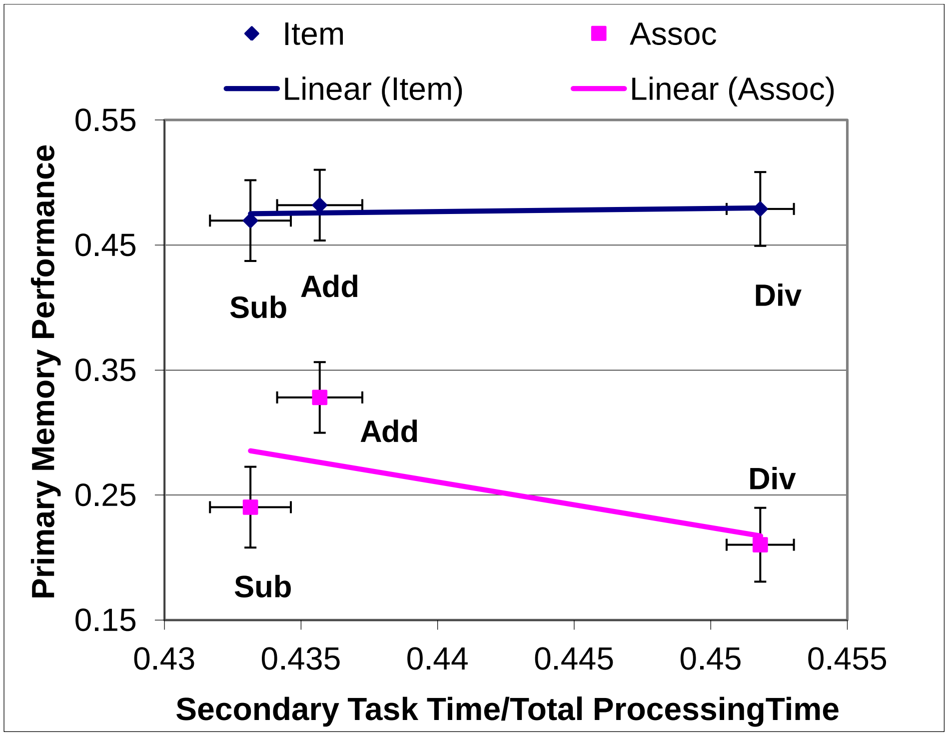
In Experiment 2, we found a pattern of negative linear relationship between the processing/storage time of the secondary task and the primary memory performance only when the dissimilar storage condition was combined with associative memory (see Figure 16A). However, this relationship was not statistically significant, F (1, 199) = .01.p>.05. Next, to examine the time difference between the similar storage and dissimilar storage tasks, a 2 (storage) x 3 (number of letters) ANOVA was conducted. The main effect of number of letters was significant, F (2, 132) = 48.18, p<.001, η_p^2=.42. Follow-up t-tests revealed that the 2L (M=.381, SD=.024) task had a longer processing/storage time than the 3L (M=.375, SD=.017), t (65) = 2.88, p<.01, and the 3L had a longer processing/storage time than the 4L (M=.363, SD=.015), t (65) = 7.10, p<.001. Thus, these results support the time-based resource-sharing hypothesis, but they do not explain why we did not find a difference in the primary memory performance between the 2L and 3L conditions. Since we found differences in the processing time among the three letter tasks, these results do not support the explanation that the reason we did not find the differential effect of the secondary task in Experiment 2 was because the processing/storage time among the three letter tasks were similar. Moreover, the main effect of storage revealed that participants devoted more time to completing the similar storage task (M=.383, SD=.017) than the dissimilar storage task (M=.363, SD=.022) even though there was no difference between these two storage conditions in primary memory performance, F (1, 66) = 65.86, p<.001, η_p^2=.50. Therefore, although participants spent more time completing the 2L task than the 3L and 4L tasks, this was not consistently linked to poorer memory performance. Also, there was no significant two-way interaction, F (2, 132) = .89, p>.05, η_p^2=.01.

Figure 16. Item and Associative Memory Performance for Each Dual-Task Condition as a Function of the Proportion of Time Devoted to Perform Each Secondary Task Along with Linear Regression Line For Each with Standard Error Bars Around Both the X- and Y-Axes **(A)** Experiment 2, **(B)** Experiment 3.

(A) Experiment 2



(B) Experiment 3



In Experiment 3, we conducted a one-way ANOVA to examine the time difference between three math conditions, and it was significant, F (2, 152) = 60.61, p<.001, η_p^2=.45. The follow-up t-tests revealed that participants spent more time on the division task than the addition and subtraction tasks t (76) > -8, p<.001, as expected, and their associative memory performance was the lowest in that condition. Critically, however, participants also performed relatively poorly in the associative test when it was combined with subtraction, yet subtraction required the least amount of time of the three secondary tasks (see Figure 16B). However, there was no significant time difference between the addition and subtraction conditions, t (76) = 1.38, p>.05. This result was consistent with what we expected. Participants needed more time to process the division problems so that they did not have enough time to encode the associations, and it lead them to have a larger associative deficit in the division condition compared to the addition and subtraction conditions. However, there was no significant relationship between the storage/processing time of the secondary task and associative memory performance, $F(1, 229) = .69$, $p > .05$.

Overall, the results showed that the time-based resource-sharing hypothesis does not fully explain the difference we found between the two experiments, suggesting that the difference is not likely due to the time required to complete the secondary task. However, it is possible that we did not find the expected patterns because there was very little variability in the secondary task times in both studies.

Appendix E: Examination of the Relationship between WM Span and WM Processing and Further Analysis of an Associative Deficit as a Function of Span Size and Processing Ability

Unsworth et al. (2009) reported that individuals who process math problems faster and more accurately in the O-span task tend to remember more letters compared to those who perform less well on the math problems. We wanted to determine whether this result is also true of the current data. First, we examined whether there were differences in the O-span score and math accuracy among the three experiments. The results show that there were no differences among the three groups on the O-span score (*M*=42, *SD*=17 for Experiment 1; *M*=40, *SD*=16 for Experiment 2; *M*=41, *SD*=19 for Experiment 3), F (2, 216) = .11, p>.05, η_p^2=.00, or math accuracy (*M*=.93, *SD*=.04 for Experiment 1; *M*=.92, *SD*=.05 for Experiment 2; *M*=.93, *SD*=.05 for Experiment 3), F (2, 216) = 1.82, p>.05, η_p^2=.02. Since there were no differences among them, we combined all the data obtained from the three experiments (*N*=219) to investigate whether participants who scored high on the O-span task also solved the math problems more accurately.

The result showed that there was a strong positive relationship between the O-span score and math accuracy, r (220) = .37, p<.001, one-tailed. Thus, individuals who were more accurate when solving the math problems were also more successful when remembering letters in the O-span task. This result is consistent with previous studies (e.g., Engle et al., 1992, Experiment 2; Salthouse et al., 2008; Shah & Miyake, 1996; Unsworth et al., 2009; Waters & Caplan, 1996). This result indicates that individuals classified as low-span are also more likely to be classified as low-processing. In fact, we found this relationship be to significant, r (220) = .21, p=.001, one-tailed.

Based on these results and the results obtained from each experiment, we examined whether the low-span and low-processing individuals would show an associative deficit compared to the high-span and high-processing individuals. Among all three experiments, we selected participants who belonged to both the high-span and high-processing groups (N=60; the high-WM group) and those who were categorized as low on both measures (N=72; the low-WM group). Then, we conducted 2 (WM: high, low) x 2 (test) ANOVA within the FA condition. The two-way interaction was significant, F (1, 130) = 5.44, p=.02, η_p^2=.04. The follow-up one-way ANOVA revealed that the groups (M=73, SD=19 for high-WM, M=70, SD=20 for low-WM) performed the item test equally well, F (1, 130) = .39, p>.05, η_p^2=.00. On the other hand, as expected, the low-WM group (M=49, SD=25) performed significantly worse on the associative test compared to the high-WM group (M=62, SD=26), F (1, 130) = 9.13, p<.01, η_p^2=.07. Converging with the results obtained from each experiment, these results show that a reduction in WM resources impairs associative memory, leading to an associative deficit.

In Experiment 1, we found a negative relationship between the O-span score and the associative deficit, but we found only a marginal relationship between these scores in Experiment 2. Thus, we conducted a partial correlation between the O-span score and the difference between item and associative memory in the FA condition, controlling for math accuracy and using the combined data from all 3 experiments. The result showed a negative relationship between them, r (219) = -.17, p<.01, one-tailed, revealing that individuals who have higher WM storage have a smaller associative deficit. Thus, O-span score is a predictor of individuals' associative deficit. However, we did not find a relationship between math accuracy and an associative deficit when controlling the O-span score, r (219) = -.06, p>.05, one-tailed. Although we found the usefulness of math accuracy to split the data into high- and low-processing groups in Experiment 3 to observe the group difference, it seems that variability in math accuracy is not large enough to predict individuals' associative deficit. One possible reason we failed to find a relationship between math accuracy and an associative deficit is because there is less variability in math accuracy scores (ranging .73-1; M=.93, SD=.05) compared to the O-span score (ranging 0-75; M=41, SD=.17). Also, the mean math accuracy was very high with only 20 participants scoring below .85 (the typical cutoff for exclusion).

In conclusion, the additional analysis provided converging evidence that reduced WM resources (both storage and processing) might be one reason older adults have an associative deficit. Also, the results obtained from high-WM and low-WM groups are in line with the suggestion that older adults allocate most of their WM resources to storing and processing each component, leading to equivalent item memory performance to young adults but leaving them with fewer WM resources to bind components together, leading an associative deficit.

VITA

Yoko Hara was born and raised in Japan. She left Japan after graduation from college and she has lived in Hawaii, California, and Pennsylvania before attending the University of Missouri. She loves to cook and eat good food.