The Source of the Associative Deficit in Aging:

The role of attentional resources for processing relational information

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ABSTRACT

SO-YEON KIM: The Source of the Associative Deficit in Aging:
The role of attentional resources for processing relational information
(Under the direction of Kelly S. Giovanello)

Previous studies have proposed an associative deficit hypothesis (ADH: Naveh-Benjamin, 2000), which attributes part of older adults' deficient episodic memory performance to their difficulty in creating cohesive episodes. According to the ADH, older adults show disproportionate deficits in relational memory (RM) relative to item memory (IM). The disproportionate RM deficit in older adults has been demonstrated with a variety of memory tasks, such as word-word, word-font, and face-name pairs. Despite rich evidence of an age-related RM deficit, the source of this deficit remains unspecified. One of the most widely investigated factors is the reduction in attentional resources in older adults. To investigate the effect of reduced attentional resources on RM performance, previous researchers have imposed a secondary task load on young adults during encoding of memory lists to divide attentional resources into two different tasks (e.g., Naveh-Benjamin, 2003). However, none of the existing studies have found a disproportionate RM impairment in young adults under divided attention conditions. The current project investigated whether a reduction in attentional resources for relational processing underlies the memory impairments observed in aging. Using behavioral and functional neuroimaging techniques, I conducted three studies aimed at determining: 1) whether imposing a secondary task load for relational

processing makes young adults' memory performance mimic the age-related RM deficit, and

2) whether the effect of reduced attentional resources for relational processing on RM is

similar to the effect of aging at the neural level, using functional magnetic resonance imaging

(fMRI). The results from the two behavioral studies indicate that a reduction in attentional

resources for relational processing in young adults during encoding equates their

performance in RM to that of older adults. Furthermore, the results from the fMRI study

demonstrate that both aging and reductions in relational attention processing in young adults

significantly reduced activity in the brain areas critical for RM formation, namely, the

ventrolateral and dorsolateral PFC, superior and inferior parietal regions, and left

hippocampus. This converging evidence from behavioral and neuroimaging studies thus

documents the first evidence that the reduction in attentional resources for relational

processing is the critical factor for the age-related RM deficit.

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INTRODUCTION

As people age, not only their physical health, but also some cognitive abilities decline. The degree of cognitive impairment by aging is, however, different depending on the type of cognitive processes. For example, previous research has shown that older adults tend to perform similarly to young adults on tasks of implicit memory, which depends on automatic activation processes and does not require conscious retrieval of experiences. For example, researchers have demonstrated that older adults show similar repetition priming effects as that of young adults when study and test modalities are matched (e.g., Light & Singh, 1987). In contrast, aging seems to affect performance on tasks of episodic memory (Light & Singh, 1987). Episodic memory refers to memory of events and experiences that have happened in the individuals' personal past, and it involves the conscious encoding and retrieval of contextually-specific information, such as memory for perceptual, conceptual, and affective components that are placed within an ongoing context of personal events (Tulving, 1983). In fact, one of the best established findings in the field of cognitive aging is that older adults do not perform as well as young adults on episodic memory tasks. A rich body of literature suggests that older adults have a disproportionate deficit in episodic memory relative to other types of memory due to their problems in remembering contextual details (e.g., Burke & Light, 1981). Age-related impairments in contextual details have been found in memory for location (Glisky, Rubin, &Davidson, 2001), temporal order (Fabiani & Friedman, 1997;

Cabeza, Anderson, Houl, Mangels & Nyberg, 2000), and perceptual attributes of the information (Naveh-Benjamine & Craik, 1996; Pilotti, Mead & Gallo, 2003). In fact, in a meta-analysis, Spencer and Raz (1995) found that the size of age differences in *context memory* is reliably greater than in *content memory*.

Remembering contextual information largely relies on successful binding of an event with its context. In accordance with this idea, Chalfonte and Johnson (1996) generalized the age differences in memory for contextual information to a *binding problem*, by suggesting that abilities to integrate pieces of information into complex memories may be diminished with aging. To test their hypothesis, the researchers manipulated study instruction, by asking one set of participants to study only a single stimulus (a simple line drawing) or only contextual information (color or location of the drawing), while emphasizing the other group to study combined stimuli (i.e. either drawing with its location or drawing with its color). During the test phase, participants were presented with three types of stimuli. Some studied drawings presented in the same color or location as at study (i.e. *intact*), and some studied drawings presented in a new color or location. Unstudied, new drawings were also included at test. Participants were asked to discriminate "intact" stimuli among these three types of stimuli. The researchers found that older adults' memory for individual object or contextual information (e.g., colors or locations) was just as good as that of young adults. However, the older participants were less able to remember object-color or object-location pairs relative to young adults. When a test required participants to identify the color or location of a given drawing during the encoding phase, the older adults showed worse performance relative to the young adults. This finding suggests that older adults have specific difficulties in the

process of associating different information together, rather than general deficits of encoding new information or new context.

Since the findings of Chalfonte and Johnson (1996), there has been an accumulation of evidence supporting the claim that older adults experience an inability to bind features together into relatively complex memories (e.g., Bayen et al., 2000; Mitchell et al., 2000; Naveh-Benjamin, 2000; 2002; Naveh-Benjamin et al., 2003; 2004; For review, see Old & Naveh-Benjamin, 2008). Importantly, Naveh-Benjamin (2000) proposed an associative-deficit hypothesis (ADH), expanding the scope of feature-binding notion in memory and aging by focusing on different effects of aging on *item* vs. *relational memory*. The ADH is based on the idea that complex events consist of multiple kinds of information sources, such as a semantic content and information about the time and place in which it occurred, or acting agents and their characteristics. In fact, there has been rich evidence that supports a separation within memory of information about single items (i.e., *item memory*) from information about associative relationships among separate items (i.e., *relational memory*) (Anderson & Bower, 1973; Chalfonte & Johnson, 1996; Gillund & Shiffrin, 1984; Hockley & Cristi, 1996; Humphreys, 1976; Johnson, 1992; Johnson & Chalfonte, 1994; Murdock, 1982). For instance, item memory and relational memory are differently affected by word frequency (Craik & Jennings, 1992) and differ in their rates of forgetting (Hockely, 1991). The ADH suggests that older adults have difficulty forming and retrieving associations among single units of information or episode (i.e., relational memory), which may contribute to their episodic memory deficits.

Specifically, Naveh-Benjamin (2000) employed a method originated by Humphreys (1976) to demonstrate relational memory deficits in older adults both in inter- and intra-

relationships. The method was specifically developed to assess memory for item and associative information separately (Humphreys, 1976). In this method, participants study a list of pairs of items (e.g., A-B, C-D). During a test phase for item memory, participants receive some of the original items paired with some new items, and are asked to recognize the old items that they have seen at the study phase (e.g., detect A in A-F). For testing relational memory, participants also receive pairs of items, but pairs can be either originally intact ones (e.g., A-B) or recombined pairs which include items that were presented during the study phase but not together (e.g., A-C). Participants have to recognize intact ones to perform this test. This procedure by Humphreys (1976) has advantages since participants encode the same information during the study phase and are provided with all of the information in both item- and relational memory test phases. Thus, this method is beneficial to exclusively detect differential memory for item and relational information.

Using such procedures, Naveh-Benjamin (2000) tested the ADH in a series of experiments and found a relational memory deficit in older adults for both inter- and intra-item relations. In his first two experiments, Naveh-Benjamin tested memory for item and inter-item associations using unrelated word-nonword pairs and unrelated word-word pairs. The results supported ADH by demonstrating that older adults showed a disproportionally greater deficit in the relational memory when memory for item and for associative relationships among items were compared directly. Naveh-Benjamin extended this finding to memory for intra-item associations (i.e. words and their fonts) and compared young and older adults' memory for event's attributes and their relationships with each other. Results indicated that memory for single attributes (words or fonts) was comparable between older and young adults, whereas memory for conjunctions of attributes was deficient in older

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adults. In the last experiment, Naveh-Benjamin (2000) investigated memory for semantically related and unrelated word pairs in young and older adults and used three different memory tests: free recall, cued recall, and recognition. As opposed to general belief that free recall would be the most difficult among above three tests due to lack of environmental support (e.g., cues), Naveh-Benjamin found that older adults showed disproportionally poorer performance in a cued-recall task of unrelated pairs relative to their disadvantage in free-recall and recognition task. He also demonstrated that older adults performed just as well as young adults in a cued-recall task for semantically related word pairs, where they did not have to create new associations among words. Finally, Naveh-Benjamin manipulated task instructions for item- and relational memory tasks, and demonstrated that both incidental and intentional learning for associative information are differentially impaired in older adults.

Since the initial proposal of ADH by Naveh-Benjamin (2000), a growing body of research has provided evidence for disproportionate deficits in relational memory in older adults using a variety of materials. For example, Naveh-Benjamin, Hussain, Guez, and Bar-On (2003) extended the early findings on ADH to pictorial stimuli. The researchers presented young and older adults with pairs of simple familiar objects that were unrelated in meaning, sound, or appearance, and provided an item or relational recognition test for each pictures or pairs. Results in this study using visual materials echoed the findings with verbal materials, showing older adults' relational memory deficit for picture stimuli despite their intact item memory for pictures. The results that older adults showed less of a relational memory deficit for semantically related objects also supported an ADH, suggesting that older adults' relational memory deficit increased to the extent that a task required the creation of new association.

Furthermore, previous researchers extended the ADH to materials with higher ecological validity. Several researchers demonstrated that older adults have difficulty in recognizing face-name pairings (Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Troyer, Hafliger, Cadieux, & Craik, 2006). The researchers were also able to isolate the associative link as the primary source of the age-related deficit, by showing that name recognition and face recognition had much smaller age declines than recognition of the paired items. More recent studies also found disproportionate impairments in association of two faces in older adults relative to their intact recognition ability to individual faces (Bastin & Van der Linden, 2006; Rhodes, Castel, & Jacoby, 2008). Moreover, in a recent study, Old and Naveh-Benjamin (2008) employed dynamic stimuli which involved acting agents and their actions, and demonstrated that the ability to link an action with an acting agent was also differentially impaired in older adults despite the spared recognition memory for each person or action.

Finally, previous researchers also investigated ADH for within- or between domain associations. Previous studies have suggested that there are functional distinction between within-domain associative recognition memory (e.g., face-face) and between-domain associative recognition memory (e.g., face-house) (Cohen, Poldrack, & Eichenbaum, 1997; Mayes et al., 2001, 2004, 2007). Specifically, previous neuroimaging studies suggest that the between-domain association is dependent upon the hippocampus, whereas both hippocampus and perirhinal cortex may contribute the within-domain association (Preston et al., 2004; Staresina & Davachi, 2008). Furthermore, neuropsychological evidence also supports the notion that those two types of association are different, by showing that hippocampal patients were more impaired on between-domain relational memory than on within-domain relational memory (Mayes et al., 2001, 2002, 2004, 2007; Vargha-Khadem et al., 1997). Based on

these findings, a recent study by Bastin and Van der Linden (2006) quantitatively compared older adults' relational memory deficits in different types of associations. The researchers questioned whether the effects of aging would also differ between recognition for associative stimuli between- and within- domains. To test their hypothesis, the researchers compared older adults' recognition performance on face-face pairs to their performance on recognition of face-spatial pairs. In their results, the researchers replicated disproportionate age-related differences on relational memory compared to intact item recognition memory. However, the degree of older adults' impairments on relational memory was equal across different types of association (e.g., within- or between-domain). Hence, the results also supported the ADH, which suggested that the older adults revealed a general deficit in the creation and retrieval of links between individual components.

In sum, a number of evidence supports the associative deficit hypothesis for older adults' impairments on episodic memory. Disproportionate deficits in relational memory among older adults have been found in numerous studies using different types of materials, and the impairment seems to be greater for the creation of novel associations than for retrieving the pre-existing associations.

Sources of the disproportionate deficits in relational memory in older adults

Despite rich evidence for a disproportionate relational memory deficit in aging, the source of the deficit is still unclear. In fact, there exist several hypotheses to explain general deficits in memory in older adults. Some researchers proposed a failure of controlled mnemonic processing as a possible mediator for memory impairments in older adults (Craik, 1982, 1986; Jennings & Jacoby, 1993; Hay &Jacoby, 1999), while others suggested a failure

of inhibitory processes for unnecessary information as a cause of the deficit (Hasher & Zacks, 1988). Furthermore, reduction in contextual encoding (McIntyre & Craik, 1987; Light, 1991), reduction in processing speed (Salthouse, 1996), or reduction in attentional resources (Anderson et al., 2000) have also been proposed as a possible source of the memory impairments in older adults. Although none of the theories provides an explanation for the full range of phenomena related to older adults' relational memory deficits, two proposals have been particularly explored to determine the source of the relational memory deficits in aging: reduction in mnemonic processing and reduction of attentional resources.

Reduction in mnemonic processing

According to Jacoby's dual-process models of recognition memory (1991), mnemonic process can be differentiated into two separate processes: *recollection* and *familiarity* (Hasher, 1979; Jacoby, 1991; Mandler, 1980). Recollection is generally described as a conscious, attention-demanding process which entails conscious retrieval of specific episodic information, including perceptual details, the source of information, temporal or spatial information, and emotions that accompany the event. This type of memory process has been known to underlie recall of past events or thoughts (Jacoby, 1991; Yonelinas, 1994, 1997, 2002). Unlike the recollection, familiarity refers to the feeling that an item was previously encountered, and it is conceptualized as an unconscious, relatively automatic process which supports performance on recognition tasks to a greater degree than recall.

Previous studies have provided evidence that the contributions of recollection and familiarity processes are different in item and relational memory; item recognition is largely based on familiarity, whereas recollection plays a significant role in performance on

relational memory tests (Kelly & Wixted, 2001; Rotello & Heit, 1999, 2000; Rotello, Macmillan & Van Tassel, 2000; Yonelinas, 1997). Specifically, recollection is especially important for tasks where individuals must discriminate intact from recombined versions of studied associations and discriminate items from different lists, sources, or other contents. In contrast, familiarity behaves in a fairly item-specific manner, providing graded feelings of familiarity of recency about individual studied items (Quamme, Yonelinas, & Kroll, 2004). The dual-process theory suggests that familiarity engendered by the old components of feature and conjunction lures biases individuals to commit false recognition errors, but recollection for a word presented earlier in a study phase can be used to overcome the influence of familiarity to avoid such errors (Jones & Atchley, 2002; Jones & Jacoby, 2001; Lampinen, Odegard, & Neuschatz, 2004).

Age-related changes are also different for the recollection-based and the familiarity-based processes. Previous studies have reported that aging is accompanied with declines in controlled mnemonic processing of recollection, whereas the familiarity-based mechanisms seem to be relatively spared in aging (Light, Prull, La Voie, & Healy, 2000; Howard et al., 2006; Yonelinas, 2002, Zacks, Hasher, & Li, 2000). For example, older adults are more susceptible to source errors due to familiarity in the absence of recollection (Bartlett, Strater, & Fulton, 1991; Jennings & Jacoby, 1993). A recent neuro-anatomical study also indicated that age related decreases in hippocampal volume led selectively to lower levels of recollection and decrease in memory performance in recall tests (Yonelinas et al., 2007).

Since older adults show both reduced controlled mnemonic process (i.e. recollection) and impaired relational memory, a group of researchers have suggested the reduction in recollection as a cause of the relational memory deficits in aging. Using relational memory

tasks, previous researchers found impaired recollection and relatively preserved familiarity processes in aging, by showing older adults' higher false alarm rates for the conjunction of two items which previously presented separately (Castel & Craik, 2003; Rhodes & Castel, Jacoby, 2008). The researchers suggested that reduction in the recollection-based processing and increased dependence on familiarity may account for associative deficits in older adult. Consistent with such hypotheses, previous researchers demonstrated that increasing the level of familiarity led more associative errors in older adults (Jones & Jacoby, 2005; Light, 2004, 2006). Specifically, Light and colleagues (2004; 2006) varied the length of presentation rates and the number of repetition of stimuli during the study phase in order to manipulate the level of familiarity in relational memory tasks. The researchers found that repetition of the study list increased hit rates for both young and older adults, whereas the repetition and a longer deadline increased false alarm rates for rearranged pairs only for the older adults. Jones and Jacoby (2005) provided further evidence on the effects of impaired recollection process on increased associative deficits in aging, by showing that study repetition decreased errors in young adults but increased errors in older adults. The researchers also demonstrated that the conjunction errors were modality-free for the older adults, whereas repetition of the words in the same modality (e.g., visual presentation) aided the young adults to avoid conjunction errors. Together, previous findings provide evidence for which declined recollection-based processing and increased reliance on familiarity-based processing influence the associative deficits observed in older adults to some degree.

However, it cannot be concluded that the reduction in the recollection process is a direct cause of the relational memory deficits in aging. In other words, there could be a third factor which influences both reduced recollection-based processing and relational memory deficits

in aging. Reduction in attentional resources, for instance, could be a potential and direct

cause for both reduced recollection process and relational memory deficits in older adults. In

fact, recollection is generally described as a conscious, attention-demanding process, and a

number of studies have demonstrated age-related reduction in attentional resources in older

adults (e.g., Craik, 1983; Craik & Byrd, 1982; Madden et al., 2005, 2007). Thus, the

contribution of the reduced attentional processing should not be ignored when searching for

the source of the deficient relational memory observed in aging. Hence, in the next section, I

will describe evidence of the effects of reduced attentional resources on relational memory in

order to elucidate the direct source for the relational memory deficits observed in aging.

Reduced attentional resources: Evidence on divided attention and relational memory

As stated previously, relational memory requires successful binding processes. It has

been suggested that successful binding involves conscious attentional processes mediated by

the frontal lobe, as well as more automatic processes mediated by medial temporal structures

(Moscovitch, 2000; Moscovitch & Winocur, 1992). If conscious attentional processing

enables optimal binding, it is plausible to hypothesize that reduced resources for attentional

processing should lead to inefficient binding and poor formation of associations. Consistent

with such hypothesis, previous researchers have demonstrated that normal aging is

accompanied by a reduction in attentional resources (Craik, 1983; Craik & Byrd, 1982; Craik

& Simon, 1980; Madden et al., 2005, 2007), and that a reduction in attentional resources

plays a role in memory deficits in aging (Anderson et al., 1998; Craik et al., 1996; Troyer et

al. 2000).

Craik and colleagues (Craik, 1983; Craik & Byrd, 1982) have proposed the common mechanism view which considers the reduced attentional resources as a major cause of episodic memory problems in older adults. Craik and colleagues (1996) have shown that division of attention at the time of encoding greatly reduces subsequent cued recall for unrelated noun pairs, and this impaired performance may be attributed to a failure to establish the adequate relational linkage between the component items. Subsequent researchers supported this view by showing that divided attention at encoding worsened memory for contextual information (Troyer & Craik, 2000; Troyer et al., 1999). Moreover, Anderson et al. (1998) showed that divided attention at encoding disrupted memory performance of both young and older adults in free recall, cued recall, and recognition tasks. Using various secondary tasks and episodic memory tasks, Fernandes and Moscovitch (2000) also found that dividing one's attention at encoding disturbed the performance in episodic memory tasks.

Despite consistent evidence on effects of attentional resources on episodic memory in aging, it is still unclear whether a lack of attentional resources also mediates the relational memory deficits in older adults. To test the effects of attention on relational memory, researchers have given young adult participants a secondary task, while they encoded memory lists, and subsequently tested whether the participants showed disproportionate relational memory deficits under divided attention (DA), relative to full attention (FA) conditions (Castel & Craik, 2003; Naveh-Benjamin et al., 2003, 2004; Kilb & Naveh-Benjamin, 2007).

For example, Naveh-Benjamin and colleagues (2003) provided a group of young adults with a secondary digit-monitoring task while they were encoding pairs of unrelated object

pictures (i.e. divided attention (DA) condition). Another young adult group received only the study list without any concurrent tasks (i.e. full attention (FA) condition). With this paradigm, the authors found that the young adults under DA showed reduced accuracy, indicative of general decline in memory performance. Nonetheless, unlike the pattern of the older adults' associative deficits, the secondary task affected the memory performance for item and association to the same degree.

Naveh-Benjamin and colleagues (2004a) replicated these findings using different memory and attention tasks. The authors instructed a group of young adults to perform a concurrent attention task while they were encoding face-name pairs. The attention task was a continuous reaction time (CRT) task that involved a sequential presentation of auditory tones by a computer, presented one at a time, and a manual response on a computer keyboard to each tone. One of three tones (all of which differed from each other in frequency) was presented at random, and the task was to press a pre-designated corresponding key on the keyboard. In this study, the authors replicated their earlier findings, by showing that young adults under DA showed reduced accuracy overall, but not disproportionately for associations as is found in aging.

The proportionate effect of attention on both item and relational memory was again replicated with a somewhat different task paradigm in which researchers equated the amount of information provided at test by adding a forced-choice item recognition test. Specifically, in a forced-choice item recognition test, Naveh-Benjamin et al. (2004b) presented two words to participants, and instructed participants to identify which of the two items was presented at study. Older adults under FA were compared with young adults under FA or under DA, in which they performed a digit-monitoring task during encoding. The results demonstrated

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that the young adults under DA condition performed similarly to the older adults group in the forced-choice item recognition test. However, the older adults performed more poorly on the relational test than on the item test, whereas the young adults under DA showed the same level of performance in the two tests. Thus, these results also argue against the suggestion that the age-related deficits on relational memory can be explained by reduced attentional resources, or by the related suggestion that the relational memory test is simply more demanding.

Using a dual-task procedure in which participants receive two different tasks concurrently, a recent study by Kilb and Naveh-Benjamin (2007) further investigated whether the relational memory deficit in older adults is mediated by a reduction in attentional resources. Both young and older adults studied lists of word pairs either under full attention (FA) or while performing a concurrent auditory choice RT task in which they detected one of the three pitches that could be identified as low, medium, or high (i.e. divided attention (DA) condition). The researchers replicated their earlier findings supporting the hypothesis that the relational memory deficit in older adults was not mediated by reduced attentional resources. That is, although a disproportionate associative deficit was found in older adults under FA, it was not observed in young adults under DA. The same results were found when the researchers reduced the amount of attentional resources required at encoding by making the older adults to concentrate on only one aspect of the study list at a time (i.e. either the item or the association) rather than two aspects concurrently. That is, older adults showed an associative deficit even when they were instructed to learn the components and pairs separately. Furthermore, neither young nor older adults showed a larger associative deficit under DA than under FA. Hence, these findings also suggest that reduced attentional

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resources cannot explain the disproportionate age-related deficits in relational memory performance.

Although most of the studies have demonstrated that the effects of the secondary task were equal for both item and relational memory tasks, a study by Castel and Craik (2003) showed a somewhat different picture. The researchers divided participants into three groups; older adults under full attention (FA), young adults under FA, and young adults under divided attention (DA), who performed a secondary task only at encoding or both at encoding and retrieval. The secondary task required participants to monitor and detect target strings (i.e. consecutive three odd digits among a series of digits). The findings from this study supported the prediction that a reduction in attentional resources may at least partially explain the age-related deficits in relational memory, by showing disproportionate relational memory deficits in young adults under DA at encoding condition.

Nevertheless, a closer look of results in Castel and Craik (2003) provides different conclusions. In their discussion, the authors pointed out that although overall accuracy performance was similar between young adults under divided attention condition and older adults under full attention, the patterns of accuracy were different between groups. Whereas the effects of divided attention was primarily seen as a reduction in hit rates with relatively small increases in false-alarm rates in young adults under DA, the effect of aging was seen most dramatically in the older group's greatly increased false-alarm rates in pair recognition, especially for the recombined pairs. Thus, dividing young adults' attention at encoding did not mimic the relational memory deficits in older adults, and this distinct pattern in fact limits the conclusion that a reduction in attentional resources could serve as a key factor for relational memory deficits in aging. Rather, this differential pattern highlights the possibility

that the similar memory performance across the two age groups may have been the consequence of different underlying processes: a higher dependence on familiarity in older adults and a decrease in recollection in both aging and dividing attention. Thus, even though Castel and Craik (2003) found the expected patterns of accuracy results by the hypothesis regarding reduced attentional resources as a cause of the relational memory deficits, the patterns of the results, in fact, are not in line with the suggestions by Craik that the effects of aging can be mimicked in all respects by division of attention. Rather, their findings provide further support for the alternative hypothesis that the reduction in attentional resources cannot fully account for the relational memory deficits in older adults.

In sum, a number of studies with divided attention (DA) and ADH paradigm suggest that reduced attentional resources may not be a critical source of disproportionate relational memory deficits in aging. The vast majority of studies (e.g., Naveh-Benjamin et al., 2003, 2004; Kilb & Naveh-Benjamin, 2007) have shown that although dividing attention may contribute to a general decrease in memory performance, it does not disproportionately affect relational memory. Such findings imply that reduced attentional resources cannot explain the age-related deficit in relational memory processing. Furthermore, previous research has shown that behavioral patterns of young adults under the DA condition are different from the behavioral patterns of older adults; that is, young adults under the DA condition reveal decreased hit rates rather than increased false alarm rates for the recombined pairs in an relational memory test (Castel & Craik, 2003). Taken together, the findings imply that despite a marked effect of divided attention on episodic memory performance, it does not mimic the specific pattern of impairment seen in aging, namely the disproportionate relational memory deficits.

Sources of disproportionate deficits in relational memory in older adults: An alternative view

Even though previous studies have demonstrated that reduced attentional resources in older adults cannot fully account for disproportionate relational memory deficit in aging, I propose an alternative account in which reduction in a specific type of attentional resources plays a critical role in age-related relational memory deficit. I believe that the attentional manipulation in previous studies with divided attention (DA) paradigms may not have been the correct way to examine the effects of attentional resources on relational memory. Most of the previous studies used target detection tasks or digit monitoring tasks as a secondary task to divide and reduce participants' attentional resources during episodic memory encoding or retrieval, and found that dividing one's attention during episodic memory encoding worsened both item and relational memory performance to the same degree. In other words, previous researchers manipulated general processing resources, rather than specific attentional resources for associative memory, and found that reduction in general attentional resources did not equate young adults' performance in relational memory task to that of older adults. However, attention is not a unitary system; rather, it involves different processes, such as selection, orienting, inhibition. Attention can also be distinguished by modalities of resources for which the attentional mechanism requires, such as visual, spatial or auditory attention (Navon & Gopher, 1979). Furthermore, since attention is not a unitary system, dividing attention into two different tasks does not always disturb the performance on both tasks. In fact, studies investigating interaction between attention and other cognitive processes have demonstrated inconsistent findings due to the different types of attentional resources required in different cognitive tasks.

For instance, studies on attention and working memory (WM) have shown that effects of WM load on attentional tasks vary depending on the type of resources that each system requires. Dual-task impairments can be observed if WM load overlaps and conflicts with attentional processes required for a task, consistent with the common intuition that performance suffers when people try to do two or more tasks at once (Marois & Ivanoff, 2005; Pashler, 1998). Specifically, loading spatial WM with irrelevant spatial information impairs performance in tasks, such as visual search, that require spatial attention (Oh & Kim, 2004; Woodman & Luck, 2004). Using a response conflict task, de Fockert et al. (2001) also demonstrated that a concurrent WM load increased the amount of response conflict from distractors.

However, loading WM does not always disrupt the efficiency of selective attention if the type of WM load does not overlap with processes required for the selective attention task. For example, a color WM load does not disrupt visual search for shapes (Woodman et al., 2001), and a WM load of face stimuli does not disrupt background scene processing (Yi et al., 2004). Moreover, Kim et al., (2005) demonstrated that the performance on an attention task can be significantly improved or disturbed depending on the relation between resources required for concurrent WM and attention tasks. Using a variety of Stroop tasks and WM tasks, the authors demonstrated that different types of WM load had different effects on attentional selection, depending on whether WM load overlapped with mechanisms involved in target or distractor processing in an attention task. Specifically, the authors showed that when a concurrent WM task utilize the same type of cognitive resources (e.g. spatial or verbal) as a target processing in an attention task, the WM load significantly disturbed performance in the attention task, whereas a simultaneous WM task can improve attentional

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selection processing if the WM task involved the same cognitive resources as a distractor processing in the attention task. Motivated by those previous studies, in the current project, I tested the role of attention on relational memory deficits in older adults, by manipulating types of resources required for a concurrent attention task.

In Experiment 1 and 2 in this dissertation, I hypothesized that there would be a specific type of attentional process required for relational memory. Specifically, I propose a new term, "*relational attention*", a mechanism to selectively focus on relational aspects among stimuli. As in the case of relational memory which requires a *binding process* of separate memory units, I believe that relational attention may involve a specific type of processing to selectively focus on associative aspects of separate items. For example, tasks requiring comparison of specific attributes of stimuli (e.g., color matching, size comparisons) may involve relational attention to successfully perform the tasks. To perform such tasks, individuals may have to focus and allocate their attentional resources to the connection or relationship between two or more stimuli. In the current project, I hypothesize that lack of resources for relational attention plays a critical role in age-related relational memory deficit. That is, the reduced attentional process to focus on the connection between items may contribute older adults' relational memory impairments. To test this hypothesis, I divided participants into separate attention groups (i.e., a full attention and different divided attention groups), and tested their item- and association-recognition abilities under different attentional loads at encoding. Critically, I selected secondary tasks which particularly involve processing of relations in order to deprive participants' cognitive resources for relational attention. Secondary tasks which require little or no relational processing were also recruited to serve measures of general effect of secondary task on both item- and relational memory

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performance. Experiments 1 and 2 of this dissertation examined behavioral effects of

concurrent relational attention tasks on relational memory tasks.

The roles of MTL and PFC regions in episodic memory encoding

Studies with animals, human patients, and neuroimaging techniques have shown that the

formation of episodic memories is prominently linked to the medial temporal lobes (MTLs)

(e.g., Eichenbaum et al., 1994) and the prefrontal cortex (PFC) (e.g., Moscovitch, 1994).

According to the "working-with-memory model" put forward by Moscovitch and colleagues

(Moscovitch, 1992, 1994; Moscovitch & Winocur, 1995), memory involves the interaction of

a frontal lobe system that mediates strategic encoding and retrieval processes and a modular

medial temporal lobe-hippocampal (MTLH) system that automatically picks up information

that has been consciously processed. Previous neuroimaging studies have provided

convergent evidence to support this model, and demonstrated that the PFC is associated with

controlled processing of relational information both at encoding and retrieval (Henson,

Shallic, Josephs, & Dolan, 2002), while MTL structures are associated with the incidental

encoding and retrieval of contextual associations (For a review, see Cabeza, 2006). These

working-with-memory functions are particularly critical for relational memory, and

neuropsychological studies have provided evidence that damage on the PFC and/or MTL

tends to yield large deficits on episodic memory tasks involving relational memory

(Shimamura, 2002; Stuss et al., 1994; Wheeler et al., 1995; Yonelinas, 2002). That is, lesion

studies showed that areas in the lateral prefrontal cortex implement cognitive processes that

contribute to successful episodic long-term memory encoding (Blumenfeld & Ranganath,

2007). Specifically, lesions that lead to relational memory deficits are often in the

dorsolateral PFC (Milner et al., 1991; Petrides, 1994), whereas lesions in the ventromedial PFC seems to be more prominent for item memory (Bachevalier & Mishkin, 1986). Lesion studies have also shown that medial temporal areas, including the hippocampus and adjacent cortices, play a critical role in episodic memory, specifically in the encoding of new memories (Squire, 1992; Eichenbaum, 1992; 2002). Furthermore, studies of amnesic patients with damage to the MTL demonstrated that lesions in the MTL were associated with a deficit in the ability to form relations among elements (Cohen et al., 1997; Giovanello, Verfaellie, & Keane, 2003; For review, see Eichenbaum & Cohen, 2001; Eichenbaum, 2007).

Studies using neuroimaging techniques have also supported a notion that both PFC and MTL play an important role in episodic memory encoding. Early PET (positron emission tomography) and fMRI (functional magnetic resonance imaging) studies of episodic memory encoding used "blocked" experimental designs, where encoding-related activity was captured in contrasts between tasks that were associated with relatively good later memory performance versus tasks associated with relatively poorer performance. To obtain good or poor memory performance, most of the blocked-design studies employed a "depth of processing" manipulation (Craik & Lockhart, 1972), which varied whether study stimuli were processed semantically or nonsemantically (For review, see Rugg, Otten, & Henson, 2002, Wagner, Koutstaal, & Schacter, 1999). For instance, previous researchers had participants make either semantic (e.g., abstract/concrete judgment) or phonological judgment during encoding of word lists and demonstrated that the incidental encoding under semantic judgment yielded greater activation in left inferior PFC and in the MTL regions compared with more superficial encoding (Fletcher et al., 1998; Montaldi et al., 1998; Shallice et al., 1994).

Later studies using event-related fMRI techniques have further provided direct evidence

that neural activities in both PFC and MTL regions are involved in successful encoding of

episodic memory. Specifically, Wagner and colleagues (1998) first implemented a powerful

approach, the"subsequent memory procedure", with an event-related fMRI paradigm to

examine neural activity during encoding correlated with later remembering. In this procedure,

neural responses to distinct stimulus events are recorded and then classified based on testing

the participant's memory for the stimuli at a later time. The neural responses (as indexed by

blood oxygenation level dependent signal change) elicited by the items at study are then

contrasted according to whether these items were remembered or forgotten in the subsequent

memory test. Differences between the responses associated with subsequently remembered

and forgotten items (subsequent memory effects) are interpreted as putative neural correlates

of memory encoding (Wagner et al., 1998; Paller & Wagner, 2002). With this paradigm,

Wagner and colleagues (1998) demonstrated that activation in posterior and left

parahippocampal and left PFC regions during semantic decision task for words were

correlated with successfully remembered events.

After this initial study, numerous studies employed this method to examine neural

correlates of episodic memory encoding with different task materials and procedures. Using

different materials in memory tasks, previous researchers have demonstrated that verbal

semantic and phonological processing preferentially engages anterior and posterior portions

of left inferior frontal gyrus, while encoding of pictorial stimuli activates right PFC (Brewer

et al., 1998; Poldrack et al., 1999). Furthermore, other researchers manipulated the nature of

encoding procedures (i.e., deep vs. shallow), and demonstrated different neural circuits were

correlated with different types of encoding processes (Otten & Rugg, 2001; Prince et al.,

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2005; Rugg, Otten, & Henson, 2002). For example, researchers asked participants to make animacy or syllable judgments about words followed by a recognition memory test, and demonstrated that activation in the left inferior frontal gyrus correlated with memory formation for items processed in the semantic (i.e. animacy) task. However, the authors also found that episodic memory formation in the non-semantic task was associated with activation in different cortical regions, including right prefrontal, bilateral parietal, and fusiform cortices (Otten & Rugg, 2001). Overall, previous findings suggest that different parts in PFC are engaged in episodic memory encoding depending on the type and nature of the encoding task.

Recently, several studies have investigated the neural correlates of relational episodic encoding using the subsequent memory procedure, and demonstrated the engagement of PFC and MTL activation correlated with successful encoding of relational information. Specifically, Kirwan and Stark (2004) directly compared neural correlates of successful item- and relational encoding, and found that the hippocampus and posterior parahippocampal gyrus selectively correlated with relational memory formation. The recruitment of hippocampus and posterior parahippocampal gyrus during relational memory encoding has been consistently reported in other literatures using different materials (e.g., face-name pairs, face pairs, word pairs) and different task requirement (intentional or incidental, deep encoding) (Davachi et al., 2003; Kirwan & Stark, 2004; Ranganath et al., 2004; For review, see Davachi, 2006). Along with activation in MTL regions, engagement of lateral PFC has also been evident in relational memory construction. A recent study suggests that dorsolateral regions of the PFC (DLPFC) may contribute to the ability to organize multiple pieces of information in memory, thereby enhancing memory for associations among items in long-

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term memory (Murray & Ranganath, 2007). The authors showed greater DLPFC activity during relational compared with item-specific encoding in a sequential encoding of unrelated word pairs, and demonstrated that DLPFC activity predicted successful memory for associations. However, other studies also emphasized the role of inferior frontal gyrus to supports generation of associative information (Addis & MacAndrews, 2006). Even though studies on the PFC engagement in relational memory formation have reported somewhat different findings in terms of the specific regions correlated with successful encoding, both dorsolateral and inferior frontal gyrus have been revealed to be critical in relational memory formation, along with hippocampus and posterior parahippocampal regions.

Effects of aging on the neural basis of relational memory

Given the rich behavioral evidence on age-related deficits in relational memory, it can be expected to observe dysfunctions in the PFC and/or MTL in older adults. In fact, it has been evident that several brain structures essential for self initiated processes and associative memory (e.g., the PFC and MTL) deteriorate structurally with age (Raz et al., 2005; Resnick et al., 2003). Foremost, lateral prefrontal cortex volume decreases around 5% per decade, starting at age 20 (Raz et al., 2005, Resnick et al., 2003). Similar decline is observed in the hippocampus (0.79%), but age-related degeneration of the frontal lobe is the most prominent. Consistent with the structural degeneration in the PFC with aging, previous studies have posited that age-related cognitive deficits are primarily due to PFC dysfunctions (Dempaster, 1992; Moscovitch & Winocur, 1995; West, 1996). Older adults tend to be more impaired in cognitive tasks sensitive to frontal damage, such as interference, recall, and source memory tasks, than in other tasks (Moscovitch & Wincur, 1995; West, 1996).

Furthermore, neuroimaging studies have repeatedly found significant age-related differences in PFC activity during cognitive performance (Cabeza, 2001). Importantly, several studies demonstrated positive correlations between older adults' performance in relational memory tasks and their scores in 'frontal lobe tasks' (Craik et al., 1990; Glisky et al., 1995; Parkin et al., 1995; Henkel et al., 1998). Neuroimaging studies have also provided direct evidence linking age-related deficits in relational memory to PFC dysfunction. First, several studies using positron emission tomography (PET) or functional MRI found age-related decreases in encoding activity in left and right PFC regions (Cabeza et al., 1997; Grady et al., 1995; Iidaka et al., 2001; Mitchell et al., 2000). The first study which documented older adults' reduced activity in the prefrontal cortex during episodic memory encoding was a work by Grady and colleagues (1995). The researchers used face encoding and recognition tasks during PET scans, and demonstrated that older adults failed to show significant activation in the inferior and middle prefrontal cortex during face encoding, whereas those regions were significantly activated in young adults during the face encoding. Later, other studies employed relational memory tasks and found similar reduction in PFC in older adults during relational memory encoding compared with young adults. Specifically, Cabeza and colleagues (1997) showed that older adults revealed decreased activity in the left ventral PFC during intentional learning of word pairs compared to young adults, and suggested a direct relation between the PFC function and older adults' deficit to form new semantic associations. Mitchell and colleagues (2000) also reported weaker PFC activity in older adults than young adults, during a spatial relational memory task requiring binding of object drawings with their spatial locations. Similar findings were found using pairs of drawings as well (Iidaka et al., 2001). Iidaka and colleagues (2001) found that only young

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adults showed enhanced activation in PFC during the encoding of unrelated objects, whereas older adults failed to show significant activities in any of PFC regions in the same condition. Overall, these previous studies suggest that the under-recruitment of PFC is accompanied with aging in different memory tasks including relational memory.

However, other researchers have also found over-recruitment of PFC in older adults during memory encoding. First, Morcom and colleagues (2003) used an event-related fMRI technique and found that both young and older adults showed increased neural activity for successful word recognition in left MTL and PFC regions. Additionally, the researchers found that older adults also recruited the right PFC regions for the successful memory process. The latter finding is consistent with evidence of reduced functional specificity in older adults (Cabeza, 2002). Similarly, a picture encoding study found that, compared to young adults, older adults showed reduced activity in bilateral MTL regions but greater activity in bilateral PFC regions (Grady et al., 1995; Gutchess et al., 2005).

However, the over-recruitment of additional prefrontal regions, which leads to the reduced functional specificity in older adults during memory encoding, was not in fact consistently evidenced in the neuroimaging literature, especially when a relational memory task was used. For example, Dennis et al. (2008) found decreased PFC activity in older adults compared to young adults when participants encoded face and scene stimuli together, whereas older adults showed additional recruitment of PFC when they were memorizing only the scene information. The researchers concluded that older adults activate additional PFC regions only for the highly memorable stimuli that they can deploy compensatory strategies, and these strategies are not likely to be used when older adults encode more demanding information (i.e., associative information) that leave older adults with fewer cognitive

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resources available for compensation. Consistent with this reasoning, Cappell et al. (2010)

also showed that memory load is a strong moderator of the age differences in frontal lobe

activity during task performance. Specifically, the researchers found older adults over-

recruit dorsolateral PFC compared to young adults under low memory load conditions, but

they under-recruit the PFC under high memory load. Thus, the prefrontal compensatory

function may not be observed during the relational memory encoding because the

discrepancy between available resources and task demands is too large in older adults during

the relational memory encoding.

Along with the dysfunction in the PFC, previous researchers also demonstrated the

decreased MTL functions in health aging, although the MTL decline in aging is milder than

the PFC decline. Structurally, aging is often accompanied with significant reductions in

neurons, synapses, and overall volumes of hippocampus and the surrounding areas (For

reviews, Raz, 2000; West, 1993). Furthermore, age-related MTL atrophy correlates with

measures of memory performance (Raz, 2000). Neuroimaging studies also suggest the link

between age-related relational memory deficits and MTL declines. Older adults have shown

decreased hippocampal activation relative to young adults in associative encoding tasks

involving objects in arrays (Mitchell et al., 2000) and face-name pairs (Sperling et al., 2003).

Using event-related fMRI and a spatial relational memory task, Mitchell et al. (2000)

demonstrated that young adults showed greater left anterior hippocampal activity for

combination of object and location pairs than for each item trials, whereas older adults did

not show the same patterns of activity in the hippocampal area. Furthermore, Dennis and

colleagues (2008) demonstrated a greater reduction in the hippocampus in older adults

compared to young adults, when they encoded face and scene pairs. However, other

researchers in fact found that older adults activated the hippocampus to a similar degree as young adults. Specifically, recent fMRI studies found similar degree of activity in the hippocampus between young and healthy older adults during successful associative encoding tasks for face-name pairs (Rand-Giovannetti et al., 2006; Miller et al., 2008), as well as for unrelated object-drawing pairs (Leshikar et al., 2010). Collectively, the literature currently offers reliable patterns of PFC dysfunction in older adults during associative memory encoding, but an inconsistent pattern in which hippocampal activity is only sometimes reduced in older compared to younger adults during relational memory formation.

Effects of divided attention on the neural basis of episodic memory

Previous researchers have also investigated the neural underpinning of effects of divided attention on encoding and retrieval of episodic memory. Anderson and colleagues (2000) tested the neural effects of divided attention at encoding and retrieval both in young and older adults. Using PET, the researchers found that left PFC regions were more activated under full attention (FA) condition than divided attention (DA) condition during intentional encoding of word pairs in both age groups. Activation in MTL region was also reduced under DA condition at encoding in both young and older groups, although only older adults showed decreased activity in hippocampus under the DA condition. Finally, the researchers found that only the left inferior prefrontal activity was reduced similarly by aging and by DA at encoding, and suggested that both aging and reduced attentional resources at encoding affected elaborated encoding operations involving the left inferior PFC. Other episodic memory studies with divided attention paradigm (Iidaka et al., 2000; Fletcher, Shallice, & Dolan, 1998; Fletcher et al., 1995; Shallice et al., 1994) also found an attenuation of putative

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encoding-related activity in the PFC under divided attention conditions, consistent with an idea that divided attention exerts its detrimental effect on encoding by reducing the processing resources for memory performance.

Upper mentioned neuroimaging studies in divided attention and episodic memory encoding employed a blocked design to investigate neural effects of attention on episodic memory. To date, however, only three studies investigated the effect of divided attention on episodic memory encoding using a subsequent memory procedure. Kensinger and colleagues (2003) manipulated the level of difficulty in attention tasks during encoding of word lists and demonstrated that divided attention was coupled with quantitative reduction in the magnitude of subsequent memory effects in the left inferior frontal gyrus as well as in left hippocampus. Specifically, the researchers found that the subsequent memory effect in left PFC and hippocampus was attenuated with hard attention task during encoding and only a subset of neural correlates of successful encoding, namely right inferior PFC and left parahippocampal gyrus, was activated in hard DA condition. This quantitative reduction, however, was not evident in a later study with divided attention paradigm. Using different attention task (i.e. digit monitoring task), Uncapher and Rugg (2005) demonstrated similar neural circuits of successful encoding in the left ventral inferior frontal gyrus and left anterior hippocampal formation. They, however, did not find any evidence on attenuated activity in those regions under easy or hard divided attention conditions. Instead, the researchers reported brain regions where study (memory) item activity was reduced and attention task item activity enhanced. Interestingly, such overlap was identified in the dorsolateral PFC and lateral parietal cortex, the regions consistently identified as supporting task-general executive and control processes (Wager & Smith, 2003; Collette & Van der Linden, 2002). Thus, the

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authors concluded that dividing attention during encoding of episodic memory disturbed task-generic processing instead of reducing the availability of resources supporting encoding processing. Recently, however, the same authors employed different attention tasks and demonstrated that divided attention interfered with the memory encoding in both task-generic and task-specific manners (Uncapher & Rugg, 2008). Using semantic and non-semantic attention tasks, the authors demonstrated that an attention task involving semantic decision attenuated activation in the left IFG and left hippocampus, and the attenuation of subsequent memory effects was associated with the emergence of additional effects in other prefrontal regions, such as bilateral dorsolateral PFC and superior parietal cortex. Thus, in sum, neuroimaging studies with subsequent memory procedure and divided attention paradigm have reported diverse effects of divided attention on episodic memory at the neural level, depending on the precise interplay between the processing demands of the memory and attention tasks.

Effects of divided attention on the neural basis of relational memory

Then, what are the effects of divided attention on relational memory at the neural level? Despite the rich body of evidence on the behavioral effects of attention on item and relational memory, the neural correlates of the effects of divided attention on the relational memory have not yet been widely investigated. Up to now, only a PET study utilized a relational memory task to investigate the neuronal effects of divided attention on relational memory (Anderson et al., 2000). In their study, the authors imposed a secondary task during encoding or retrieval of word pair recognition task in young and older adults. Using PET, the researchers demonstrated that both young and older adults revealed reduced left prefrontal

and medial temporal lobe activity under divided attention at encoding of relational memory task. To date, this is the only imaging study which tested effects of reduced attentional resources during encoding of relational memory. Moreover, to my knowledge, no published study directly investigated the neural correlates of effect of divided attention on successful relational memory encoding using an event-related fMRI. Thus, Experiment 3 of this dissertation project documents the first fMRI analysis of effects of divided attention on relational memory in both young and older adults. In Experiment 3, I examined whether imposing a relational attention task during encoding of associative information would alter neural correlates of relational memory. Based on evidence that divided attention at encoding in episodic memory task attenuates neural activities in the left inferior PFC and left hippocampal regions, I tested whether reduced specific attentional resources during the relational memory encoding would also decrease the subsequent memory effects in those areas in young adults. Furthermore, I also tested whether reducing young adults' resources for the relational attention at encoding of associative information equated neural activities of young and older adults. That is, in the last study of this dissertation, I tested whether the same attenuation of activation in areas for successful relational memory encoding can be found both in young adults with reduced relational processing resources and in older adults with full attention.

CHAPTER 2

EXPERIMENT 1: Verbal Item/Relational Memory Tasks with Visual Attention Tasks.

The primary goal of Experiment 1 was to determine whether a lack of resources for relational attention plays a critical role in the associative memory deficit observed in aging. Previous studies used a divided attention paradigm to impose attentional load during encoding and/or retrieval of item and relational memory tasks (e.g., Naveh-Benjamin et al., 2003). Using different type of attention and memory tasks, previous researchers demonstrated that imposing attentional load at the time of encoding in young adults significantly worsened their performance in both item and relational memory tests to the same degree. That is, none of the previous studies found evidence that reducing young adults' attentional resources during encoding equates young adults' performance in relational memory to that of older adults since older adults reveal disproportionate relational memory deficits compared to their relatively intact item memory (Naveh-Benjamin et al., 2003; 2004; 2007). Nonetheless, it is worthwhile to note that no studies employed an attention task involving processing of association in information. That is, all of the previous studies with divided attention paradigm used a simple detection or monitoring task which tagged general cognitive load rather than specific attentional load related to associative memory processing. Thus, in Experiment 1, I tested whether the lack of resources for relational processing played a critical role in the relational memory deficit in aging, by using a secondary task which

involved relational attention processing. I hypothesized that performance in relational memory task would be disproportionately impaired only when attentional load for relational processing was imposed during encoding.

Methods.

Participants.

Thirty six undergraduate students from the University of North Carolina at Chapel Hill participated and received course credits for their participation (Age: 17-25, Mean=19.7 years old, SD=1.73; Female: 22). Participants were randomly assigned to one of three attention groups: Full attention (FA), Divided attention with Item processing (DA-I), and Divided attention with Relational processing (DA-R).

Materials and Tasks.

Total 96 common words with less than four-syllables were used. Thirty two word pairs were presented in the encoding phase and 48 word pairs were used for two types of memory tests; an item memory and a relational memory test. To avoid possible floor effects (see Anderson et al., 1998), intentional encoding was used in which participants were informed with the nature of following memory tasks. For divided attention conditions, 128 face stimuli were used, which were selected from PAL face data base (Minear & Park, 2004; 64 females and 64 males; age 30-90). Faces in different gender were paired in each trial in two divided attention (DA) conditions. The age gap between two face stimuli in each pair was varied randomly from 5 years old and 55 years old. In each encoding phase in both DA conditions, word pairs were presented above the fixation cross and faces were presented

below the fixation cross (Figure 1B). Thirty two other face pictures from the same database, which were not used in actual experiment, were used in practice trials for each DA condition. In the full attention (FA) condition, scrambled images of faces were used to balance the amount of visual inputs across all conditions (Figure 1A). Participants in the FA condition were told to ignore the scrambled images during the entire encoding phase. After the encoding phase, each participant was tested with both item and relational memory tests and the order of the tests was counterbalanced across all participants. Each test phase consisted of three types of pairs: word pairs consisted of previously seen pairs (Intact pairs), pairs of two words presented in the encoding phase but not together (Recombined pairs), and pairs with two new words (New pairs). All participants saw the same 96 words, and stimuli in the six test conditions (3 (pairings) X 2 (memory tests)) were counterbalanced across all participants using the Latin square design. The experiment was presented on an Apple iBookG4 using a program, *MacStim* (Darby, 2006). All data were collected via computer key-press.

Procedures.

Participants were randomly assigned either to the full attention (FA) condition or to one of the two divided attention conditions (DA-I or DA-R). Before the actual study block, all participants performed a practice block. A practice block consisted of a study list of six word pairs, and two memory tests (item and relational). An encoding phase in an actual task block consisted of 32 word pairs and each pair was presented for 4 seconds. All participants were instructed to memorize both individual words and word pairs to prepare for later recognition tests. In addition, participants in two divided attention conditions were instructed

with each of the secondary tasks before the encoding phase. Participants in the divided attention with item processing (DA-I) condition were asked to detect a male face between two faces during each trial in memory encoding, whereas participants in the divided attention with relational processing (DA-R) group were asked to compare ages of two faces and to detect an older one between the two (Figure 1B). Participants were instructed to press "K (marked as LEFT)" on a computer keyboard if the target face was presented on the left of the computer screen and to press "L (marked as RIGHT)" if the target was presented on the right. Each pair of faces was presented for 2 seconds in both conditions; thus, each word pair was accompanied with two different face pairs. To avoid possible involuntary attentional capture to the face pairs due to sudden changes in faces every 2 seconds, the word pairs switched their locations every 2 seconds in order to produce the equivalent visual changes as the face pairs. In between each word pair, only a fixation cross was presented on the middle of the screen for 500 ms to separate different word pairs. Participants in both DA conditions were instructed to pay equal attention to both word and face pairs, and were told to make responses as quickly and as accurately as possible while encoding words or word pairs. The secondary task was included during the encoding phase only, not during the test phases. In the full attention (FA) group, participants were presented with a word pair and a pair of scrambled images in each trial of the encoding phase. The images were scrambled images of face stimuli used in the two DA conditions. The images were presented in the same location as the face stimuli in the DA conditions to equate perceptual loads between full and divided attention conditions. Participants in this group were instructed to ignore the scrambled images presented under the word pairs while memorizing the word stimuli during the entire

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encoding phase (Figure 1A). Both images and words switched their locations every 2 seconds to mimic the trials in the DA groups.

Each participant received one encoding phase, and item and relational memory tests were followed after an interpolate activity of 30 seconds (subtracting 3 continuously from 1000). The procedures of two recognition tests were equal for participants in all three groups. In the item memory test, participants were asked to decide whether they saw both words in the previous study phase. They were instructed to press "Z (labeled as "YES")" if they had seen both words either together or separately during the study phase. If participants did not see either word, they were asked to press "X (labeled as "NO"). Twenty four word pairs were presented; 8 Intact (pairs of words previously seen together), 8 Recombined (pairs of words that were presented during the study phase but not together), and 8 New pairs (word pairs with two new words). Thus, in the item memory test, the correct answers for the Intact and Recombined pairs were "YES", whereas the proper answer for the New pairs was "NO". In the relational memory test, participants were instructed to determine whether they saw both words together during the study phase. Thus, in this test, the correct answer for Intact pairs was "YES", while the correct answers for Recombined and New pairs were "NO". Again, total 24 pairs were presented and the response buttons and the presentation rate for each pair was fixed at 4 seconds in both memory tests. In both tests, participants were told to make their responses as accurately and as quickly as possible. All participants were received both types of tests, and the order of the tests was counterbalanced across all participants.

Results.

Attention task performance.

Accuracy and reaction times (RT) for correct responses were averaged for each divided attention task, and the results are presented in Table 1. Independent samples t-tests on accuracy and RT measures revealed significant differences in both measures; for accuracy, *MD* (mean difference)=.20, *t*(22)=12.63, *p*<.05, and for RT, *MD*=182 ms, *t*(22)=2.53, *p*<.05. That is, participants in DA-R group performed significantly worse in their attention task than participants in DA-I group. These results indicated that detecting "Older faces" in the relational attention task was more difficult than detection of "Male faces" in the item attention task.

Memory Accuracy.

Measures of proportion of hits minus proportion of false alarms were computed for each participant and then averaged over each group for both item and relational memory tests. Separate hit and false alarm rates in the item and relational memory tests for each group appear in Table 2. Also, Figure 2 shows the proportion of hits *minus* proportion of false alarm rates in each memory tests in each group. A 3 x 2 mixed ANOVA with Attention Group as a between-subject factor and Memory Task as a within-subject factor was conducted to examine effects of different attentional loads on item- and relational memory tests. The results showed a significant main effect of Memory test, *F*(1,33)=17.13, *p*<.05, as well as a significant main effect of Attention group, *F*(2,33)=10.26, *p*<.05. Furthermore, an interaction between attention and memory tasks was significant, *F*(2,33)=8.63, *p*<.05, suggesting different effects of different attentional loads on item and relational memory tests.

As depicted in Figure 2, post-hoc t-tests showed significantly worse performance in participants in DA-R group in relational memory test relative to their performance in item memory test, $MD=.26$, $t(11)=5.36$, $p<.05$. Such effect of attentional loads was not evident in either DA-I or FA group, suggesting that only the attentional loads involved relational processing disproportionately affected performance in the relational memory test.

Retrieval latency.

A 3 x 2 ANOVA using attention groups and memory tests as factors showed no significant main effects of memory, $F(1,33)<1$, or attention group, $F(2,33)<1$, on retrieval latencies for memory tests. Also, the interaction between two factors was not significant, $F(2,33)=2.491$, $p>.05$. These results confirm that results from memory accuracy data were not consequences of speed-accuracy trade-off. The group means for retrieval latency in Experiment 1 are displayed in Table 3.

Discussion.

Unlike previous studies with divided attention and relational memory paradigm (e.g., Castel & Craik, 2003; Naveh-Benjamin et al., 2003; 2004; 2007), the current experiment manipulated the type of attentional resources required for concurrent attention tasks during memory encoding. Using different types of attention task imposed during encoding, the current study tested the hypothesis that shortening resources for relational attention would disproportionately impair young adult's performance on a relational memory test. The results supported the hypothesis. That is, imposing an attention task which involved relational processing disproportionately affected the relational memory test compared to the

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item memory test. Furthermore, a different attention task, which involves little or no relational processing, impaired both item and relational memory performance proportionately. Thus, the current study provides the first evidence that reduction in attentional resources specific to the relational processing may be a crucial factor for disproportionate relational memory deficits shown in aging.

Although the current experiment demonstrated that resources for relational attention significantly interact with performance in relational memory test, several components of the design merited follow-up. First, it is worthwhile to test whether the interaction between relational attention and relational memory can be manipulated by different types of materials used in attention and memory tasks. Previous studies on interaction between attention and other cognitive processes (e.g., working memory) suggest that the interaction effect is different depending on the type of materials used in each cognitive task. In Experiment 1, visual domain of resources were used in both attention tasks (i.e., pictures of faces), but verbal domain of resources were utilized in memory tasks (i.e., word pairs). Therefore, it will be informative to test whether the effect of relational attention would be increased or decreased when the same domain of materials are used both in attention and memory tasks. Experiment 2 was thus designed in part to address this question by examining whether the pattern of effect of relational and/or item attention tasks on item and relational memory performance would be altered due to changes in materials in attention tasks.

Secondly, different levels of performance in two attention tasks limits a conclusion that specific type of attentional resources, namely the relational attention, is the critical factor which caused the disproportionate relational memory impairments in the current study. From the results in attention task performance, it was evident that the attention task involving

relational processing was more difficult than the attention task with item processing. Thus, it is plausible that the disproportionate effect of relational attention task is not due to the specific type of attentional resources imposed during encoding but due to larger attentional demands in the relational-attention task than in the item-attention task. To address this issue, Experiment 2 was conducted with an additional attention condition, namely "*Divided attention with item processing, harder condition (DA-IH)*". During encoding of word stimuli, participants in the DA-IH group performed the same attention task as divided attention with item processing group, but I increased the level of difficulty for the attention task in the DA-IH group by increasing the speed of the presentation rate of the stimuli in the attention task. By examining the effect of more difficult, attention-demanding task during memory encoding, the results in Experiment 2 will elucidate whether the disproportionately impaired relational memory performance in relational attention group was due to the level of task difficulty or due to the specific type of attentional resources imposed during encoding of episodic memory tasks.

Lastly, a goal of the present set of studies was to test whether the age-related relational memory deficit can be observed in young adults by diminishing their cognitive resources for relational attention processing. Although the disproportionate relational memory impairment, relative to item memory performance, was found in young adults in a divided attention with relational processing group in Experiment 1, it does not provide direct evidence that the pattern of relational memory deficit in those young adults were equivalent to the older adults' relational memory deficit because older adults were not tested in this experiment. Even though numerous previous studies have provided evidence that older adults show disproportionate relational memory deficit (For review, Old and Naveh-

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Benjamin, 2008), testing the deficit with the current design and tasks will provide more direct evidence that a lack of resources for relational attention is critical factor for the age-related associative memory deficit. Hence, in Experiment 2, I recruited healthy older adults to provide further evidence on age-related associative memory deficit. Furthermore, the pattern of the relational memory deficit in older adults was directly compared to that of young adults under relational attention condition to confirm the importance of relational attention resources on memory for association.

CHAPTER 3

EXPERIMENT 2: Verbal Item/Relational Memory tasks with Verbal Attention tasks with Difficulty manipulation.

Experiment 2 tested three primary questions. The first question was whether the effect of relational attention on associative memory found in Experiment 1 would be generalized with a different relational attention task using stimuli in different modalities. Previous studies on attention and working memory (WM) have demonstrated a modality-specific interaction between these two systems, by showing different effects of WM loads on attentional selection process depending on the types of materials used in attention and memory tasks (Oh & Kim, 2004; Kim, Kim, & Chun, 2005; Woodman et al., 2004). In Experiment 1 in the current project, I demonstrated that a reduction in attentional resources affected relational memory performance in a processing-specific manner. However, it is unknown whether the effect of relational attention on relational memory is material-specific or domain-general. Thus, in Experiment 2, I changed materials in the attention task from the visual to the verbal domain, and investigated whether the effects observed in Experiment 1 could be generalized to an attention task using different materials. The second question was whether the disproportionate effect of relational attention on memory performance found in Experiment 1 was due to a large task-demand in relational attention task or due to specific attentional resources utilized in the relational attention task. To answer this question, Experiment 2 included an additional attention group with increased item-processing

attentional demand during memory encoding, and tested the effect of general task difficulty on item and relational memory tasks. Lastly, here I recruited healthy older adults as well as young adults in order to test disproportionate relational memory deficit in older adults and also to examine whether the pattern of relational memory deficit in young adults under divided attention with relational processing at encoding could mimic that of older adults under full attention condition.

Methods.

Participants.

Forty eight undergraduate students (Age: 18-28, Mean=19.7 years old, SD=1.89; Female: 33) from the University of North Carolina at Chapel Hill, who did not participate in Experiment 1, participated and received course credit for their participation. Participants were randomly assigned to one of four conditions: Full attention (FA, N=12), Divided attention with Item task (DA-I, N=12), Divided attention with Relational task (DA-R, N=12), and Divided attention with Item, Harder task (DA-IH, N=12). In addition, 12 older adults (Age: 70-81, Mean=74.6 years old, SD=3.20; Female: 5) were recruited from the local community and were paid $10 per hour. Older adults participated in the full attention condition only.

Materials and Tasks.

The word stimuli in two memory tests were identical to those used in Experiment 1. However, instead of pictorial stimuli, number stimuli were used for secondary tasks in this experiment. Specifically, numbers from one to ten were used in attention tasks, and all

numbers were written in English alphabet, not in Arabic numbers (e.g., "THREE" instead of "3"). In each trial of divided attention conditions, an odd number and an even number were randomly paired. In all of the DA conditions, number pairs were presented below the fixation cross and the word pairs were appeared above the fixation cross (Figure 3B, 3C). In the FA condition, meaningless strings of Xs and Ys (i.e. "XXXXX   YYYYY") were presented in the same location of the number stimuli in the DA conditions to balance the amount of visual inputs across all conditions (Figure 3A).

Procedures.

All the experiments in Experiment 2 were presented on an Apple iBookG4 using the program, MacStim (Darby, 2006). The procedures in Experiment 2 were identical to those in Experiment 1 with a couple of exceptions. As in Experiment 1, 32 word pairs were used in each of memory encoding phase, and attention tasks were imposed during memory encoding phase in each of divided attention groups. Young adults in Experiment 2 were randomly assigned either to the full attention (FA) condition or to one of the three divided attention conditions (DA-I, DA-R, or DA-IH). Participants in the DA-I group were asked to detect an odd number and individuals in the DA-R condition were asked to compare two numbers and to detect a numerically bigger one between the two numbers. Thus, the attention task in the DA-R group required processing of relational information (i.e., comparison), whereas the attention task in the DA-I group did not. Participants were instructed to press an appropriate button (LEFT or RIGHT) to each attention task trial. As in Experiment 1, each pair of numbers was presented for 2 seconds in both DA-I and DA-R conditions, and the word pairs switched their locations every 2 seconds to prevent unwanted attentional bias to the changes

in numbers. Participants in the DA conditions were instructed to pay equal attention to both word and number pairs.

As stated above, a more difficult item-based attention task condition (i.e., DA-IH condition) was also included in this study in order to test effects of overall task difficulty on relational memory deficits. Although young adults in Experiment 1 showed a disproportionate relational memory deficit when their relational attention was reduced during encoding, it is unclear whether the overall task difficulty or the specific attentional resources (i.e., relational attention) played a key role for the deficit since the relational attention task was more difficult than the item attention task. Thus, in Experiment 2, I added a more demanding item attention task (DA-IH task) to rule out an effect of potential compound (i.e., overall task difficulty) and to test whether increasing the level of difficulty in a secondary task involving item processing disproportionately affects item or relational memory performance. Specifically, participants in the DA-IH group performed the same secondary task as those in the DA-I group, but the presentation rate for stimuli in the attention task was accelerated. To impose more demanding task load, each number pair was presented for 1 second instead of 2 seconds. Thus, participants in this group had to respond to four different number stimuli while encoding one word pair. Finally, participants in the full attention (FA) condition were presented with a number pair and a meaningless string pair (i.e. strings of Xs and Ys) in each trial of memory encoding, and instructed to pay attention to and memorize the words and word pairs during the encoding block ignoring the strings. Both strings and words switched their locations every 2 seconds to mimic the trials in the DA groups. Like previous studies on divided attention and relational memory deficits, older adults were assigned to the FA group only to verify age-related relational memory deficits in this

experiment. As in Experiment 1, the word stimuli were randomly selected and counterbalance across all participants. Figure 3 illustrates stimuli and procedures in each encoding condition in Experiment 2.

After the study phase, all participants received the same interrupting activity as Experiment 1 (i.e., subtraction activity), and two recognition tests, item and relational memory tests, were followed. The procedures of the two memory tests were equal to those in Experiment 1, and the order of the tests was counterbalanced across participants.

Results.

Secondary-task performance.

Accuracies and reaction times (RT) for correct responses were averaged for each divided attention group. The accuracy and RT data for each group are presented in Table 4. To test whether the level of difficulty was different among three attention group, a one-way ANOVA was conducted for accuracy data from three attention groups (i.e., DA-I, DA-R, and DA-IH groups). The result showed significant differences in accuracy among three groups, $F(2,33)=32.69$, $p<.05$. To examine where the differences came from, planed contrast t-tests were conducted. The results revealed significant differences between performance in young adults under DA-I group and young adults under DA-IH group, MD (Mean difference)=.25, $t(33)=7.46$, $p<.05$. Moreover, the accuracy in young adults under DA-IH group was also significantly worse than that of young adults under DA-R group, $MD=.22$, $t(33)=5.84$, $p<.05$. Unlike results in Experiment 1, accuracies from DA-I and DA-R group were not significantly different from each other, $MD=.04$, $t(33)=1.04$, $p=.56$, indicating that the level of difficulty in item- and relational attention tasks in Experiment 2 were not statistically different. Since the

presentation rate in DA-IH group was different from those of DA-I and DA-R groups (i.e. 1

second vs. 2 seconds), a comparison of reaction time (RT) data between DA-IH group and

other two attention groups was not meaning. Thus, only an independent samples t-test was

conducted for RT data from DA-I and DA-R groups. As in the case of accuracy, the RT

results from the two attention groups were not significantly different from each other, *MD*= -

5, *t*(22)=-.08, *p*=.94. In sum, the accuracy data confirmed that the attention task under DA-

IH group was significantly harder than attention tasks under DA-R or DA-I group. Moreover,

the level of difficulty in tasks under DA-I and DA-R groups was not significantly different

from each other as revealed in both accuracy and RT measures.

Memory Accuracy.

Measures of proportion of hits minus proportion of false alarms were computed for

each participant and then averaged over each group for both item and relational memory tests.

Separate hit and false alarm rates in the item and relational memory tests for each group

appear in Table 5. Also, Figure 4 shows the proportion of hits minus proportion of false

alarm rates in each memory tests in each group. A 5 x 2 mixed ANOVA with Attention

Group as a between-subject factor and Memory Task as a within-subject factor revealed

significant main effects of Attention Group and Memory Task, *F*(4,55)=12.22*, p*<.05, and

F(1,55)=12.15*, p*<.05, respectively. An interaction between two factors was also significant,

F(4,55)=4.29*, p*<.05, indicating that participants' performance in each memory task was

different depending on the concurrent attention tasks imposed during encoding in each group

(Figure 4). To address specific hypotheses to be tested in this experiment, I conducted

specific comparisons for each hypothesis. First, to test the presence of an age-related deficit

in relational memory in the current study, a 2 x 2 mixed ANOVA was carried out to compare young and older adults under full attention condition. The results revealed a main effects of age group (young vs. older), $F(1,22)=16.16$, $p<.05$, indicating significantly worse accuracy in older adults than young adults under full attention. A main effect of memory test (item vs. relational) was also significant, $F(1,22)=7.04$, $p<.05$, indicating poorer performance in the relational memory test than in the item memory test. This main effect of memory test was due to a reduction in relational memory in older adults, as revealed in a significant interaction between memory and age group, $F(1,22)=7.04$, $p<.05$. Specifically, post hoc comparisons showed no age differences in the item test, $MD=.10$, $t(22)=1.69$, $p>.05$, but there was a significant difference between young and older adults in the relational memory test, $MD=.34$, $t(22)=4.28$, $p<.05$. Finally, separate paired t-test in each age group revealed significant differences between two memory tests only in the older adult group, $MD=.24$, $t(11)=3.67$, $p<.05$, confirming the disproportionate relational memory deficit in older adults.

Next, a 4 x 2 mixed ANOVA was performed including young adult groups only, in order to test effects of different attentional loads on memory performance in young adults. The test revealed a significant main effect of Attention Group, $F(3,44)=15.27$, $p<.05$, indicating that participants in divided attention groups performed worse in both of memory tests. Interestingly, an interaction between Attention Group and Memory Test was also significant, $F(3,44)=3.19$, $p<.05$. To identify the locus of the interaction, paired t-tests between two memory tests in each group were conducted. The results from the t-tests indicated that only the young adults under DA-R group showed significantly worse accuracy in relational memory test compared to their item memory performance, $MD=.19$, $t(11)=3.14$, $p<.05$. Importantly, the disproportionate effect of attention task on item and relational

memory in young adults under DA-R group was strikingly similar to the disproportionate

relational memory deficits in older adults, as revealed in a separate paired t-test between item

and associative performance in older adults, *MD*=.24, *t*(11)=3.67, *p*<.05 (Figure 4). Overall,

the current results replicated findings from Experiment 1, indicating that reducing resources

for relational attention disproportionately impaired relational memory performance in young

adults, while attentional loads which involved little or no relational processing

proportionately affected performance in item and relational memory tasks. Furthermore, the

different effect of different attentional loads were not due to the overall task difficulty, as

indicated in proportionate memory impairments in item and relational memory tests in young

adults with the hardest attention task involving item attention processing (i.e., in DA-IH

group, *MD*= -.04, *t*(11)= -.64, *p*>.05). Finally, the remarkably similar patterns of relational

memory deficit between young adults under DA-R group and older adults under FA group

suggest that a lack of resources for relational attention is a critical factor for age-related

relational memory deficit.

Retrieval latency.

The group means for retrieval latency are displayed in Table 6. The results of a 5 x 2

ANOVA using attention group and memory test showed neither significant main effect of

memory nor interaction between two factors. However, the main effect of group was

significant. Post hoc testing showed significantly slower retrieval response times (RTs) in

older adults compared to those in young adults under each attention groups; *MD*=450 ms,

287 ms, 316 ms, and 486 ms for young adults under FA, DA-I, DA-R, and DA-IH group

respectively, all *ps*<.05. Retrieval RTs for young adults under difference attention groups

were not significantly different from each other. These results thus indicate that older adults take longer to respond than young adults in both memory tasks. Although older adults were slower to retrieve their memory in general compared to young adults, older adults may experience more difficulty in retrieving associative information and, in turn, take longer time to response in a relational memory test compared to an item memory test. Thus, a two way ANOVA with age group (young and older groups with full attention) and memory test (item and associative) as factors was carried out, in order to examine whether the relational memory deficits in older adults were also presented in the reaction time measures, as in the case of accuracy. The results from the ANOVA test verified the hypothesis, showing significant interaction between age group and memory test in retrieval RTs, $F(1,22)=4.504$, $p<.05$. Post hoc t-tests confirmed significantly slower RTs in relational than item memory test only in the older adult group, $MD=196$ms, $t(11)=4.480$, $p<.05$. Interestingly, separate two way ANOVAs comparing older adults with young adults under each of attention condition (DA-I, DA-R, DA-IH) resulted significant interaction between group and memory test, except for the test with older adults under full attention condition and young adults under DA-R condition, $F(1,22)=1.981$, $p>.05$. These results thus provide additional evidence for the similar pattern of relational memory deficits in older adults under full attention and young adults who lacked their relational attention resources during encoding.

Discussion.

The results from Experiment 2 replicated the findings from Experiment 1, and confirmed the hypothesis that the relational memory deficit in older adults was mediated by a reduction in attentional resources specific to the relational processing. Furthermore, using

different materials in attention task, the results in Experiment 2 generalized the processing-specific effect of attention on relational memory to different modalities. This finding is in accordance with previous finding which showed general relational memory deficits in older adults regardless of the type of association, such as within- or between- domain associations (Bastin & Van der Linden, 2006). Bastin and Van der Linden (2006) compared older adults' recognition performance on face-face pairs (i.e., within-domain association) to their performance on recognition of face-spatial pairs (i.e., between-domain association), and found that the degree to older adults' impairments on relational memory was equal across different types of association (e.g., within- or between-domain). In other words, the authors demonstrated that an age-related relational memory deficit was a domain-free rather than domain-specific deficit in terms of materials used in memory tasks. Consistent with this notion, the current study demonstrated that the effect of relational attention on relational memory was also domain-general, similar to the effect of aging on relational memory.

Importantly, the results from Experiment 2 rule out an alternative explanation that the relational memory deficit in young adults under relational attention condition is mediated by the increased task difficulty in attention task. Using a more difficult attention task involving little or no relational processing (i.e., DA-IH group), the current study showed that the more difficult attention task with item processing proportionately impaired item and relational memory performance in young adults, unlike the case of relational memory deficit in older adults. Furthermore, the levels of difficulty in the item and relational attention tasks in the current experiment were in fact not significantly different from each other as revealed in the similar accuracy and reaction time data between two attention tasks. In other words, detection of a numerically larger one between two numbers was not attentionally more

demanding than detection of an odd number, yet the two tasks differed in regard to their processing. That is, only the bigger number detection task involved relational processing to compare two numbers on the screen, and only young adults who performed memory encoding with this attention task revealed disproportionately impaired performance in memory task for association. Moreover, their performance in the relational memory test was remarkably similar to older adults' deficits in the relational memory test.

The similar pattern of deficits between young adults under relational attention condition and older adults under full attention condition is worth noting. Previously, Castel and Craik (2003) found disproportionate relational memory deficit in young adults whose attention was divided during memory encoding. However, the authors indicated that the pattern of the deficit in young adults under divided attention (DA) condition was different from that of older adults. Specifically, while older adults' relational memory deficit was due to the increased false alarm rate in recombined pairs, the relational memory impairment in young adults under DA condition was resulted from the decreased hit rate in intact pairs. Furthermore, the size of the deficit was larger in older adults compared to young adults under DA condition. Unlike the findings Castel and Craik (2003), the current study demonstrated that reducing a specific type of resources in young adults during memory encoding can in fact equate young adults' relational memory performance to that of older adults. That is, the disproportionately greater decrease in relational memory performance in young adults under DA-R condition in the current study was resulted not only from decreased hit rate in intact pairs, but also from increased false alarm rate in recombined pairs. Critically, this pattern of the deficit was also evidenced in older adults under full attention condition, and the magnitude of impairments between young adults under relational attention condition and

older adults under full attention condition was equivalent. Thus, the current study provides evidence that a reduction in attentional resources specific to the relational processing is a crucial factor for relational memory deficits shown in aging.

General Discussion for Behavioral Studies.

Two behavioral experiments in the current dissertation demonstrated a unique finding suggesting that a lack of resources for relational attention plays a critical role in the age-related relational memory deficits. Experiment 1 demonstrated that reduction in relational attention during memory encoding disproportionately impaired young adults' performance in the relational memory test compared to the performance in the item memory test. Such a disproportionate effect was not found when young adults' attention was divided with a task which did not require relational processing (i.e., item attention task). Experiment 2 further supported the hypothesis that lack of attentional resources for relational processing is a key factor for relational memory deficit in older adults. In Experiment 2, the level of difficulty in attention tasks was manipulated to test whether the increased attentional load contributed to the relational memory impairment in young adults under divided attention condition. The results verified that the effect of relational attention on relational memory found in two experiments was not due to the general task difficulty in attention task, by showing that the most difficult attention task involving little or no relational processing proportionally impaired item and relational memory performance. Importantly, the less difficult task which involved relational attention processing disproportionately affected memory for association, and in turn, it equated young adults' performance in a relational memory test to that of older adults. Finally, the lack of relational attention affected the relational memory performance in

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a modality-general manner. That is, the effect of relational attention task involving visual stimuli on verbal relational memory task (Experiment 1) was similar to that of relational attention task involving verbal materials (Experiment 2). Overall, Experiment 1 and 2 demonstrated a novel finding that a reduction in specific attentional resources, namely *relational attention*, in young adults during memory encoding equated their relational memory performance to that of older adults at the behavioral level.

As stated earlier, previous studies investigating effect of divided attention on relational memory have demonstrated different findings than results in the current study. Naveh-Benjamin and colleagues have suggested that the effects of age and the effect of divided attention are mediated, at least partially, by different mechanisms, by showing proportionate deficit in item and relational memory in young adults under divided attention conditions (Naveh-Benjamin et al., 2003; 2004; 2007). Furthermore, Castel and Craik (2003) demonstrated different patterns of impairment between young adults under attentional division condition at encoding and older adults, although the researchers found worse relational memory performance than item memory performance in young adults under divided attention (DA) condition. In their discussion, the authors pointed out that older adults' relational memory deficit was from increased false alarm rate in recombined pairs, whereas relational memory impairment in young adults under DA condition was resulted from decreased hit rate in intact pairs. Furthermore, the authors compared the size of impairment between young adults under DA condition and older adults, and concluded that aging was associated with a differentially greater loss of associative memory performance compared to division of attention. Overall, previous studies agreed that reducing attentional

resources of young adults during encoding did not cause them to simulate the behavior of older adults in regard to their relational memory deficit.

The results in the present study are in part consistent with previous findings, showing that the division of attention at encoding with a certain type of attention tasks (i.e., item attention tasks) proportionately affected item and relational memory performance in young adults. The results in the current experiments, however, also indicated the important relationship between age-related associative memory deficit and reduction in attentional resources for relational processing. Critically, the degree to attentional resources interfering with each episodic memory process differs depending on the type of processing resources that the attention and memory systems utilize. It should be noted that previous studies with divided attention paradigm utilized attentional tasks not specific to the processing required in relational memory. Instead, previous researchers used tasks which tagged general attentional resources and/or involved short-term memory processing. For instance, some studies used simple visual or auditory detection tasks (e.g., Kilb & Naveh-Benjamin , 2007) which tagged general attentional resources, while others used monitoring tasks of detecting three consecutive odd digits (e.g., Castel & Craik, 2003) which required both attention and working memory processing. However, in the current study, I manipulated the type of processing required in concurrent attention tasks, and found a specific type of attentional resources, namely resources for relational attention, mediated relational memory deficit observed in older adults.

This novel finding partially supports the common mechanism hypothesis proposed by Craik (Craik, 1982; 1986; Craik & Byrd, 1982), which posits that a major cause of deficient episodic memory in older adults is their characteristic of reduction in attentional resource.

The common mechanism view has been supported by studies with divided attention and episodic memory paradigm (Anderson, Craik, & Naveh-Benjamin, 1998; Anderson et al., 2000), but not favored by studies on divided attention and relational memory paradigm as observed in different effect on relational memory of aging and divided attention. The current finding can reconcile the conflict on common mechanism view by indicating the importance to measure the effect of attentional deprival not only in quantitative aspect but also in qualitative feature. That is, the quantitative reduction in attentional resources related to aging may contribute linear and general decrease in item and relational memory performance as shown in linear decrease in performance in both tasks as function of the difficulty of the attention task (Experiment 2). However, using qualitatively but not quantitatively different attentional loads, the current study also demonstrated that reduction in a certain type of attentional resources can account the relational memory deficit in older adults.

Although this is the first study demonstrating a significant effect of reduced relational attention processing on relational memory, a recent study reported somewhat related findings. Castel (2007) investigated the role of expertise in relational memory in older adults. In his study, he questioned whether expertise can benefit in performance in an associative memory task which involved stimuli in expertise-related domain. In his experiment, the researcher asked participants to memorize short phrases including information of a number, location, and object (e.g., "58 nails in the bowl"), and provided a cued-recall test with a location as a cue. Participants had to recall both number and object associated with the cue to perform the test. Critically, the researcher recruited older adults without or with expertise in number (e.g., retired accountants and bookkeepers) along with young adults. Castel examined whether older adults with expertise in number showed an advantage in tests involving association

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between numbers and locations due to their strategy or tendency to allocate more attentional resources in numbers and related context. Interestingly, he found that expertise reduced the age-related relational memory deficit in the domain of the skill. Specifically, he replicated relational memory impairments in older adults in both object and number information, but the deficit disappeared for number targets in older adults with expertise in numbers. This finding suggests that older adults who have been trained to pay attention to the relationship between numbers and other information could overcome the age-related deficit in relational memory. In other words, this recent finding highlights the importance of attentional allocation on relational aspects of stimuli, by showing that older adults who were trained or motivated to allocate sufficient attention to relation between certain information (e.g., number and another stimulus) did not exhibit relational memory impairment for those information. In relation to this previous study, the current findings also stress the importance of attentional resources allocated in relational aspects of stimuli for memory for association. Whereas Castel showed increased older adults' relational memory ability with larger allocation of attention on the stimuli, the current study demonstrated decreased young adults' relational memory performance with division of resources in relational attention. Future studies with integration of these two separate findings will be able to elucidate the critical role of relational attention for age-related memory deficit in associative memory.

Although not tested in this project, it will be beneficial to investigate the effect of reduction in relational attention during retrieval of relational memory in young adults. That is, if older adults suffer in relational memory test due to their lack of resources for relational attention, it is possible that the reduced relational attention resources might play a role during the relational memory retrieval as well as during the encoding. Previous researchers, in fact,

have investigated effect of divided attention (DA) at retrieval on associative memory, and demonstrated that DA at retrieval in young adults has little or no effect on memory performance, especially when recognition tasks are involved (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Naveh-Benjamin, Craik, Guez, & Dori, 1998; Naveh-Benjamin, Craik, Gavrilescu, & Anderson, 2000; Anderson, Craik, & Naveh-Benjamin, 1998). However, as in the case of DA at encoding, none of the studies manipulated the type of attention tasks loaded during retrieval. Although the current study demonstrated significant effects of DA at encoding with relational attention task, in a future study, it will be informative to test whether depriving resources in relational attention during retrieval can also simulate the age-related associative memory deficit.

In the two behavioral studies in this dissertation, I demonstrated a critical finding that a reduction in relational attention could account for relational memory deficit in older adults. Even though a behavioral study can provide a unique explanation for a critical factor for relational memory deficit in aging, adding neural evidence on such effects could offer further elucidation on how the reduction in relational attention resembles the aging in terms of its role in associative memory deficits. Of note, Moscovitch and colleagues (Moscovitch, 1992, 1994; Moscovitch & Winocur, 1995) suggest that memory involves the interaction of a frontal lobe system that mediated strategic encoding and retrieval processes as well as a medial temporal lobe-hippocampal (MTLH) system that automatically picks up information that has been consciously processed. In fact, neuropsychological and neuroimaging studies have highlighted the importance of the prefrontal cortex (PFC) in promoting successful relational memory formation (Prince et al. 2005; Staresina & Davachi, 2006; Murray & Rannganath, 2007). Furthermore, a number of studies have been reported significant relation

between medial temporal lobe activity (especially hippocampus) and successful relational memory formation (Davachi et al, 2002, 2003; Henke et al., 1997, 2003; Prince et al, 2005; Staresina & Davachi, 2006). Critically, older adults tend to show malfunction of neural activity in PFC and hippocampal and its surrounding region during relational memory tasks (Anderson et al., 2000; Cabeza, Grady, et al., 1997; Dennis et al., 2008; Mitchell et al., 2001; Sperling et al., 2001), consistent with behavioral evidence on age-related relational memory deficit. Moreover, several researchers indicated that the associative memory deficit in older adults may stem from impairments in the prefrontal cortex (PFC) (Hedden & Gabrieli, 2005), which is involved in the strategic organization or manipulation of associative features (Buckner, 2003; Dobbins, Foley, Schacter & Wagner, 2002), or may stem from impairments in the circuitry between the PFC and the hippocampus (Li, Naveh-Benjamin & Lindenberger, 2005; Mitchell, Johnson, Raye & D'Esposito, 2000b). Then, what is the effect of divided attention on relational memory at neural level? Despite rich behavioral evidence on effects of divided attention on relational memory formation, the neural effect of reduced attention on relational memory has not been widely studied. In fact, to my knowledge, no event-related study has investigated the effect of divided attention on associative memory formation. Thus, in the third study in the current project, I utilized an fMRI technique to examine neural effects of reduced attentional resources on relational memory encoding. Critically, based on my behavioral findings that relational attention plays a critical role in relational memory deficit in aging, I utilized different types of attention (i.e., item attention, relational attention) and tested effects of different attentional loads on relational memory formation at the neural level. That is, I tested whether the effect of reduction in relational attention on relational memory formation would be similar to that of aging on relational memory at the neural level.

The effect of aging and of each type of attentional reduction on the roles of PFC and MTL

during relational memory formation is examined in detail in Experiment 3.

CHAPTER 4

EXPERIMENT 3: Effects of Relational Attention and Effects of Aging on Relational Memory at Neural Level

Experiment 3 used the event-related fMRI technique to investigate the neural architecture of the effects of different types of attentional loads on relational memory encoding in young and older adults. Because the neural architecture of item memory was beyond the scope of this dissertation project, only a relational memory task was used in Experiment 3. The hypotheses and goals in Experiment 3 are described below.

The first goal was to examine and identify the neural basis of relational memory in healthy young adults. Previous neuropsychological and neuroimaging evidence has indicated the importance of the prefrontal cortex (PFC) and medial temporal lobe (MTL) in relational memory formation. The MTL memory system has a hierarchical organization; inputs from various sensory association cortices are channeled through the parahippocampal region (the perirhinal cortex and the parahippocampal cortex) to the entorhinal cortex, and from there to the hippocampus (Squire & Zola-Morgan, 1991). Studies on episodic memory have shown that the different functions of each part of the MTL system contributes differently to relational memory and item memory. Specifically, previous researchers demonstrated that the hippocampus is more critical for relational memory than item memory (Aggleton & Brown, 1999; Brown and Aggleton, 2001; Davachi et al, 2002, 2003; Eichenbaum et al., 1994; Giovanello, Schnyer, &Verfaellie, 2004; Henke et al., 1997, 2003; Kroll et al., 1996;

Mishkin et al., 1998). For example, Aggleton and Brown reviewed a large amount of evidence demonstrating that hippocampal lesions produce greater deficits in relational memory whereas perirhinal/parahippocampal lesions yield greater deficits in item memory (Aggleton & Brown, 1999; Brown & Aggleton, 2001). Furthermore, studies using neuroimaging techniques (PET or fMRI) have also provided evidence supporting the notion that hippocampal activity is critical for successful relational memory encoding. For example, previous researchers have reported greater hippocampal activity for tasks involving the formation of associations among word pairs or word triplets in comparison with single-word learning conditions (Henke et al., 1999, Davachi & Wagner, 2002; Meltzer & Constable, 2005). In addition, other studies using different types of materials have also found the hippocampus to be more activated during encoding of relational information (e.g., face-name pairs or face-house pairs) compared to during item-based or non-relational encoding (Henke et al., 1997; Montaldi et al., 1998). Thus, consistent with the evidence from lesion studies, the neuroimaging studies also support the idea that hippocampus in the MTL system plays a critical role in formation of relational memory.

With the hippocampus, the prefrontal cortex (PFC) also serves an important role in relational memory encoding. Like the effect of MTL lesions (Ryan et al., 2000), lesions to PFC (especially dorsolateral) also produce larger deficits to relational memory than item memory (Stuss, Eskes & Foster, 1994). Moscovitch's (1992) component process model suggests that the frontal lobes are critical for the manipulation or organization of associations, including elaborative learning strategies that operate under effortful, intentional learning conditions. More recent research from functional neuroimaging provides convergent evidence that the MTL and PFC make important, though distinct, contributions to relational

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memory. While MTL structures have been associated with the incidental encoding and retrieval of contextual associations, the PFC has been associated with controlled processing of relational information, both at encoding (e.g., Henson, Shallice, Josephs & Dolan, 2002) as well as at retrieval (e.g., Badgaiyan, Schacter & Alpert, 2002; Velanova et al., 2003; For a review, see Cabeza, 2006). Of note, a recent review on the functions of the PFC on relational memory encoding provides evidence on distinctive roles of different prefrontal area on relational memory formation (Blumenfeld & Ranganath, 2007). The authors suggest that ventrolateral regions of the PFC (VLPFC) contribute to the ability to select goal-relevant item information, whereas the dolrolateral PFC (DLPFC) contribute to the ability to organize multiple pieces of information in memory to enhance memory for associations among different items. Based on above previous findings on the role of PFC and hippocampus in relational memory formation, the first goal of the current study was to replicate the critical neural areas for successful relational memory formation in healthy young adults using the relational memory task and paradigms in the current project. Specifically, I hypothesized that stronger activation in the dolsolateral and ventrolateral part of the PFC and the hippocampus would be involved in successful relational memory encoding compared to failure of associative memory encoding.

The second goal of Experiment 3 was to examine the effect of aging on relational memory encoding at the neural level. Previous behavioral studies have provided consistent evidence that older adults show disproportionate difficulty in memory for association than memory for single items (Naveh-Benjamin, 2000; For review, Old & Naveh-Benjamin, 2008). The age-related deficit in relational memory have been found in different types of relational memory tasks, including tasks involving association of separate stimuli (e.g.,

unrelated word pairs, Nabeh-Benjamin et al., 2000; 2003), intra-item association (e.g., word

and its font; Naveh-Benjamin, 2000), spatial relation (e.g., location of word or objects; Park

et al., 1982, 1983), and temporal relation (e.g., recall of the temporal order; Kausler et al.,

1988; Naveh-Benjamin, 1990). In accordance with the findings on important roles of the

PFC and MTL in relational memory formation, previous studies have evidenced that the

relational memory deficits in older adults are most likely a consequence of age-related

decline in MTL and PFC functions. In particular, Cabeza and colleagues (1997) found age-

related decrease in PFC activity during encoding of a semantic relational memory task. In

their study, participants were scanned during intentional learning of word pairs, and the

authors found reduced activity in the left ventolateral prefrontal cortex activity in older adults

compared with young adults. Furthermore, using pairs of drawings, Iidaka and colleagues

(2001) also demonstrated weaker activity in left ventral and right dorsal prefrontal cortex in

older adults during formation of new association, relative to young adults. Using face and

scene pairs, Dennis et al. (2008) also demonstrated a significant reduction in PFC in older

adults compared to young adults during the associative memory encoding.

Regarding MTL regions, aging is sometimes associated with smaller MTL volumes in

structural studies, as well as overall decreased MTL activation in functional studies, across

different types of tasks (for a review, see Raz, 2000). However, there has been mixed

evidence as to whether or not weakened MTL activity is directly linked with age-related

episodic memory declines. Several studies have reported reduced MTL activity, especially

hippocampus, during relational memory encoding in older adults compared to young adults.

For example, older adults have shown decreased hippocampal activation relative to young

adults in associative encoding tasks involving objects in arrays (Mitchell et al., 2000) and

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face-name pairs (Sperling et al., 2003). However, recent fMRI studies found that older adults activated the hippocampus to a similar degree as young adults during successful associative encoding tasks for face-name pairs (Rand-Giovannetti et al., 2006; Miller et al., 2008) as well as for unrelated object-drawing pairs (Leshikar et al., 2010). In summary, the literature currently offers reliable patterns of PFC dysfunction in older adults during associative memory encoding, but an inconsistent pattern in which hippocampal activity is only sometimes reduced in older compared to younger adults during relational memory formation. Thus, in the current study, I investigated whether older adults show reduced activity in both the PFC and MTL regions critical for relational memory formation or reveal selective reduction in some part of the neural network for the relational memory encoding, such as the PFC regions.

The third goal of Experiment 3 was to test and compare neural effects of different attentional loads on successful relational memory encoding in young and older adults. Although behavioral effects of attentional reduction on relational memory encoding have been well-investigated, the neural effects of attention on relational memory formation have not yet been widely studied. In fact, only a PET study investigated the effect of divided attention during encoding of associative memory (Anderson et al., 2000). Specifically, the authors imposed an auditory detection attention task during encoding and retrieval of word pairs in both young and older adults, and demonstrated significant reduction in left prefrontal cortex in both young and older adults during memory encoding under the divided attention condition. The authors also found significant reduction in some part of MTL areas under divided attention during memory encoding, although only older adults showed significant reduction in hippocampal activity under the divided attention condition. To date, this is the

only imaging study which tested effects of reduced attentional resources during encoding of relational memory. In fact, to my knowledge, no event-related fMRI study has investigated the effects of divided attention on relational memory formation. Instead, there have been three event-related fMRI studies which examined the effects of divided attention on item memory formation (Kensinger et al., 2003; Uncapher & Rugg, 2005, 2008). All of these three studies manipulated the attentional load (i.e., easy task vs. hard task) during memory encoding, and demonstrated somewhat different findings. First, Kensinger and colleagues (2003) reported that divided attention was associated with a quantitative reduction in the magnitude of activity in the left inferior frontal gyrus and left hippocampus. However, such attenuation in the PFC and hippocampus was not found in another study with divided attention manipulation (Uncapher & Rugg, 2005). Rather, Uncapher and Rugg (2005) found increased activity for the distracting items, in particular, in the dorsolateral prefrontal cortex and the superior parietal cortex. The authors explained that such increased activity was for task-generic, executive processes to support the both memory and secondary task performance. Finally, the same authors observed both reduced activity in encoding-specific regions in the PFC and MTL and enhanced task-generic activity under more demanding divided attention condition during item memory encoding (Uncapher & Rugg, 2008).

Although upper mentioned studies provide useful findings for the neural effects of attention on memory encoding, they do not offer direct evidence for the neural effects of attentional reduction on relational memory formation since none of the studies used memory tasks for association. Furthermore, the three studies manipulated the difficulty level of attention tasks (i.e., quantitative aspects of attentional loads) rather than the types of attentional processing required in the secondary task (i.e., qualitative aspects of attentional

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loads). Of note, in this dissertation project, I have demonstrated significantly different behavioral effects of qualitatively, not quantitatively, different attention tasks on relational memory encoding. Thus, in experiment 3, I tested the effects of qualitatively different attentional loads on relational memory formation at the neural level. Specifically, I investigated whether the reduction in relational attention during encoding disproportionately reduced the activity in the critical neural regions for relational memory (i.e., the PFC and hippocampus) compared to the case of reduction in item attention both in young and older adults.

Finally, the last goal of this experiment was to compare the effects of aging and the effects of reduced relational attention on associative memory formation at the neural level. Behaviorally, two studies in the current dissertation provided evidence that the reduced attentional resources in relational attention could equate the relational memory performance in young adults to that of older adults. Using an event-related fMRI technique, Experiment 3 tested whether the lack of resources in relational attention in young adults resulted in reduced activity in the critical neural correlates of successful relational memory encoding, and compared such patterns of neuronal reduction to that of older adults. Critically, I predicted that both young adults under divided attention with relational attention condition and older adults under full attention condition would show the similar attenuation in activities in the neural correlates of the successful relational memory encoding, as in the case of their similar behavioral patterns in relational memory performance.

Methods.

Participants.

Eighteen healthy young adults (Age: 18-31, Mean=20.9 years old, SD=3.26; Female: 12; mean education= 14.5 years, SD= 1.56) and twelve healthy community-dwelling older adults (Age: 66-89, Mean=74.8 years old, SD=8.36; Female: 8; mean education = 15.8 years, SD= 2.22) with normal or corrected-to-normal vision participated in the experiment. No subjects in Experiment 3 had participated in Experiments 1 or 2. Each participant provided informed written consent and all were paid $20 per hour for participation. Screening for MR safety was completed both during recruitment as well as on the day of scanning to ensure that no changes occurred that would affect eligibility for MR. Five young adult participants were excluded; one due to problems understanding the attention task instructions, four due to not enough misses during memory retrieval. All participants were right-handed Native English speakers with no history of neurological or psychiatric conditions. Both young and older adults received relational memory encoding under full attention (FA) blocks, encoding under divided attention with an item detection (DA-I) blocks, and encoding under divided attention with a relation detection (DA-R) blocks.

Prior to participation, both young and older adults received a general health screen completed a battery of neuropsychological tests to assess memory, language, attention, visuo-spatial abilities, and general intellectual functioning. These tests included the Mini Mental State Examination (MMSE), American National Adult Reading Test (ANART), Trail Making Test parts A and B, Vocabulary from the WAIS-III, and the Morningness-Eveningness questionnaire. Mean scores for this battery of tests in participants in Experiment 3 are listed in Table 7.

Materials and Tasks.

All the materials and tasks were modeled after Experiment 2 with the following modifications. First, the attention condition (i.e., FA, DA-I, and DA-R) in Experiment 3 was a within-subject factor in order to access neural correlates of relational memory under different attention conditions. All participants in Experiment 3 received two blocks of each of attention condition followed by a memory test block corresponding to each encoding block. Second, participants received only a relational memory test followed by each encoding phase due to the time constriction in the MRI scanner. Third, one-third of the trials in each encoding block in Experiment 3 were control (i.e., null) trials to assess baseline activity during memory encoding (Josephs & Henson, 1999). In control trials, strings of dollar signs ("$") and pound signs ("#") were presented in the same locations as the word- and number pairs in each experimental trial. Participants were asked to detect whether the strings of dollar signs appears on the left or right when they saw those strings. A randomized jittered ISI (inter stimulus interval) for control trials ranged from 2, 4, 6, 8, or 10 seconds to increase the power to detect hemodynamic response differences that are specific to individual trial events. OptSeq (http://surfer.nm.mgh.harvard.edu/optseq) was used to determine the list order for each experimental and control trial that should optimally assess event-related activation. Finally, for young adults group only, a problem solving task block was inserted in between each of encoding and memory test block in order to equate memory performance level between young and older adults. In each of the problem solving task block, participants saw 40 equations (e.g., $1832 + 29 = 1851$) and they were asked to judge whether each equation was true or false. Figure 5 depicts examples of trials in the encoding block and the problem solving task block.

Procedures.

Before starting an actual experimental block in the MR scanner, each young adult completed a practice block for each attention condition outside of the scanner. Each encoding phase in the practice block consisted of eight pseudo-experimental trials (not included in any analysis) and three control trials. After each encoding phase (i.e., FA, DA-I, and DA-R), each young adult received a problem solving task block which consisted of four equations, followed by a relational memory test. Young adults were informed that the problem solving task was equally important to the memory task and they were asked to do their best for both problem solving and memory tasks. Due to the complexity of current experiment, older adults received two practice blocks of each attention condition. Older adults did not have any interpolated activity to ensure enough hit responses in relational memory tests. After completion of practice blocks, all participants completed six experimental tasks took inside the scanner, following a structural T1-weighted scan for 7 minutes.

Each participant received two separate blocks of study-test phases for each attention condition. FMRI was obtained during the memory encoding phases only. In each of the encoding and test phase, 40 unrelated word pairs were used; thus, a total of 240 word pairs were used for the actual study and test phases. Approximately 20 control trials were included in each of the encoding runs. In the full attention (FA) condition, participants were instructed to memorize all word pairs for a later memory test, and they were also asked to detect strings of dollar signs whenever they saw the strings of dollars and pounds during the encoding phase. Furthermore, participants were instructed to press a button (i.e., either button 1 or 2) when they saw a new word pair as well as when the two words switched their

location. This manipulation was imposed in the full attention condition in order to equate brain activity by the finger movement between full and divided attention conditions. That is, in the two divided attention conditions, participants made a button press to each attention trial, which can affect the activity in the motor cortex during each memory encoding trials. Thus, participants were also asked to make a button press in each experimental trial in the full attention condition to rule out the movement activity elicited by a button press across all attention conditions. In the divided attention with item detection (DA-I) condition, participants saw both word- and number pairs, and they were asked to detect an odd number in each trial while memorizing word pairs. In the divided attention with relation detection (DA-R) condition, participants were asked to compare two numbers presented below each word pair and instructed to detect a numerically bigger number while encoding word pairs. After the encoding phase, only young adults performed a problem solving task block and instructed to solve each equation as accurately as possible. Each equation stayed on the screen for 6 seconds and each problem solving task block consisted of 40 equations. After the problem solving task block for young adults, and after each of encoding block for older adults, all participants received a relational memory test corresponding to the previous encoding phase. Forty word pairs were presented in each test block, and for each of word pair, participants were asked to detect whether they had seen both words together or separately in the previous encoding phase. Participants recorded all task responses by pressing a button on an MR-compatible response box using the index or middle finger of their dominant (right) hand. The order of the attention conditions were counterbalanced across all participants.

Imaging methods and analyses.

 Image acquisition. All the imaging data were acquired with a Siemens 3 Tesla Allegra head-only imaging system equipped for echo planar imaging (EPI; Siemens Medical Systems, Iselin, NJ) using a 3 axis gradient head coil at the University of North Carolina's High Field MR Center. Visual stimuli were back-projected onto a screen and viewed in an MR-comparable mirror mounted above the participant's head. Responses were recorded via response box using the dominant (right) hand. Head motion was restricted with a pillow and foam inserts. All participants completed six functional runs (i.e., two runs for each of the FA, DA-I, and DA-R blocks), along with an anatomical scan. An anatomical scan was acquired for each participant using a high resolution T1-weighted MPRAGE sequence (TR = 1700 ms, TE = 4.38 ms, flip angle = 8°, FOV = 280 x 320, 160 slices, matrix = 224 x 256, 1.25 x 1.25 x 1.25 mm resolution, 382 sec acquisition time). For the functional runs, imaging were performed using a T2*-weighted EPI sequence designed to minimize susceptibility artifact in the anterior hippocampal regions and fully volume the long axis of the hippocampus (TR = 2000ms, TE = 30 ms, flip angle = 80°). Each brain volume were composed of 34 transverse slices (FOV = 243 x 243, matrix = 64 x 64, 3 x 3 x 3 mm resolution, with 5 mm skip between slices; slices were oriented along the long axis of the hippocampus, collected interleaved, inferior to superior). In all functional runs, data from the first two volumes were discarded to allow for stabilization of magnetic fields.

 Image Processing and Statistical Analyses. Imaging data were preprocessed using SPM 8 (Wellcome Department of Cognitive Neurology, London) run within Matlab (Matlab Mathwork, Inc., Natick, MA). For preprocessing, data were slice-time corrected for

acquisition order (referenced to the slice acquired in the first of the time sequence), realigned and unwarped to correct for motion across runs. Next, the images were spatially normalized (with trilinear interpolation and preserving the intensities of the original images) to the SPM EPI template corresponding to the MNI (Montreal Neurological Institute) defined standardized brain space, and then spatially smoothed with a Gaussian kernel of 8 mm FWHM. The time series were high pass filtered at 128 seconds.

Statistical analyses were performed using the general linear model for event-related designs in SPM 8. For each participant, a whole-brain voxelwise analysis was conducted in which individual events were modeled as a canonical hemodynamic response. Each event type was first modeled for each subject using a fixed effects analysis. To identify the neural correlates of successful encoding, the "subsequent memory procedure" (Wagner et al., 1998; For review, see Paller & Wagner, 2002) was used. In this procedure, neural activity elicited by a series of study items is back-sorted according to whether the items are remembered or forgotten on a later memory test. To investigate neural correlates of the successful relational memory effect under different attentional manipulations, subsequently remembered trials (i.e., encoding trials leading to "together" recognition responses for intact pairs) and subsequently forgotten trials (i.e., encoding trials leading to "separate" recognition responses for intact pairs) were modeled separately in each attention condition (Full attention (FA), Divided attention with Item (DA-I), and Divided attention with Relation (DA-R)). Within each attention condition, activation for the successful memory effect was identified by directly comparing subsequently remembered and forgotten trials. Furthermore, separate pairwies contrasts of interest were conducted to compare the successful memory effect under full attention condition to that of each divided attention condition. After completion of fixed

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effects analysis for each participant, the resulting least squares parameter estimates of the height of the modeled hemodynamic response for each condition were then entered into a between-subjects random effects analysis, and were examined for significance at $p < .005$ with a minimum cluster size of 5 contiguous voxels ($k > 5$).

To test neural effects of each attentional load on relational memory encoding, pairwise t-tests were conducted to compare contrast maps of successful memory under FA runs and those under each of DA conditions in each age group. To identify different neural correlates of relational memory between young and older adults, two-sample t-tests were conducted for contrast maps of successful memory effects from young adults under FA runs and contrast maps from older adults under FA runs. The results from the two sample t-test were subsequently used as an inclusive mask for identifying common effects of aging and relational attention load on relational memory encoding at $p < .05$ and 5 contiguous voxels. Thus, the conjoint probability following inclusive masking approached $p < .00025$ (Fisher, 1950; Lazar, Luna, Sweeney, & Eddy, 2002), but this estimate should be taken with caution given that the contrasts were not completely independent (Dennis et al., 2008).

Results.

Behavioral results.

<u>Secondary-task performance.</u>

Accuracies and reaction times (RT) for correct responses were averaged for each divided attention condition (Divided attention with Item (DA-I) and Divided attention with Relation (DA-R)) in each age group (Young adults (YA) and Older adults (OA)). The accuracy and RT data for each group are presented in Table 8. For the accuracy data, a 2 x 2

mixed ANOVA with age group as a between-subject factor and attention condition as a within-subject factor was conducted, and the analysis revealed neither significant main effects nor interaction between attention and age group (all $p > .05$). However, the same analysis for the RT data revealed a significant interaction between attention condition and age group, $F(1,23)=4.70$, $p<.05$. Paired t-test between the two attention tasks in each age group resulted in significant differences in attention RT data between the two attention conditions only in the older adult group, $t(11)= -2.23$, $p<.05$. That is, older adults revealed significantly slower response time to the attention task with relation processing than to the attention task with item processing, whereas RTs in two attention tasks in young adults were not significantly different from each other. Furthermore, independent-samples t-tests for RT data from each attention task between young and older adults revealed a significant difference in a relational attention task between two age group; older adults' responses were significantly slower in relational attention task compared to that of young adults, $t(23)=.2.17$, $p<.05$. Thus, these results suggest that older adults exhibit more difficulty in an attention task which involves relational attention processing than in attention task requiring little or no relational attention processing. Such differences were not observed in the young adults group. That is, two attention tasks were equally difficult for young adult participants, replicating results from Experiment 2.

Memory performance.

For memory accuracy, measures of proportion of hits minus proportion of false alarms were computed for each participant and then averaged over each attention condition in each age group. Figure 6 depicts the proportion of hits minus proportion of false alarm

rates in each memory tests in each group. Also, separate hit and false alarm rates in the relational memory test for each age group appear in Table 9. A 2 x 3 mixed ANOVA with age group as a between-subject factor and attention condition as a within-subject factor revealed significant main effect of attention condition, $F(2,46)=27.73$, $p<.05$, and significant interaction between attention condition and age group, $F(2, 46)=4.29$, $p<.05$. Paired t-tests for contrasting each of attention condition in each age group revealed significant differences in relational memory performance between FA and DA-I condition, $MD=.11$, $t(12)=3.82$, $p<.05$, between FA and DA-R condition, $MD=.21$, $t(12)=5.94$, $p<.05$, and between DA-I and DA-R condition, $MD=.10$, $t(12)=2.68$, $p<.05$, in young adults. That is, loading relational attention task during relational memory encoding disproportionately impaired young adults' performance in the relational memory test although both divided attention conditions significantly worsened their memory performance compared to the full attention condition. The effect of the item attention condition on relational memory test was somewhat different in the older adult group. Unexpectedly, there was no effect of item attention task on relational memory in older adults, $MD=.01$, $t(11)=.32$, $p>.05$. However, older adults presented significantly lower memory accuracy scores under relational attention condition compared to both full attention, $MD=.11$, $t(11)=3.69$, $p<.05$, and divided attention with item condition, $MD=.10$, $t(11)=3.72$, $p<.05$. Finally, under full attention condition, older adults revealed significantly lower performance in the relational memory test than young adults, $MD=.20$, $t(23)=2.61$, $p<.05$, confirming older adults' deficits in relational memory task compared to young adults.

For retrieval latency, a 2 x 2 mixed ANOVA with age and attention condition as factors revealed neither main effects nor interaction between two factors, all $ps>.05$.

Separate t-tests for each attention and age groups also revealed no significant differences in any of the comparison. The group means for retrieval latency are displayed in Table 10.

Imaging results.

The results of the fMRI analyses are described as a function of each research question of interest. The results are listed systematically in table format (Tables 11-20). Below I provide a description of each table, and in the subsequent sections I describe targeted findings in each research question. First, Table 11 shows regions of significance for the successful memory effect from the whole-brain voxelwise analysis in each attention condition in young adults. The regions for successful memory effect in older adults in each attention condition are listed in Table 12. Table 13 and 14 show the results of the two-sample t-test for the successful memory effects between young and older adults. Regions more active in young than older adults are listed in Table 13, and regions more active in older than young adults are in Table 14 in each attention condition. Table 15 and 17 list regions of successful memory effects, which were more active in full attention than each of divided attention condition in young and older adults respectively. Table 16 and 18 show regions of successful memory effects, which were more active in each of divided attention condition than full attention condition in young and older adults, respectively. Finally, common regions which showed significant attenuation both by aging and by each attention task (DA-I and DA-R) compared to young adults under full attention condition are listed in Table 19, and the common regions that showed greater activity both by aging and by each attention condition relative to young adults under full attention condition are shown in Table 20.

Neural correlates of successful relational memory encoding in young and older adults.

      I contrasted activity for hit trials greater than miss trials in young adults under full attention condition to test whether the critical neural regions for successful relational memory encoding reported in previous studies could be identified with the current task paradigm. Consistent with previous findings on neural correlates of relational memory encoding, the results showed significant activity in bilateral inferior frontal gyrus (BA 11/45/47), bilateral middle/superior frontal gyrus including dorsolateral prefrontal cortex (BA 6/9/10/46), left inferior parietal lobule (IPL; BA40), and left parahippocampal gyrus (BA36), as well as the left anterior hippocampus (Table 11; Figure 7). The same contrast analysis using subsequent memory procedure was conducted for older adults under full attention condition. As listed in Table 12, the results revealed significant activation in left inferior and superior temporal gyrus (BA20, BA22), left posterior entorhinal cortex (BA28), right perirhinal cortex (BA35), and right middle temporal gyrus (BA 37). Additionally, activation in right insula (BA13), anterior cingulate (BA24), and right medial frontal gyrus (BA10) were also significant. Notably, none of the critical regions for successful relational memory encoding, including DLPFC, VLPFC, left IPL, left parahippocampal gyrus, and left anterior hippocampus, was not significantly activated in older adults under full attention condition. To examine whether aging significantly attenuated the activity in regions in critical neural correlates of relational memory formation, I conducted two-sample t-tests to directly examine the differences between young and older adults.

To identify neural regions for successful relational memory encoding which showed significant attenuation by aging, I conducted a two-sample t-test with young and older adults under full attention condition. The results showed that young adults engaged critical regions for successful relational memory significantly more than older adults. Specifically, activity in the bilateral inferior frontal gyrus (BA 11/45/47), bilateral dorsolateral prefrontal cortex (BA 6/9/10/46), and left inferior parietal lobule (BA 40) was significantly attenuated by aging (Table 13; Figure 8). A reversed contrast analysis was also conducted to identify the neural regions where older adults showed significantly more activation than young adults for successful relational memory encoding. As listed in Table 14, older adults exhibited more activity in the bilateral anterior cingulate (BA24/32), right insula and cingulate gyrus (BA 13, BA24), indicating more cognitive efforts on successful relational memory performance in older adults compared to young adults (Allman et al., 2001; Petersen et al., 1998). Additionally, older adults showed more activity in right superior temporal gyrus (BA22), and left inferior and medial frontal gyrus (BA 47, BA 10) than young adults for successful relational memory encoding.

Neural regions for successful relational memory encoding showing significant differences between full and divided attention conditions in young adults.

To test whether each attentional load significantly attenuated the activity in the critical neural regions for successful relational memory formation, I conducted separate contrast analyses for successful memory effects between full and each of divided attention condition in young adults. As revealed in Table 15, only the right posterior cingulate (BA29)

and the right medial frontal gyrus (BA9) showed significant attenuation by attentional load with item processing in young adults, compared to their full attention condition. However, when young adults' attention was divided with relational attention task during relational memory encoding, young adults exhibited significant failure or attenuation in activity in most of the critical neural regions for successful relational memory formation. Specifically, there was significantly reduced activation in young adults under relational attention condition compared to their full attention condition in the bilateral inferior frontal gyrus (BA 47), bilateral middle/superior frontal gyrus including dorsolateral prefrontal cortex (BA 6/9/10), left inferior parietal lobule (IPL; BA40), and left anterior hippocampus. Of note, the two attention tasks were quantitatively equivalent and equally difficult from each other as revealed in the accuracy and response time data from the two tasks. However, they were qualitatively different since the two tasks required different attentional processing. That is, only the attention task in DA-R condition required resources for relational attention, and only this relational attention task significantly attenuated the core neural regions for successful relational memory formation in the PFC and hippocampus (Figure 9).

Regions that were more active during each of the divided attention condition than the full attention condition in young adults are listed in Table 16. Regions that were more active during divided attention with item than full attention conditions in young adults included left precentral gyrus (BA44), right medial frontal gyrus (BA6), bilateral insula (BA 13), right cingulate gyrus (BA24), bilateral middle temporal gyrus (BA37/39) and left middle occipital gyrus (BA19), and right amygdala and right parahippocampal gyrus (BA19). Young adults under divided attention with relation processing condition showed more active than their full

attention condition only in a subset of these regions, namely right middle temporal gyrus (BA39), left middle occipital gyrus (BA19), along with left cingulate gyrus (BA24).

Neural regions for successful relational memory encoding showing significant differences between full and divided attention conditions in older adults.

Since older adults originally showed a reduction in activity in most of the critical neural regions for successful relational memory encoding under their full attention condition, the contrast analyses between full and each of divided attention condition in older adults showed somewhat different results compared to young adults. As listed in Table 17, older adults showed greater activity in left inferior temporal gyrus (BA20) and right middle temporal gyrus (BA39) in the full attention condition compared to the divided attention with item condition. Additionally, the same contrast revealed significant activity in the right inferior frontal gyrus (BA47), right middle frontal gyrus (BA6), right insula (BA13) and bilateral medial frontal gyrus (BA25/10). Interestingly, the reversed contrast revealed more regions related to the neural correlates of successful relational memory formation (Table 18). That is, when older adults' attention was divided with an item detection task, they showed more activation in bilateral dorsolateral prefrontal cortex (BA6/9) and right inferior frontal gyrus (BA44). This neural pattern is in fact congruent with the behavioral results found in older adults group in the current study. That is, unlike young adults, older adults did not show more impaired relational memory performance in the divided attention with item detection condition than in their full attention condition. The null effect of item attention on relational memory in older adults was not consistent with results from a previous PET study with a divided attention paradigm (Anderson et al., 2000), since the previous study showed significant effects of a concurrent attention task on relational memory performance in older

adults. However, consistent with the current behavioral results, older adults in this study showed significantly enhanced activation in critical regions for successful relational memory when an item attention task was imposed during encoding compared to the full attention condition. The reason for this unexpected effect of item attention task on relational memory encoding in older adults is beyond the scoop of this dissertation. However, it is worth to note that when older adults could defeat attentional load during encoding, the critical neural correlates for successful relational memory encoding was active, probably as an outcome of the overcome process.

In contrast, older adults showed more impaired behavioral performance in a relational memory task, when attentional load for relational attention was imposed during encoding. Consistent with this behavioral pattern, older adults exhibited attenuated activation in the bilateral inferior prefrontal gyrus (BA13/47), left superior frontal gyrus (BA8), bilateral superior temporal gyrus (BA22/38), and left anterior hippocampus in their divided attention with relation condition compared to the full attention condition (Table 17). Additionally, older adults showed greater activity in the full attention than divided attention with relation condition in the right medial frontal gyrus (BA8), right insula (BA13), right anterior cingulate (BA 25) and the right cingulate gyrus (BA24). Unlike the other divided attention condition, no regions related to the successful relational memory formation showed greater activity in the divided attention with relation compared to the full attention condition in older adults. Instead, the contrast showed greater activity in the left middle frontal gyrus (BA11), bilateral cingulate gyrus (BA31, BA32), and left precuneus (BA7) in the divided attention with relation than the full attention condition (Table 18). These data additionally support the hypothesis that the reduction in relational attention resources affects the formation of

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relational memory, by showing greater degree of reduction in activity in the critical neural

areas for relational memory encoding when the relational attention load was imposed during

encoding in older adults.

Neural regions for successful relational memory encoding showing significant attenuation
both by aging and by the relational attention load during encoding in young adults.

To address the question whether the effect of a reduction in relational attention in

young adults during relational memory encoding is similar to the effect of aging on the

relational memory encoding at the neural level, a conjunction analysis was conducted with

the data from two sample t-tests between young and older adults under their full attention

condition and the data from paired-sample t-tests between young adults' full and each of

divided attention conditions. As described in the method section, the common regions were

identified by using an inclusive making procedure. Specifically, the results from the two-

sample t-tests between young and older adults under full attention condition were used as an

inclusive mask for identifying common effects of aging and relational attention load on

relational memory encoding at $p < .05$ and 5 contiguous voxels. The conjoint probability

following inclusive masking approached $p < .00025$ (Fisher, 1950; Lazar, Luna, Sweeney, &

Eddy, 2002). Table 19 listed the common regions that showed significant attenuation in

older adults under the full attention condition and in young adults under the divided attention

with item or relational processing condition compared to young adults under the full attention

condition. First, the conjunction analysis between young adults under divided attention with

item condition and older adults under full attention condition revealed no regions which

showed significant reduction by both groups compared to young adults under full attention

condition. In contrast, a subset of the critical neural correlates of successful relational

memory encoding was significantly attenuated both by relational attention load in young adults and by aging. Specifically, these included the bilateral dorsolateral prefrontal cortex (BA 6/9/10), right inferior prefrontal gyrus (BA 45/47), and left inferior parietal lobule (BA 40) (Figure 10). Additionally, the left middle orbito frontal gyrus (BA 11), right insula (BA 13), and the left superior temporal gyrus (BA22) were commonly reduced by a reduction in relational attention in young adults and aging compared to young adults under full attention condition.

In addition, the reversed conjunction analyses were conducted. Table 20 listed the common brain areas showing greater activity by both aging and the reduction in each of attentional resources in young adults compared to young adults under full attention condition. The results revealed that only the right cingulate gyrus (BA 24) was significantly more active by aging and both attentional loads relative to the young adults under full attention condition.

Discussion.

Behavioral Performance.

Performance on the relational memory task was less accurate when attentional loads were imposed during encoding in young adults group. Also, changing the attention condition as a within subject factor, the behavioral results of young adults in Experiment 3 replicated previous findings in the current dissertation by showing that subsequent memory was significantly worse when a relational attention task was imposed during encoding compared to when an item attention task was imposed. Furthermore, the reduction in relational attention during encoding equated young adults' relational memory performance to that of older adults under full attention condition. Unlike Experiment 2 in this dissertation, older

adults in Experiment 3 had all three attention conditions during relational memory encoding. Consistent with previous findings, older adults in the current study showed the relational memory deficits compared to young adults under full attention conditions. However, unlike young adults, older adults did not show significant impairments by concurrent attentional load with an item attention task during memory encoding.

The results from older adults in the current study are in part consistent with findings in a previous behavioral study by Kilb and Naveh-Benjamin (2007). In their behavioral study, Kilb and Naveh-Benjamin (2007) tested both item and relational memory performance in young and older adults, and manipulated attentional loads (Full attention vs. Divded attention) during encoding in both age groups. The researchers questioned whether the relational memory deficit shown by older adults was mediated by reduced attentional resources. Specifically, they tested whether associative deficit observed in older adults under full attention condition would become exacerbated under divided attention condition. In their experiments, the authors found that divided attention in older adults during encoding did not significantly reduced older adults' relational memory performance to a greater degree than their item memory performance compared to in the full attention condition. In fact, the researchers found that only the item memory performance was significantly impaired by divided attention manipulation. The authors concluded that older adults did not show a larger relational memory deficit under divided attention condition, contrary to the predictions of the reduced attentional resources hypothesis. In their study, older adults rather showed smaller relational memory deficit under divided attention than under full attention condition.

Consistent with Kilb and Naveh-Benjamin (2007), the current study showed an absence of greater impairments in older adults' relational memory under divided attention

with item condition than under full attention condition. In fact, unlike young adults who exhibited significantly reduced relational memory performance under the divided attention with item condition, older adults in fact overcame the obstacle (i.e., reduction in attentional resources in item attention) and showed equivalent relational memory performance between full attention and divided attention with item condition. This behavioral pattern was consistent with the fMRI results in the current study, showing that older adults in fact recruited more neural regions for successful relational memory encoding under divided attention with item condition than full attention condition. The underlying factor for this effect of item attentional load in older adults is beyond the scoop of the current dissertation. However, the balance of the resources in item and relational attention processing in older adults may possibly be a reason for this null or even beneficial effect of item-focused attentional load on their relational memory performance. In other words, if older adults experience an unbalanced reduction in relational attention relative to in item attention, balancing the reduction between two attentional process may benefit their relational memory performance to a certain degree although the benefit cannot exceed the absolute amount of deficit in their original relational memory performance (i.e., older adults' relational memory performance under full attention). A future study including both item and relational memory tasks and different attentional loads may be able to provide a rationale for the null effect of item-attentional loads on relational memory performance in older adults.

In contrast to the item attention condition, a reduction in relational attention during encoding significantly impaired relational memory performance in older adults to a greater degree than full attention condition. This result is inconsistent with a previous finding showing a smaller relational memory deficit under divided attention than under full attention

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condition (Kilb & Naveh-Benjamin, 2007). Rather, the result found in the divided attention with relation condition is consistent with the predictions of the reduced attentional resources hypothesis (Craik, 1982; 1986). In summary, together with findings in young adults demonstrating larger relational memory impairments in the divided attention with relation condition than other attention conditions, the behavioral results in Experiment 3 indicate that the reduction in relational attention processing plays a critical role in the relational memory deficit observed in older adults.

fMRI Findings.

Experiment 3 in this dissertation used the event-related fMRI technique to examine effects of aging and effects of different types of attentional loads on relational memory encoding at the neural level. The fMRI results are discussed in terms of each hypothesis tested in this study.

The neural correlates of successful relational memory formation

Using a subsequent memory procedure (Wagner et al., 1998; Paller & Wagner, 2002), I first identified brain regions which support successful relational memory encoding (i.e., encoding of word pairs that participants later recognized correctly) in young adults under full attention condition. Previous research on relational memory encoding with full attention showed a relationship between successful relational memory encoding and magnitude of activation in the left ventrolateral prefrontal cortex (PFC) (Addis & MacAndrews, 2006; Park & Rugg, 2008; Prince et al., 2005), dorsolateral PFC (Murray & Ranganath, 2007; Dennis et al., 2008; Staresina & Davachi, 2006; Summerfield et al., 2006), and left hippocampus and

parahippocampal gyrus (Addis & MacAndrews, 2006; Davachi et al., 2003; Kirwan & Stark, 2004; Prince et al., 2005; Ranganath et al., 2004; For review, see Davachi, 2006). The neuroimaging results in the current study converge with these previous findings: bilateral ventrolateral PFC (BA 11/45/47), bilateral dorsolateral PFC (BA 6/9/46), left parahippocampal gyrus (BA36), and the left anterior hippocampus all showed subsequent memory effects for word pairs encoded with full attention in young adult participants.

Previous researchers suggest that the PFC plays strategic roles in long term memory formation by generating associations among different information. Recently, Addis and MacAndrews (2006) manipulated generative load for relational aspects of information during memory encoding, and demonstrated that left inferior frontal gyrus were more active when a task required participants to generate semantic association for irrelevant stimuli. Consistent with this finding, significant activity in the ventrolateral PFC during successful memory encoding has been evidenced in numerous neuroimaging studies (Cabeza et al., 1997; Cabeza & Nyberg, 2000; Iidaka et al., 2000; Kapur et al., 1994; Lepage et al., 2000; Park & Rugg, 2008; Prince et al., 2005). Specifically, Prince, Daselaar, and Cabeza (2005) compared encoding and retrieval successful activity during semantic or perceptual associative memory and demonstrated that left ventrolateral PFC is strongly associated with successful encoding of relational memory for semantic information. Furthermore, Park and Rugg (2008) demonstrated that the robust involvement of the left ventrolateral PFC is critical for successful memory encoding for inter-item association in both semantic and phonologically related information.

In addition to the activity in the ventrolateral PFC, recent neuroimaging studies reported significant activation in the dorsolateral PFC during relational memory encoding.

Specifically, Murray and Ranganath (2007) directly compared neural correlates of item vs. relational memory encoding, and demonstrated that dorsolateral PFC activity was grater during relational compared to item-specific encoding. Furthermore, the authors found that dorsolateral activity predicted successful memory for association, whereas ventrolateral PFC activation predicted successful memory for both relational and item memory. This finding is consistent with findings from lesion studies showing that the dorsolateral PFC lesions in human brain often lead relational memory deficit (Milner et al., 1991; Petrides, 1994), whereas lesions in the ventromedial cortex is associated with item memory impairments (Bachevalier & Mishkin, 1986). Furthermore, a recent review on the role of PFC on episodic memory encoding suggests distinct roles between dorsolateral and ventrolateral PFC (Blumenfeld & Ranganath, 2007). Specifically, the authors reviewed both lesion studies and neuroimaging studies, and concluded that the ventrolateral PFC is important for directing attention toward goal-relevant items which in turn enhances representation for both item and relational memory formation, whereas the dorsolateral PFC contributes to the ability to organize and chunk multiple pieces of information in working memory, which in turn enhances memory for association among items in long term memory. Consistent with this account, in Experiment 3, I also found significant involvement of both dorsolateral and ventrolateral parts of PFC for successful relational memory encoding in young adults with full attention.

In addition to the PFC, the hippocampus has been recognized as an important neural region for successful relational memory encoding. Converging evidence suggests that medial temporal lobe structures are critically involved in episodic memory encoding (Cohen & Squire, 1980), with the hippocampus mediating memory for inter-item relationships (Cohen

& Eichenbaum, 1993). The role of the hippocampus in associative encoding has been well established in previous fMRI experiments (Dougal et al., 2007; Kensinger & Schacter, 2006; Staresina & Davachi, 2006; Staresina & Davachi, 2008; Uncapher et al., 2006; Prince et al., 2005; Jackson & Schacter, 2004; Kirwan & Stark, 2004; Ranganath et al., 2004; Davachi et al., 2003; Sperling et al., 2003). For example, Staresina and Davachi (2008) directly compared neural circuits for successful relational memory and for item memory, and demonstrated a role of the hippocampus in domain-general associative encoding. Also, Uncapher and colleagues (2006) found a stepwise increase in hippocampal activity during memory encoding as number of associations to be remembered (e.g., number of sources for an item) increased.

In the current study, the left anterior hippocampus was significantly active for successful relational memory encoding in young adults with their full attention. Such engagement of anterior hippocampus is consistent with recent findings in the relational memory (Addis & MacAndrews, 2006; Giovanello, Schnyer, & Verfaellie, 2009; Sperling et al., 2003). For example, using event-related functional MRI during the encoding of novel face-name associations, Sperling and colleagues (2003) found that successfully remembered face-name pairs showed significantly greater activation in the anterior hippocampal formation as well as the left inferior prefrontal cortex, compared to pairs that were forgotten. Furthermore, a recent study reported significant activation in the left anterior hippocampus in participants when a task required generation of relational information during encoding (Addis & MacAndrews, 2006). Finally, Giovanello, Schnyer, and Verfaellie (2009) have shown that different regions along the long axis of the hippocampus make distinct contributions to relational memory processing. The authors concluded that posterior

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hippocampus is involved in the structured reinstatement of perceptual information, whereas anterior hippocampus is shown to be involved in flexible relational operations at retrieval. Although Giovanello and colleagues suggested that the anterior hippocampus is important for flexible retrieval of relational memory, this finding is in a line with the findings in this dissertation. That is, in the current paradigm, participants encoded word pairs which switched their location after initial presentation. This manipulation was included in order to prevent the potential attentional capture by new stimuli in the number stimuli presented together with word pairs (Kim & Hopfinger, 2010). However, this manipulation may also force participants to use a flexible encoding strategy to memorize each word pair which changes their location after initial presentation (i.e., A-B, then B-A). In summary, the fMRI results in the current study are consistent with previous neuroimaging evidence that hippocampus, especially the anterior hippocampus, is critical for binding information for relational memory formation.

In the current study, I also found significant activation in the left superior parietal lobule (SPL; BA 7) and inferior parietal lobule (IPL; BA 40) associated with successful relational memory encoding in young adults under full attention condition. While the role of PFC and hippocampus in episodic memory has been demonstrated in numerous imaging and lesion studies, recent neuroimaging studies suggest that a complete story of the functional neurobiology of episodic memory may require appreciation of possible contributions from parietal cortex (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008; Uncapher & Wagner, 2009). For example, recent neuroimaging studies have evidenced that the engagement of dorsal and ventral regions of posterior parietal cortex (PPC) is consistently active during episodic retrieval (Eldridge et al., 2000; Henson et al., 1999; For review, see Cabeza et al.,

2008). The engagement of PPC has in fact been reported in numerous attention literature, in part of two dissociable, yet interacting, fronto-parietal attentional systems (e.g, Corbetta & Shulman, 2002; Corbetta, Patel, & Shulman, 2008; Hopfinger et al., 2000). Specifically, researchers suggest that dorsal parts of PPC (superior parietal lobule (SPL) and intraparietal sulcus (IPS)) mediate goal-directed or 'top-down' attention, whereas ventral PPC regions (inferior parietal lobule (IPL) and temporo-parietal junction (TPJ)) mediate stimulus-driven or 'bottom-up' attention. Recently, Uncapher and Wagner (2009) conducted a meta-analysis to explore the critical role of dorsal and ventral parts of parietal cortex on episodic memory encoding. In their conclusion, the authors suggested that dorsal PPC, including SPL, supports the allocation of goal-directed attention, which may, in turn, increase the probability that the attended information is encoded into episodic memory via the medial temporal lobe. Furthermore, the authors also suggested that ventral PPC, including IPL, may contribute to successful episodic memory by fostering the encoding of surface event details that impact retrieval over short retention intervals. Given that the current paradigm did not include deep encoding processing (i.e., elaborative processing during encoding) and also given that the interval between study and test was relatively short, the recruitment of both SPL and IPL during successful memory encoding is consistent with the conclusion by Uncapher and Wagner (2009). Although it is not clear whether the recruitment of parietal regions is for episodic memory encoding in general or specifically for the relational memory encoding, it is worth note that the involvement of these regions is likely to reflect attentional processing required for episodic memory encoding.

In sum, the findings from young adults with full attention in Experiment 3 identified critical neural correlates of successful relational memory formation. Consistent with

previous literature, the successful relational memory encoding was associated with significant activation in the ventrolateral PFC, dorsolateral PFC, and left anterior hippocampus. Furthermore, consistent with recent neuroimaging findings, the successful memory effect was correlated with significant activation in left SPL and IPL. In following sections, I will discuss which parts in these critical neural areas are significantly attenuated by aging and/or by different types of attentional loads.

The effect of aging on relational memory encoding at neural level

During the encoding of word pairs under full attention condition, the older adults showed less activation of those areas responsible for intentional learning of relational stimuli than did the young adults. Specifically, older adults did not show significant activation in the dorsolateral or ventrolateral PFC, hippocampus, or posterior parietal cortex. Instead, older adults revealed significant activation for subsequent relational memory in the left posterior entorhinal cortex, right perirhinal cortex, right anterior cingulate and medial frontal gyrus, along with the left inferior and superior temporal gyrus. The significant activation in entorhinal cortex and perirhinal cortex in older adults with full attention is worth to mention, since dysfunction in these regions, especially in the entorhinal cortex, is likely to be an important marker for predicting Alzheimer's disease (AD). Many studies of neuronal loss have found the entorhinal cortex degeneration with AD, but not with normal aging (Fukutani et al., 2000; Giannakopoulos et al., 2003; Gomez-Isla et al., 1996; Hof et al., 2003; Kordower et al., 2001; von Gunten et al., 2006). Additionally, low entorhinal cortex volume has been shown in a number of studies to be a good predictor of future AD onset or cognitive decline (de Toledo-Morrell et al., 2004; Dickerson et al., 2001; Killiany et al., 2002; Stoub et al.,

2005). Although previous studies suggest that the hippocampus mediates associative

memory more than does the neighboring cortex in medial temporal lobe (Davachi & Wagner,

2002; Staresina & Davachi, 2006), entorhinal and perirhinal cortices also have been shown to

be recruited during tests of associative memory (Ekstrom et al., 2007; Jackson & Schacter,

2004; Kirwan & Stark, 2004; Klingberg et al., 1994). Also, a recent study demonstrated

significant activation in the entorhinal cortex, anterior cingulate and medial frontal cortex in

cognitively intact health older adults during associative memory retrieval (Braskie, Small,

Bookheimer, 2009). Thus, the current results that healthy older adults with their full

attention showed significant activity in the entorhinal and perirhinal cortex, anterior

cingulate, and medial frontal cortex are consistent with the previous finding, and the

engagement of those MTL and PFC regions are perhaps resulted due to compensatory

function for their reduced functions in the critical neural circuits for successful relational

memory in the frontal, parietal, and temporal regions.

In fact, the direct comparison between young and older adults with full attention

revealed the significant age-related attenuation in most of the critical regions for subsequent

relational memory. Specifically, older adults showed significantly reduced activity in

bilateral dorsolateral PFC, right ventrolateral PFC, and the left SPL and IPL. The reduction

in the ventrolateral and dorsolateral PFC in older adults compared with young adults during

memory encoding is consistent with previous literature. For example, Locan and colleagues

(2002) found under-recruitment of left PFC in older adults compared with young adults

during intentional memory encoding. Likewise, other researchers also demonstrated age-

related decrease in PFC activity during relational memory encoding for semantic information

(Anderson et al., 2000; Cabeza et al., 1997), spatial association (Mitchell et al., 2000),

pictorial stimuli (Iidaka et al., 2001), and object-source association (Dennis et al., 2008; Mitchell et al., 2005). As discussed in the earlier section, the ventral and dorsal parts of lateral PFC play two distinct roles for successful relational memory encoding. The ventrolateral PFC is involved in the selection process of goal-relevant feature, and this attentional processing may in turn enhance representations of goal-relevant items in the long-term memory system. In contrast, the dorsolateral PFC meditates and controls organization of different information, which in turn enhances association among different items. Thus, along with the reduced activity in the parietal attentional regions (SPL, IPS) in older adults, the reduction in both parts of lateral PFC in older adults during relational memory encoding may indicate the reduction in attention and controlled processing in older adults, which contributes their poorer performance in relational memory compared to young adults. Of note, older adults showed greater activity in the ventromedial PFC (BA 10/11) than young adults during successful memory encoding across all of the attention condition. Previous neuroimaging studies have shown the involvement of the ventromedial PFC in decision making tasks involving ambiguity or guessing (Bolla et al., 2003, 2004, 2005; Ernst et al. 2002; Hsu et al. 2005; Rubinsztein et al. 2001; Tanabe et al. 2007). Thus, the significant activation in the ventromedial PFC and the absence of activity in the lateral parts of ventral and dorsal PFC in older adults suggest impaired process in relational memory encoding and possible compensatory process by other frontal areas for the impairments.

Although older adults failed to show significant activation in the hippocampus during relational memory encoding, a direct comparison between young and older adults revealed no significant differences in the magnitude of activity in the hippocampus during successful relational memory formation between two age groups. This result is inconsistent with some

of previous findings that older adults, which showed significantly reduced hippocampal activation in older adults relative to young adults in associative encoding tasks (Anderson et al., 2000; Mitchell et al., 2000; Sperling et al., 2003). However, recent fMRI studies found that older adults activated the hippocampus to a similar degree as young adults during relational memory encoding. For example, Miller and colleagues (2008) demonstrated a similar magnitude and extent of hippocampal activation during successful relational memory for face-name pairs. Other studies using different materials (e.g., object pairs) have also reported similar activity in the hippocampus between young and older adults during relational memory encoding (Leshikar et al., 2010; Rand-Giovannetti et al., 2006). This inconsistency may be resulted from different task paradigms and comparison among different studies. For example, studies which found the different activity in the hippocampus between different age groups used both item and relational memory tasks and compared the hippocampal activation between item and relational memory process. Specifically, Mitchell and colleagues (2000) found that young adults showed greater left anterior hippocampal activity for combination of object and location pairs than for each item trials, whereas older adults did not show the same patterns of activity in the hippocampal area. Therefore, it is possible that young adults differentially activate the hippocampus for the relational memory compared with item memory formation, whereas older adults activate the hippocampus both for the item and relational memory encoding to some degree. Another possible reason for non-significant aging effects on the hippocampal activity can be due to the power to detect the effect. In fact, the difference became significant when a more liberal threshold was used for the two-group comparison ($p<.05$ with 10 continuous voxels). However, it should be also noted that other regions in the prefrontal and parietal cortex showed significant differences

between young and older adults in the relational memory encoding under more conservative threshold. Thus, in summary, the current finding suggests that the attention-related neural regions, namely, ventrolateral/dorsolateral PFC and parietal regions are more affected by aging during relational memory encoding than the hippocampus, although the older adults revealed somewhat attenuated activity in the hippocampus for successful relational memory encoding.

The neural effects of different types of attentional load on successful relational memory

In the current dissertation, I manipulated the type of attentional loads imposed on relational memory encoding, and demonstrated that a reduction in specific type of attentional resources (i.e., relational attention) significantly impaired relational memory performance both in young and older adults. The significant effects of the reduction in relational attention on associative memory were also evidenced at neural level. That is, the core areas for successful relational memory formation showed significantly attenuated activation when young adults encoded relational information under divided attention with relation detection task compared with the activation in young adults with full attention. Importantly, only the attentional load involving relational attention significantly reduced activity in the dorsolateral PFC, ventrolateral PFC, inferior parietal and superior parietal lobule, and the anterior hippocampus in young adults, whereas the attentional load requiring little or no relational processing (i.e., in the item attention condition) did not attenuate any of the core regions for relational memory encoding significantly.

The significant reduction in the PFC during memory encoding with attentional loads was also reported in a PET study using a verbal association memory task (Anderson et al.,

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2000). However, Anderson and colleagues (2000) did not find significant reduction in the hippocampus due to the attentional load during memory encoding. Furthermore, the previous study was not able to test effect of attention on the *successful relational memory encoding* since the study used a blocked-design with PET imaging. That is, the previous study focused on the encoding-related neural network and the retrieval-related neural regions, instead of the successful memory effects compared to the failure of relational memory. To my knowledge, there has been no event-related fMRI study using a subsequent memory procedure to investigate the effects of attention on successful relational memory encoding. Thus, the current study reports the first finding that a reduction in relational attention significantly attenuated the activity in the neural correlates for subsequent relational memory in the prefrontal, parietal, and hippocampal regions.

To date, no studies have tested the effects of different types of attentional loads on *relational memory encoding* at the neural level. Instead, three previous studies manipulated the levels of difficulty in secondary attention tasks and tested the effect of easy or difficult attention tasks on *item memory encoding* (Kensinger, Clarke, & Corkin, 2003; Uncapher & Rugg, 2005, 2008). Specifically, Kensinger, Clarke, and Corkin (2003) imposed two types of auditory pattern detection tasks (i.e., easy vs. hard) during ending of word stimuli, and demonstrated different neural patterns of successful item memory encoding under easy vs. hard divided attention conditions. That is, the authors found significantly attenuated activity in the inferior PFC and hippocampus for successful memory encoding under the hard attention condition compared to the full or easy attention condition. However, this quantitative reduction in the neural regions for subsequent memory effects under the harder attention task condition was not replicated in a later study by Uncapher and Rugg (2005).

Uncapher and Rugg (2005) used the same item encoding task as Kensinger et al. (2003), but employed different attention tasks and paradigm. That is, the authors used voice discrimination (male/female; 'easy condition') or 1-back discrimination task (odd/even; 'hard condition), and found no differences in the magnitude of activity in the inferior PFC and hippocampus between the subsequent memory effects in easy and hard attention conditions. In a follow-up study, the same researchers used the1-back voice discrimination task and another attention task which involved the semantic judgment ('whether an object can be found *indoor* or *outdoor*'), and reported the task-specific and task-generic effects of divided attention on successful memory effects depending on the type of attention tasks. That is, the authors not only found the quantitative attenuation in activity in the inferior PFC and hippocampus during memory encoding under semantic attention task condition compared to easier attention condition (i.e., task-specific effect), but also demonstrated increased activity related to the attention task in the dorsolateral PFC and parietal cortex (i.e., the areas assists for task-generic, executive functions) during an easy attention task. With this finding, the authors concluded that the effects of divided attention on memory encoding seemed to reflect the detrimental consequences of resource limitation at both task-generic and task-specific levels.

In the current experiment, the manipulation of attention tasks was not by the task difficulty, but by the type of resources each attention task required. Using relational memory task with either item or relational attention task, I demonstrated that only the attentional load involving relational attention processing significantly attenuated activity in the core neural regions for successful relational memory encoding in the ventrolateral PFC, dorsolateral PFC, SPL, IPL, and anterior hippocampus. It should be noted that, unlike the previous

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divided attention studies with item memory encoding, the dorsolateral PFC and parietal cortex regions found in the current study are the regions which were originally activated during successful relational memory encoding under the full attention condition. That is, the reduction in those frontal and parietal areas in the current study seems to reflect the task-specific effect rather than the task-generic effect, since those areas are specifically related to the successful relational memory encoding. Because the attention task was simultaneously time-locked with the presentation of the memory stimuli, it is not possible to distinguish the activity related to the attention task from the activity related to the memory task in the current paradigm. Follow-up studies with varied onset times of attention and memory stimuli may be able to examine the task-generic effect of divided attention on relational memory encoding. Nonetheless, the current study provides important evidence that the reduction in a specific type of attentional resources, namely the *relational attention*, significantly reduced the relational memory process both at behavioral and neural levels, whereas an equally difficult item attention task did not.

Finally, the results from the conjunction analyses confirmed the similar effects of relational attention and aging on relational memory processing. That is, the neural regions showing attenuated activity by aging and the regions showing reduced activity by reduction in relational attention during successful relational memory were strikingly similar to each other. Critically, the common regions showing attenuation were mostly the regions of the critical neural correlates of successful relational memory effects. In contrast, there was no overlap between the effect of aging and the effect of the reduction in item attention on the relational memory process. That is, the two factors differentially affected the neural areas for successful relational memory. Together with the similar behavioral effects of aging and of

relational attentional load on associative memory, this result indicates that the reduction in

relational attention can account for age-related relational memory deficits both at behavioral

and neural levels.

CHAPTER 5

GENERAL DISCUSSION

The current project provides us with a greater understanding of what underlies the disproportionate relational memory deficits observed in older adults. Previous research has concentrated on exploring the effect of general attentional load on item and relational memory performance in young adults. However, the current dissertation manipulated the type of attentional resources required for secondary tasks during memory encoding and demonstrated unreported findings on the source of age-related associative memory deficits.

First, using different types of attention tasks, the current study demonstrated a novel finding that a reduction in a certain type of attentional resources can equate young adults' relational memory performance to that of older adults. Specifically, in two behavioral experiments, I found that reduced attentional resources for relational processing disproportionately impaired young adults' relational memory performance compared with their item memory performance, whereas a reduction in item attention process did not. Critically, the effect of relational attention on associative memory was not due to the overall task difficulty in the attention task. That is, an equally difficult item attention task, as well as a more difficult item attention task than the relational attention task, impaired young adults' performance in the item and relational memory tasks to the same degree. Furthermore, the patterns of relational memory deficit by the aging and by the reduction in relational attention

were remarkably similar to each other. In fact, a previous study reported disproportionate relational memory deficit for young adults under divided attention condition (Castel & Craik, 2003). However, the authors pointed out that the patterns of the deficit between young and older adults were different from each other. That is, young adults under divided attention condition in Castel and Craik (2003) revealed reduced hit rate in the relational memory task, whereas older adults showed increased false alarm rate in the memory task. Unlike this previous finding (Castel & Craik, 2003), the current study found that both aging and the reduction in relational attention in young adults affected both hit and false alarm rates in the relational memory test, which in turn resulted in large impairments in relational memory performance under the two conditions. Finally, older adults in Experiment 3 in the current study showed more impairment in their relational memory performance when their relational attention was reduced with a concurrent attention task compared with the full attention condition. Furthermore, older adults' performance in the relational attention task was significantly poorer than their performance in the item attention task. This is direct evidence that older adults experience a reduction in relational attention process, and together with results in the memory tasks, this finding also supports the hypothesis that reduced resources for relational attention plays a critical role in older adults' deficit in the associative memory.

Second, using an event-related fMRI technique, the current study provides additional knowledge on the neural correlates of successful relational memory encoding. Consistent with previous neuroimaging studies on memory encoding (Addis & MacAndrews, 2006; Davachi et al., 2003; Kirwan & Stark, 2004; Park & Rugg, 2008; Prince et al., 2005), the current study demonstrated that the activity in the ventrolateral PFC and the left anterior hippocampus predicts the successful memory effects. Furthermore, consistent with recent

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findings (Murray & Ranganath, 2007; Dennis et al., 2008; Staresina & Davachi, 2006; Summerfield et al., 2006, Uncapher & Wagner, 2009), the dorsolateral PFC and superior and inferior parietal regions were also significantly activated when the encoding for relational memory was successful. According to previous literatures, the frontal and parietal regions are highly associated with attentional mechanisms. Specifically, previous researchers demonstrated that the ventrolateral PFC plays a role in the selection of goal-relevant features/items, whereas the dorsolateral PFC controls and organizes information and helps the associative processing among different items. Furthermore, superior and inferior parietal lobules have been considered to be important for the top-down and the bottom-up attentional processing, respectively. Thus, the involvement of the ventrolateral and dorsolateral PFC and the superior and inferior parietal regions for the successful relational memory encoding seems to be essential and reasonable, since the allocation of attention and chunking of different items should be required for relational memory formation. The hippocampus has also been reported in numerous studies on both relational memory encoding (Staresina & Davachi, 2006, 2008; Prince et al., 2005) and retrieval (Giovanello, Schnyer, Verfaellie, 2004, 2009; Prince et al., 2005; For review, see Cabeza, 2006). Compared with the PFC and parietal areas, the hippocampus seems to be activated in an automatic manner for when binding process occurs in memory process. In fact, previous neuroimaging studies have demonstrated that the PFC is associated with controlled processing of relational information both at encoding and retrieval (Henson, Shallic, Josephs, & Dolan, 2002), while MTL structures are associated with the incidental encoding and retrieval of contextual associations (For a review, see Cabeza, 2006). In the third experiment in this dissertation, I demonstrated that both the controlled attention process mediated by the PFC and parietal cortex and the

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automatic binding process of hippocampus play a critical role in successful relational memory formation.

Next, the current study provides further evidence on the neural effects of aging and of reduced attentional resources on the formation of relational memory. A direct comparison between young and older adults suggests that older adults failed to show significant activation in a large subset of the critical neural circuits for successful relational memory. Specifically, older adults showed significant attenuation in activity in the ventrolateral and dorsolateral PFC, and the superior and inferior parietal cortex. Older adults also showed somewhat reduced activity in left anterior hippocampus compared with young adults, but the reduction was not statistically significant. Finally, older adults significantly activated the medial frontal lobe and the entorhinal and perirhinal cortex during successful relational memory encoding, and the recruitment of this regions seems to be a part of compensatory mechanisms for their reduced relational memory process. The result that older adults showed significant attenuation in the controlled and attention-related regions of the neural regions for relational memory deserves to mention. That is, this result not only indicates that older adults experience reduced attentional processing supported by the PFC and parietal cortex, but also suggests that the age-related deficits in relational memory can be accounted for by the age-related reduction in attentional resources required for relational memory formation.

The effect of reduced attention was also directly investigated in the current study. Specifically, here I manipulated the type of attention task imposed during relational memory encoding, and tested effects of different attentional loads on relational memory formation at the neural level. Critically, the reduction in relational attention attenuated activity in the core neural regions for successful relational memory in a similar manner to the effect of aging on

relational memory. That is, there was significantly reduced activity in the dorsolateral and ventrolateral PFC, parietal cortex, and the hippocampus in young adults under divided attention with relational attention condition compared to under full attention condition. This effect was, however, not evident when young adults' attention was divided with item attention task during memory encoding. Furthermore, older adults also showed significant reduction in the hippocampus when their relational attention resources were reduced compared to the full attention condition. This result suggests that the reduction in relational attention processing affects not only the attention-related neural regions in the PFC and parietal cortex, but also the automatic association areas of hippocampus. Finally, I found significant overlap between areas showing reduced activity by aging and neural regions showing attenuation by the reduction in relational attention in the core neural regions for relational memory formation. Thus, together with behavioral results found in the three experiments conducted in this dissertation, the results from fMRI data also suggest that the reduction in relational attention processing is the key factor for the relational memory deficit observed in aging.

Although the current dissertation answers important questions on the source of relational memory deficits in aging, future studies should be conducted to address related questions to the associative memory deficit in aging. First, the current study manipulated and imposed different types of attentional loads only during the time of memory encoding. Although previous studies have demonstrated that the effect of divided attention on memory performance is larger during encoding than during retrieval (e.g., Anderson et al., 1998, 2000), it will be informative to test the effect of relational attention during the time of retrieval of item and relational memory. That is, if older adults experience reduced resources

for relational attention, and if the reduction in relational attention causes associative memory deficits in older adults, it is possible that the lack of relational attention affects both encoding and retrieval processes of relational memory. The effect of reduction in relational attention may be larger for memory formation than for memory retrieval, but testing the effect of relational attention on retrieval of relational memory will be able to add important knowledge on the role of attentional resources in the age-related associative memory deficits.

Second, due to the time constraint in the MRI scanner and due to the purpose of this dissertation, the current neuroimaging study did not include an item memory task. However, testing the neural correlates of item memory encoding will provide additional knowledge to understand the difference between item and relational memory encoding in young and older adults. In particular, some of the neural regions activated during successful relational memory encoding in this study may not be activated during successful item memory encoding. For instance, if the dorsolateral PFC is particularly associated with relational memory formation due to its function in organization and chunking of information (Murray & Ranganath, 2007; Ranganath & Blumenfeld, 2007), it is plausible to expect to find significant activation in those regions only when the relational memory formation is required. In addition, testing the neural effects of different types of attentional load on item memory will also provide additional evidence on the special role of relational attention on associative memory. Finally, by comparing the effect of aging on relational memory and item memory at the neural level, the future study will be able to provide knowledge on the neural underpinning of disproportionate relational memory deficit in older adults compared to their item memory.

Third, the current study manipulated the type of attentional loads in a qualitative manner. That is, the two attention tasks used in the imaging study here were not different from each other in their levels of difficulty, but differed with each other in terms of their attentional processing (i.e., item vs. relational). While this manipulation is critical to investigate the role of relational attention on the age-related associative memory deficit, it will be also interesting to test the effect of task difficulty in attention task on relational memory performance at the neural level. As discussed earlier, recent neuroimaging studies with divided attention paradigm have in fact investigated the neural effect of easy vs. hard divided attention tasks on item memory encoding (Kensinger et al., 2003; Uncapher & Rugg, 2005, 2008). Using quantitatively different attention tasks during encoding of item memory, the previous researchers demonstrated that divided attention with harder task significantly attenuated the activity in the critical neural regions for item memory (i.e., the left inferior frontal gyrus and the hippocampus). Additionally, Uncapher and Rugg (2005, 2008) provided evidence that the attention task which required more cognitive resource (i.e., hard task) affected both task-specific neural regions for memory encoding and task-generic regions for executive function. Thus, in a follow up study, it will be interesting to test the effect of harder attention tasks which involve either relational or item attention processing on the relational memory task at the neural level. Specifically, examining the neural effect of harder item attention task on relational memory encoding will be able to discriminate the effect of relational attention on relational memory from that of task difficulty at the neural level.

In summary, the current data contribute several novel findings to the memory, aging, and cognitive neuroscience literatures. Collectively, the findings provide evidence that the

reduction in relational attention in older adults is the critical factor for disproportionate relational memory deficits observed in older adults. Behaviorally, a reduction in relational attention in young adults equated their performance in a relational memory task to that of older adults. The reduced relational attention processing during associative memory encoding in young adults also attenuated the brain activity in the critical neural regions of relational memory formation, as in the case of older adults with their full attention. Within the broader domain of episodic memory, these results suggest that the reduction in a specific type of attentional resources can explain at least some aspects of age-related episodic memory decline to bind separate information together (e.g., content and its context). Understanding the nature and source of age-related impairments in episodic memory is important for both theoretical and ecological reasons, since the ability to connect and associate separate information into contextual representation is essential for coherent memories of everyday events. By converging behavioral and neural evidence on the source of relational memory deficits in older adults, the current study contributes to a more comprehensive picture of cognitive aging, especially in the domain of episodic memory decline.

Table 1.

Means and Standard Deviations for Accuracy and RTs (in milliseconds) in attention tasks in each of the Attention groups in Experiment 1.

	Proportion Correct		RTs	
Group	M	SD	M	SD
DA with Item task	0.94	0.04	1165	205
DA with Relational task	0.74	0.04	1347	142

Note: DA, Divided attention; M, Mean, SD, Standard deviation; RTs, Response time in milliseconds.

Table 2.

Means and Standard Deviations for Proportion Hits and False Alarms Rates in the Item Memory and Relational memory Tests in each of the Attention groups in Experiment 1.

Group	Item Memory		Relational Memory	
	Hits	False Alarms	Hits	False Alarms
Full attention	0.84	0.08	0.82	0.09
	(0.10)	(0.10)	(0.13)	(0.11)
DA with Item task	0.77	0.12	0.83	0.21
	(0.13)	(0.16)	(0.11)	(0.19)
DA with Relational task	0.69	0.13	0.66	0.35
	(0.13)	(0.12)	(0.21)	(0.23)

Note: DA, Divided attention; Numbers in the parenthesis indicate standard deviation.

Table 3.

Means and Standard Deviations of memory RTs (millisecond) in the Item Memory and Relational memory Tests in each of the Attention groups in Experiment 1.

| | Memory RTs | | | |
| | Item | | Associative | |
Group	M	SD	M	SD
Full attention	1483	316	1555	318
DA with Item task	1605	221	1593	181
DA with Relational task	1578	278	1448	254

Note: DA, Divided attention; M, Mean of response times in milliseconds; SD, Standard deviation; RTs, Response time in milliseconds.

Table 4.

Means and Standard Deviations for Accuracy and RTs (in milliseconds) in attention tasks each of the Attention groups in Experiment 2.

Group	Proportion Correct		RTs	
	M	SD	M	SD
YA, DA with Item task	0.93	0.06	1354	146
YA, DA with Relational task	0.90	0.08	1359	183
YA, DA with Item task, Harder	0.68	0.10	670	48

Note: YA, Young adult; M, Mean; SD, Standard deviation; RTs, Response time in milliseconds.

Table 5.

Means and Standard Deviations for Proportion Hits and False Alarms Rates in the Item Memory and Relational memory Tests in each of the Attention groups in Experiment 2.

Group	Item Memory		Relational Memory	
	Hits	False Alarms	Hits	False Alarms
YA, Full attention	0.78	0.01	0.89	0.11
	(0.14)	(0.04)	(0.08)	(0.15)
YA, DA with Item task	0.77	0.09	0.85	0.23
	(0.13)	(0.09)	(0.15)	(0.16)
YA, DA with Relational task	0.78	0.16	0.74	0.31
	(0.12)	(0.16)	(0.16)	(0.17)
YA, DA with Item task, Harder	0.57	0.25	0.64	0.28
	(0.12)	(0.15)	(0.21)	(0.13)
OA Full attention	0.84	0.18	0.79	0.37
	(0.09)	(0.16)	(0.11)	(0.19)

Note: YA, Young adult; OA, Older adults; Numbers in the parenthesis indicate standard deviation.

Table 6.

Means and Standard Deviations of memory RTs (millisecond) in the Item Memory and Relational memory Tests in each of the Attention groups in Experiment 2.

Group	Item		Associative	
	M	SD	M	SD
YA, Full attention	1430	183	1460	222
YA, DA with Item task	1633	236	1590	270
YA, DA with Relational task	1540	248	1623	270
YA, DA with Item task, Harder	1435	255	1388	257
OA Full attention	1799	315	1995	354

Note: YA, Young adult; OA, Older adults; M, Mean of response times in milliseconds; SD, Standard deviation.

Table 7.
Mean scores on battery of neuropsychological tests in Experiment 3.

	MMSE (/30)	ANART (/50)	Trail Making A (seconds)	Trail Making A Errors (%)	Trail Making B (seconds)	Trail Making B Errors (%)	Vocab (/66)	Morn/Eve (/86)
YA	29.08	37.08	25.46	0.00	44.23	0.00	52.46	42.38
OA	29.67	44.33	29.33	0.00	54.42	0.00	59.17	61.50

Note: YA, Young adult; OA, Older adults; MMSE, the Mini Mental State Examination; ANART, American National Adult Reading Test; Vocab, Vocabulary from the WAIS-III; Morn/Eve, Morningness-Eveningness.

Table 8.
Means and Standard Deviations for Accuracy and RTs (in milliseconds) in attention tasks in each of the Attention conditions in Experiment 3.

a. Young Adults

Attention Condition	Proportion Correct		RTs	
	M	SD	M	SD
DA with Item task	0.96	0.04	1403	275
DA with Relational task	0.95	0.04	1378	265

b. Older Adults

Attention Condition	Proportion Correct		RTs	
	M	SD	M	SD
DA with Item task	0.97	0.03	1537	357
DA with Relational task	0.96	0.03	1633	321

Note: DA, Divided attention; M, Mean; SD, Standard deviation; RTs, Response time in milliseconds.

Table 9.

Means and Standard Deviations for Proportion Hits and False Alarms Rates in the Relational memory test in each of the Attention conditions in Experiment 3.

Condition	Young Adults		Older Adults	
	Hits	False Alarms	Hits	False Alarms
Full attention	0.82	0.17	0.74	0.3
	(0.12)	(0.12)	(0.13)	(0.14)
DA with Item task	0.80	0.26	0.72	0.28
	(0.13)	(0.16)	(0.14)	(0.14)
DA with Relational task	0.77	0.33	0.67	0.34
	(0.08)	(0.14)	(0.13)	(0.12)

Note: DA, Divided attention; Numbers in the parenthesis indicate standard deviation.

Table 10.

Means and Standard Deviations of memory RTs (milliseconds) in the Relational memory test in each of the Attention groups in Experiment 3.

Group	Young Adults		Older Adults	
	M	SD	M	SD
Full attention	1714	303	1745	311
DA with Item task	1648	288	1701	266
DA with Relational task	1713	223	1765	278

Note: DA, Divided attention; M, Means for response times in milliseconds; S, Standard deviation.

Table 11.
Regions of significance for Successful Relational Memory in each attention condition in young adults.

Contrast	Region of Activation	Hemisphere	BA	x	y	z	t	k
				Talairach Coordinates		
Full Attention (Hit>Miss)	Middle Frontal Gyrus	R	6	32	7	60	5.18	112
				38	3	55	5.15	
				46	5	53	3.98	
	Superior Frontal Gyrus	R	6	10	13	56	4.84	31
	Middle Temporal Gyrus	R	37	48	-60	7	4.82	36
	Inferior Frontal Gyrus	L	11	-24	26	-20	4.71	32
	Cuneus	L	19	-16	-92	27	4.63	46
	Cuneus	L	18	-8	-98	21	3.31	
	Cuneus	L	30	-6	-70	7	4.56	128
	Cuneus	L	17	-10	-83	13	4	
				-4	-83	6	3.54	
	Parahippocampal Gyrus	L	36	-34	-24	-22	4.53	16
	Precentral Gyrus	R	9	34	6	37	4.5	51
	Middle Frontal Gyrus	R	9	42	10	38	3.55	
	Cingulate Gyrus	L	24	-12	-20	36	4.5	12
	Inferior Frontal Gyrus	L	45	-34	28	8	4.45	17
	Precentral Gyrus	L	6	-38	-11	48	4.4	35
	Medial Frontal Gyrus	R	6	16	-1	59	4.33	8
	Superior Temporal Gyrus	R	42	67	-28	18	4.29	14
	Inferior Frontal Gyrus	R	45	44	22	15	4.25	47
	Middle Frontal Gyrus	L	10	-30	38	15	4.24	21
	Middle Temporal Gyrus	R	19	40	-80	22	4.18	18
	Superior Temporal Gyrus	L	22	-61	-4	8	4.16	7
	Superior Frontal Gyrus	L	6	-18	-12	61	4.13	24
	Superior Frontal Gyrus	R	6	6	3	68	4.1	18
	Inferior Frontal Gyrus	R	47	50	16	-1	4.09	35
	Superior Frontal Gyrus	L	9	-40	35	30	4.05	26
	Hippocampus	L	n/a	-20	-7	-22	3.83	5
	Inferior Frontal Gyrus	L	45	-48	37	2	3.75	9
	Supramarginal Gyrus	L	40	-59	-48	21	3.7	13
	Postcentral Gyrus	R	2	32	-37	70	3.63	5
	Superior Temporal Gyrus	R	13	53	-40	19	3.53	11
	Superior Temporal Gyrus	L	38	-53	9	-11	3.49	8
	Precuneus	R	7	26	-56	51	3.46	13
	Cuneus	L	19	-2	-88	32	3.44	5
	Middle Frontal Gyrus	R	46	51	45	0	3.42	11
	Inferior Parietal Lobule	L	40	-38	-44	46	3.38	31
				-46	-44	54	3.31	
				-59	-33	44	3.32	8

	Region		BA	x	y	z		k
	Superior Parietal Lobule	L	7	-34	-54	56	3.21	6
	Middle Frontal Gyrus	L	6	-34	0	48	3.2	5
DA with Item (Hit>Miss)	Medial Frontal Gyrus	R	6	20	-11	48	6.81	77
	Postcentral Gyrus	R	3	24	-30	57	6.16	111
	Sub-Gyral	R	40	28	-38	57	4.75	
	Postcentral Gyrus	R	3	32	-34	50	4.33	
	Insula	L	13	-32	-22	25	4.83	24
				-28	-26	20	3.72	
	Postcentral Gyrus	L	3	-22	-29	49	4.68	22
	Insula	L	13	-40	-15	8	3.99	23
	Cuneus	L	17	-20	-77	11	3.97	8
	Insula	R	13	40	-40	22	3.83	5
	Superior Temporal Gyrus	L	39	-50	-56	6	3.82	22
	Inferior Parietal Lobule	L	40	-57	-36	28	3.69	8
	Precentral Gyrus	L	4	-28	-24	69	3.6	5
DA with Relation (Hit>Miss)	Superior Parietal Lobule	R	7	20	-53	60	4.27	33
	Cingulate Gyrus	L	24	-4	-3	22	3.78	58
	Inferior Frontal Gyrus	L	47	-36	35	0	3.63	7
	Fusiform Gyrus	L	37	-48	-39	-10	3.55	10
	Precentral Gyrus	L	44	-50	8	7	3.44	8

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>5. DA, divided attention; R, right; L, left; BA, approximate Brodmann area based on coordinates.

Table 12.
Regions of significance for Successful Relational Memory in each attention condition in older adults.

Contrast	Region of Activation	Hemisphere	BA	x	y	z	t	k
				Talairach Coordinates				
Full Attention (Hit>Miss)	Inferior temporal gyrus	L	20	-38	-13	-33	4.64	11
	Perirhinal Cortex	R	35	22	-9	-21	4.41	18
	Middle Temporal Gyrus	R	37	57	-66	9	4.32	8
	Insula	R	13	46	-8	0	4.09	26
	Posterior Entorhinal Cortex	L	28	-24	-11	-26	3.93	7
	Superior Temporal Gyrus	L	22	-48	-6	-5	3.5	12
	Medial Frontal Gyrus	R	10	12	36	-10	3.5	5
	Anterior Cingulate	R	24	6	23	1	3.35	9
DA with Item (Hit>Miss)	Cingulate Gyrus	R	31	26	-42	22	5.65	62
	Inferior Parietal Lobule	L	40	-40	-48	58	5.49	38
	Inferior Frontal Gyrus	L	46	-51	41	5	5.43	18
	Fusiform Gyrus	R	37	40	-45	-13	5.37	11
	Precentral Gyrus	L	6	-61	-2	33	4.6	17
	Medial Frontal Gyrus	R	6	4	35	35	4.45	28
	Middle Frontal Gyrus	R	6	36	11	55	4.17	11
				57	4	40	4.05	24
	Cingulate Gyrus	L	24	-20	-7	48	4.02	17
	Middle Temporal Gyrus	R	37	55	-64	3	3.92	8
	Medial Frontal Gyrus	L	6	-2	-14	65	3.79	14
	Superior Frontal Gyrus	L	10	-30	58	4	3.66	18
	Inferior Occipital Gyrus	R	19	42	-76	-1	3.64	8
	Precuneus	R	7	22	-73	53	3.6	6
	Middle Temporal Gyrus	L	21	-51	-22	-7	3.6	8
	Superior Temporal Gyrus	L	22	-51	-27	1	3.58	6
	Medial Frontal Gyrus	L	9	-6	40	29	3.55	15
	Superior Temporal Gyrus	R	22	51	-15	3	3.5	5
	Parahippocampal Gyrus	L	36	-28	-34	-10	3.44	6
DA with Relation (Hit>Miss)	Inferior Parietal Lobule	R	40	61	-31	48	5.09	20
	Postcentral Gyrus	L	2	-53	-27	51	4.23	7
	Insula	L	13	-32	5	15	3.99	12
	Cingulate Gyrus	L	31	-22	-47	37	3.45	21
	Superior Parietal Lobule	L	7	-26	-56	43	3.43	

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>5. DA, divided attention; R, right; L, left; BA, approximate Brodmann area based on coordinates.

Table 13.
Regions more active in young than older adults in each attention condition.

Contrast	Region of Activation	Hemisphere	BA	x	y	z	t	k
				Talairach Coordinates				
YA>OA:	Middle Frontal Gyrus	R	6	30	9	60	5.11	60
Full Attention (Hit>Miss)	Precentral Gyrus	R	9	34	8	36	4.34	133
	Superior Frontal Gyrus	R	6	4	5	66	4.12	46
	Superior Parietal Lobule	L	7	-32	-56	54	3.92	58
	Sub-Gyral	R	6	18	1	57	3.87	16
	Middle Frontal Gyrus	R	46	44	28	17	3.83	54
	Superior Frontal Gyrus	L	6	-22	0	68	3.79	21
	Cuneus	L	17	-10	-83	13	3.73	14
	Fusiform Gyrus	L	37	-48	-42	-15	3.67	6
	Middle Temporal Gyrus	R	19	42	-80	24	3.65	14
	Middle Frontal Gyrus	R	6	51	10	46	3.5	50
	Middle Frontal Gyrus	R	10	48	47	14	3.49	11
	Middle Frontal Gyrus	R	6	34	1	52	3.48	25
	Middle Occipital Gyrus	R	19	32	-85	12	3.47	28
	Inferior Parietal Lobule	L	40	-42	-44	48	3.47	67
				-32	-48	45	3.19	
	Inferior Frontal Gyrus	R	45	55	18	14	3.41	63
	Inferior Frontal Gyrus	R	47	50	16	-1	3.2	
	Middle Frontal Gyrus	L	10	-28	36	17	3.41	16
	Precuneus	R	7	26	-52	50	3.37	11
	Superior Temporal Gyrus	L	22	-59	-46	19	3.26	9
	Middle Frontal Gyrus	L	11	-32	50	-11	3.25	23
	Middle Frontal Gyrus	L	9	-38	33	35	3.21	15
	Inferior Parietal Lobule	L	40	-63	-33	37	3.18	11
				-65	-28	31	3.12	
	Middle Frontal Gyrus	L	6	-34	-2	44	3.16	7
	Middle Occipital Gyrus	L	19	-48	-81	6	3.16	6
	Insula	R	13	46	-40	17	3.16	5
	Middle Frontal Gyrus	L	6	-26	-9	61	3.05	9
	Middle Occipital Gyrus	R	19	36	-80	2	2.93	5
YA>OA:	Middle Frontal Gyrus	R	6	22	-11	48	3.89	14
DA with Item (Hit>Miss)	Insula	L	13	-32	-24	23	3.77	13
				-46	-32	20	3.74	77
				-46	-24	23	3.57	
	Superior Temporal Gyrus	R	39	34	-55	25	3.52	9
	Inferior Temporal Gyrus	L	20	-44	-13	-31	3.5	17
				-44	-5	-28	3.02	
	Insula	L	13	-36	-40	24	3.21	7

	Region		BA	x	y	z	t	k
YA>OA: DA with Relation (Hit>Miss)	Superior Parietal Lobule	R	7	22	-51	58	3.61	45
	Superior Temporal Gyrus	R	38	44	16	-33	3.24	15
	Cingulate Gyrus	L	24	-6	1	24	3.21	11
				-6	-7	22	3.01	5

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>5.YA, young adults; OA, older adults; DA, divided attention; R, right; L, left; BA, approximate Brodmann area based on coordinates.

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Table 14.
Regions more active in older than young adults in each attention condition.

| Contrast | Region of Activation | Hemisphere | BA | Talairach Coordinates | | | | |
				x	y	z	t	k
OA>YA:	Insula	R	13	36	-10	24	3.85	13
Full Attention (Hit>Miss)	Cingulate Gyrus	R	24	16	-7	45	3.82	17
	Anterior Cingulate	L	32	-16	41	5	3.57	8
	Anterior Cingulate	R	32	10	34	-10	3.56	30
	Superior Temporal Gyrus	R	22	34	-50	14	3.38	10
	Anterior Cingulate	R	24	4	27	-1	3.35	44
	Inferior Frontal Gyrus	L	47	-28	9	-14	3.27	19
	Medial Frontal Gyrus	L	10	-14	36	-9	2.95	5
OA>YA:	Middle Frontal Gyrus	R	6	34	10	53	4.58	36
DA with Item (Hit>Miss)	Middle Frontal Gyrus	L	8	-28	39	39	3.86	70
	Middle Temporal Gyrus	L	19	-42	-79	21	3.78	21
	Middle Temporal Gyrus	L	21	-53	-10	-15	3.77	31
	Sub-Gyral	L	6	-20	-9	50	3.64	16
	Fusiform Gyrus	R	37	42	-49	-11	3.59	27
	Medial Frontal Gyrus	L	10	-6	58	-6	3.58	66
				-4	44	-9	2.9	
	Posterior Cingulate	R	29	10	-42	15	3.48	15
	Medial Frontal Gyrus	L	11	-6	38	-17	3.46	51
	Medial Frontal Gyrus	L	10	-12	38	-10	3.04	
	Cuneus	L	18	0	-91	10	3.42	10
	Middle Frontal Gyrus	L	6	-24	20	58	3.37	22
	Superior Frontal Gyrus	L	8	-26	28	54	2.85	
	Parahippocampal Gyrus	L	36	-28	-36	-12	3.34	28
	Posterior Cingulate	L	30	-4	-54	6	3.27	53
	Anterior Cingulate	L	32	-20	32	21	3.27	9
	Precuneus	L	7	-2	-52	56	3.22	33
	Parahippocampal Gyrus	R	19	28	-49	-3	3.18	7
	Precuneus	R	7	6	-60	34	2.93	7
OA>YA:	Postcentral Gyrus	R	2	61	-27	46	4.22	36
DA with Relation								
(Hit>Miss)	Inferior Parietal Lobule	R	40	59	-38	46	2.89	
	Superior Frontal Gyrus	R	11	26	54	-16	4.19	60
	Inferior Frontal Gyrus	R	47	30	27	-3	4	69
	Middle Frontal Gyrus	R	11	40	52	-14	3.81	38
	Middle Frontal Gyrus	R	6	40	14	55	3.79	36

Superior Temporal Gyrus	R	22	44	-26	-10	3.67	30
Inferior Parietal Lobule	R	40	59	-47	39	3.65	75
Precuneus	L	31	-20	-49	39	3.61	18
Superior Frontal Gyrus	L	11	-30	44	-16	3.59	64
Middle Frontal Gyrus	L	11	-26	42	-7	3.31	
Middle Temporal Gyrus	R	21	65	-24	-12	3.59	8
Middle Frontal Gyrus	R	8	42	27	41	3.47	30
Superior Temporal Gyrus	L	22	-32	-50	15	3.18	8
Medial Frontal Gyrus	R	10	16	48	-4	2.93	5

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>5. YA, young adults; OA, older adults; DA, divided attention; R, right; L, left; BA, approximate Brodmann area based on coordinates.

Table 15.
Regions that were more active under full attention than each divided attention condition during encoding in young adults.

Contrast	Region of Activation	Hemisphere	BA	x	y	z	t	k
					Talairach Coordinates			
FA>DI for Hit>Miss	Posterior Cingulate	R	29	14	-42	18	6.17	38
	Medial Frontal Gyrus	L	9	-20	29	25	4.16	20
FA>DR for Hit>Miss	Cuneus	L	18	-14	-75	17	6.62	216
		L	17	-10	-77	9	5.35	
				-6	-83	6	3.6	
	Superior Temporal Gyrus	L	22	-61	-50	17	5.52	106
	Middle Temporal Gyrus	L	39	-57	-64	11	3.74	
	Superior Frontal Gyrus	L	8	-4	36	50	4.97	34
	Middle Frontal Gyrus	L	10	-30	38	17	4.89	33
	Middle Frontal Gyrus	L	9	-42	33	32	4.81	149
				-36	25	34	4.57	
	Inferior Parietal Lobule	L	40	-61	-41	39	4.8	82
				-57	-33	48	3.5	
	Inferior Temporal Gyrus	L	20	-51	-55	-12	4.57	23
	Inferior Temporal Gyrus	R	20	51	-11	-33	4.47	38
				50	-4	-37	3.14	
	Middle Frontal Gyrus	L	11	-28	46	-14	4.43	77
				-36	48	-11	3.65	
	Middle Frontal Gyrus	L	10	-24	54	-9	3.55	
	Precentral Gyrus	L	6	-38	-11	52	4.43	40
	Superior Temporal Gyrus	L	22	-38	-52	17	4.38	16
	Superior Frontal Gyrus	L	8	-12	49	45	4.32	38
	Precentral Gyrus	R	9	38	6	37	4.28	29
	Middle Frontal Gyrus	L	6	-24	20	56	4.21	25
	Superior Frontal Gyrus	L	6	-20	16	51	3.87	
	Lingual Gyrus	L	19	-26	-62	3	4.14	16
	Inferior Frontal Gyrus	L	47	-24	22	-20	4.06	35
		L	47	-22	17	-13	3.15	
	Middle Frontal Gyrus	R	9	38	37	35	3.99	12
	Postcentral Gyrus	R	1	51	-24	55	3.94	19
	Anterior Cingulate	R	25	4	2	-7	3.91	6
	Medial Frontal Gyrus	L	6	0	12	47	3.91	65
	Superior Frontal Gyrus	R	8	8	14	53	3.4	
	Medial Frontal Gyrus	L	6	0	2	50	3.29	
	Superior Frontal Gyrus	L	6	-20	0	68	3.89	20
	Precuneus	L	7	-2	-79	45	3.89	13
	Middle Temporal Gyrus	R	19	50	-60	14	3.88	24

Region	Side	BA	x	y	z	t	k
Cingulate Gyrus	L	32	-12	21	34	3.85	18
Middle Temporal Gyrus	L	37	-51	-52	4	3.83	17
Inferior Parietal Lobule	L	40	-65	-26	33	3.83	9
Inferior Frontal Gyrus	L	13	-36	22	6	3.82	15
Inferior Frontal Gyrus	R	47	50	16	-1	3.79	24
Superior Frontal Gyrus	R	6	24	3	66	3.76	24
Fusiform Gyrus	R	37	40	-44	-16	3.7	20
Cuneus	R	17	14	-77	13	3.65	22
Posterior Cingulate	R	29	14	-42	13	3.65	40
	R	23	8	-40	22	3.46	
	R	29	6	-38	13	3.14	
Inferior Frontal Gyrus	R	47	34	25	-15	3.64	10
Inferior Frontal Gyrus	R	13	32	3	-12	3.63	10
Cingulate Gyrus	L	23	-6	-30	29	3.63	7
Middle Frontal Gyrus	R	8	36	35	44	3.6	8
Posterior Cingulate	L	23	-2	-32	22	3.57	10
Superior Temporal Gyrus	L	38	-55	7	-9	3.56	14
Cingulate Gyrus	R	32	14	21	28	3.53	13
Parahippocampal Gyrus	R	28	18	-1	-12	3.5	27
Cingulate Gyrus	L	31	-14	-45	23	3.46	5
Inferior Parietal Lobule	R	40	51	-41	41	3.45	24
Hippocampus	L	n/a	-30	-7	-16	3.26	7
Superior Frontal Gyrus	R	11	24	52	-16	3.43	7
Middle Frontal Gyrus	R	8	42	25	41	3.4	6
Middle Frontal Gyrus	R	8	42	25	41	3.31	9
Middle Frontal Gyrus	L	6	-36	6	48	3.31	6
Cingulate Gyrus	L	23	-10	-16	32	3.25	5
Postcentral Gyrus	L	2	-42	-24	27	3.24	6
Middle Frontal Gyrus	R	9	53	13	36	3.22	6
Middle Frontal Gyrus	R	6	30	11	58	3.2	8
Superior Parietal Lobule	R	7	44	-58	51	3.18	5

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>5. FA, full attention; DI, divided attention with item; DR, divided attention with Relation; R, right; L, left; BA, approximate Brodmann area based on coordinates.

Table 16.
Regions that were more active under each divided attention condition than full attention during encoding in young adults.

Contrast	Region of Activation	Hemisphere	BA	Talairach Coordinates x	y	z	*t*	k
DI>FA for Hit>Miss	Precentral Gyrus	L	44	-46	18	8	5.86	27
	Middle Temporal Gyrus	L	37	-44	-54	3	5.35	60
	Sub-Gyral	L	37	-46	-49	-4	3.28	
	Medial Frontal Gyrus	R	6	18	-13	50	5.35	93
	Cingulate Gyrus	R	24	20	-12	39	5.18	
	Middle Temporal Gyrus	R	39	36	-53	21	5.04	28
	Insula	R	13	40	-39	26	4.63	24
	Parahippocampal Gyrus	R	19	42	-47	-3	3.89	7
	Amygdala	R	n/a	28	-3	-27	3.86	6
	Middle Occipital Gyrus	L	19	-34	-74	4	3.85	20
	Insula	L	13	-42	-15	8	3.58	11
				-34	-40	22	3.55	19
DR>FA for Hit>Miss	Middle Occipital Gyrus	L	19	-36	-75	6	4.49	11
	Middle Temporal Gyrus	R	39	42	-55	23	3.56	5
	Cingulate Gyrus	L	23	-10	-24	23	3.52	6

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>5. FA, full attention; DI, divided attention with item; DR, divided attention with Relation; R, right; L, left; BA, approximate Brodmann area based on coordinates.

Table 17.
Regions that were more active under full attention than each divided attention condition during encoding in older adults.

Contrast	Region of Activation	Hemisphere	BA	x	y	z	*t*	k
				Talairach Coordinates		
FA>DI for Hit>Miss	Inferior Temporal Gyrus	L	20	-44	-11	-33	5.47	69
				-36	-17	-28	5.4	
	Middle Temporal Gyrus	R	39	50	-75	13	4.75	45
				57	-66	11	3.63	
	Inferior Frontal Gyrus	R	47	26	21	-14	4.36	10
	Cingulate Gyrus	R	31	6	-27	35	4.28	52
	Middle Frontal Gyrus	R	6	26	-10	41	4.1	12
	Medial Frontal Gyrus	R	25	14	30	-13	3.99	6
	Medial Frontal Gyrus	L	10	-16	49	18	3.94	10
	Cingulate Gyrus	L	32	-22	17	32	3.67	8
	Insula	R	13	44	-8	0	3.64	8
	Precuneus	R	23	4	-59	20	3.42	6
FA>DR for Hit>Miss	Amygdala/Hippocampus	L	n/a	-16	-8	-10	5.82	30
	Superior Temporal Gyrus	R	38	42	18	-33	5.57	57
	Insula	R	13	42	-8	0	5.25	42
	Superior Temporal Gyrus	R	38	30	6	-42	5.23	17
	Inferior Frontal Gyrus	L	13	-32	5	-12	5.15	92
	Medial Frontal Gyrus	R	8	8	49	42	4.53	10
	Anterior Cingulate	R	25	2	17	-1	4.5	29
	Superior Frontal Gyrus	L	8	-10	47	46	4.05	17
	Inferior Frontal Gyrus	R	47	36	30	-17	3.67	12
	Lingual Gyrus	R	28	26	4	-30	3.64	20
	Cingulate Gyrus	R	24	8	-8	26	3.47	6
	Superior Temporal Gyrus	L	22	-46	-4	-7	3.44	6

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>5. FA, full attention; DI, divided attention with item; DR, divided attention with Relation; R, right; L, left; BA, approximate Brodmann area based on coordinates.

Table 18.
Regions that were more active under each divided attention condition than full attention during encoding in older adults.

Contrast	Region of Activation	Hemisphere	BA	Talairach Coordinates			*t*	k
				x	y	z		
DI>FA for Hit>Miss	Fusiform Gyrus	R	37	38	-45	-13	5.64	25
	Superior Parietal Lobule	L	7	-30	-59	56	5.49	48
	Middle Temporal Gyrus	L	39	-42	-52	14	4.89	38
	Precuneus	L	31	-28	-71	22	4.89	13
	Inferior Frontal Gyrus	R	44	55	16	10	4.45	20
	Superior Temporal Gyrus	L	21	-51	-26	-5	4.44	16
	Posterior Cingulate	R	23	2	-30	20	4.21	26
	Supramarginal Gyrus	L	40	-40	-45	32	4.16	30
	Middle Frontal Gyrus	R	6	38	11	57	4.12	11
	Supramarginal Gyrus	L	40	-61	-47	23	4.08	11
	Cingulate Gyrus	L	32	-14	21	39	4.01	11
	Anterior Cingulate	R	32	18	34	24	3.93	11
	Superior Frontal Gyrus	R	9	20	40	29	3.34	
	Middle Frontal Gyrus	L	6	-22	-5	46	3.9	9
	Middle Frontal Gyrus	R	11	44	52	-13	3.9	6
	Medial Frontal Gyrus	R	6	20	6	49	3.75	5
	Precuneus	L	7	-22	-48	43	3.72	6
	Medial Frontal Gyrus	R	6	8	5	57	3.66	13
	Middle Frontal Gyrus	R	6	51	12	44	3.65	6
	Sub-Gyral	R	21	46	-16	-13	3.5	5
	Middle Frontal Gyrus	L	6	-30	-11	59	3.43	11
	Precentral Gyrus	L	9	-42	25	36	3.26	7
DR>FA for Hit>Miss	Cingulate Gyrus	R	32	24	11	34	5.31	87
	Precuneus	L	7	-20	-52	43	5.16	130
	Cingulate Gyrus	L	31	-20	-23	40	5.15	44
	Middle Frontal Gyrus	L	11	-30	46	-9	4.33	33

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>5. FA, full attention; DI, divided attention with item; DR, divided attention with Relation; R, right; L, left; BA, approximate Brodmann area based on coordinates.

Table 19.
Common regions where young adults (YA) under each divided attention with relation task and older adults (OA) under full attention failed to show activation compared to young adults under full attention.

Conjunction	Region of Activation	Hemisphere	BA	Talairach Coordinates				
				x	y	z	*t*	k
YA, FA>DR (Hit>Miss)	Middle Frontal Gyrus	L	10	-30	38	17	4.89	16
inclusively masked with	Middle Frontal Gyrus	L	9	-42	33	32	4.81	15
YA>OA, FA (Hit>Miss)	Superior Temporal Gyrus	L	22	-61	-48	19	4.68	9
	Precentral Gyrus	R	9	38	6	37	4.28	105
	Superior Frontal Gyrus	L	6	-20	0	68	3.89	20
	Cuneus	L	17	-12	-81	13	3.83	14
	Inferior Frontal Gyrus	R	47	50	16	-1	3.79	44
	Precentral Gyrus	R	44	53	18	8	2.47	
	Inferior Frontal Gyrus	R	45	59	22	14	2.23	
	Inferior Parietal Lobule	L	40	-65	-28	31	3.63	11
	Inferior Parietal Lobule	L	40	-63	-33	37	3.19	
	Middle Frontal Gyrus	L	11	-30	46	-14	3.62	23
	Superior Frontal Gyrus	R	6	24	5	64	3.54	60
	Middle Frontal Gyrus	R	6	30	11	58	3.2	
	Insula	R	13	40	26	19	3.36	39
	Inferior Frontal Gyrus	R	45	46	22	15	2.55	
	Sub-Gyral	R	6	18	1	57	3.05	15
	Superior Frontal Gyrus	R	6	6	3	68	2.97	35
	Insula	R	13	48	-40	19	2.8	5
	Middle Frontal Gyrus	R	6	51	14	44	2.64	38
	Middle Frontal Gyrus	R	6	46	4	50	2.57	

Note: Regions significant at the conjoint probability of p < .00025 (k>5) following inclusive masking. An explicit, inclusive t mask was imposed, and the mask was created with regions of significant in "YA (Hit>Miss) > OA (Hit>Miss)" at uncorrected p<.005 with a cluster extent threshold of k>5. YA, Young adults; OA, Older adults; DR, divided attention with Relation; R, right; L, left; BA, approximate Brodmann area based on coordinates.

Table 20.

Common regions where young adults (YA) under each divided attention with item task and older adults (OA) under full attention showed greater activation than young adults under full attention.

				Talairach Coordinates				
Conjunction	Region of Activation	Hemisphere	BA	x	y	z	*t*	k
YA, DI>FA (Hit>Miss) inclusively masked with OA>YA, FA (Hit>Miss)	Cingulate Gyrus	R	24	16	-9	45	3.04	9
YA, DR>FA (Hit>Miss) inclusively masked with OA>YA, FA (Hit>Miss)	Cingulate Gyrus	R	24	15	-8	42	2.67	9

Note: Regions significant at the conjoint probability of p < .00025 (k>5) following inclusive masking. An explicit, inclusive mask was imposed, and the mask was created with regions of significant in "OA (Hit>Miss) > YA (Hit>Miss)" at uncorrected p<.005 with a cluster extent threshold of k>5. YA, Young adults; OA, Older adults; DI, divided attention with item; DR, divided attention with Relation; R, right; L, left; BA, approximate Brodmann area based on coordinates.

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FIGURE 1.
Trial sequence for each condition in Experiment 1.
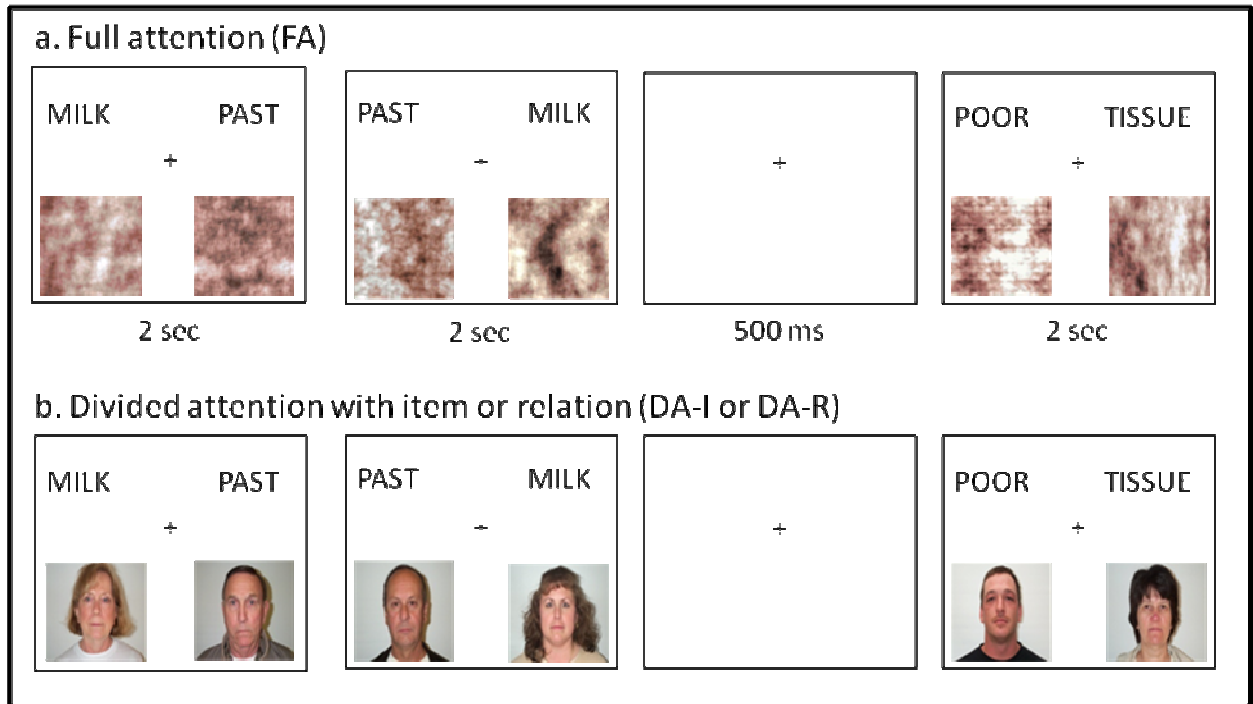
Note: In the full attention condition, participants were told to memorize both words and word pairs ignoring images presented below the word pairs (a). In the divided attention with item condition (b), participants were instructed to detect a ma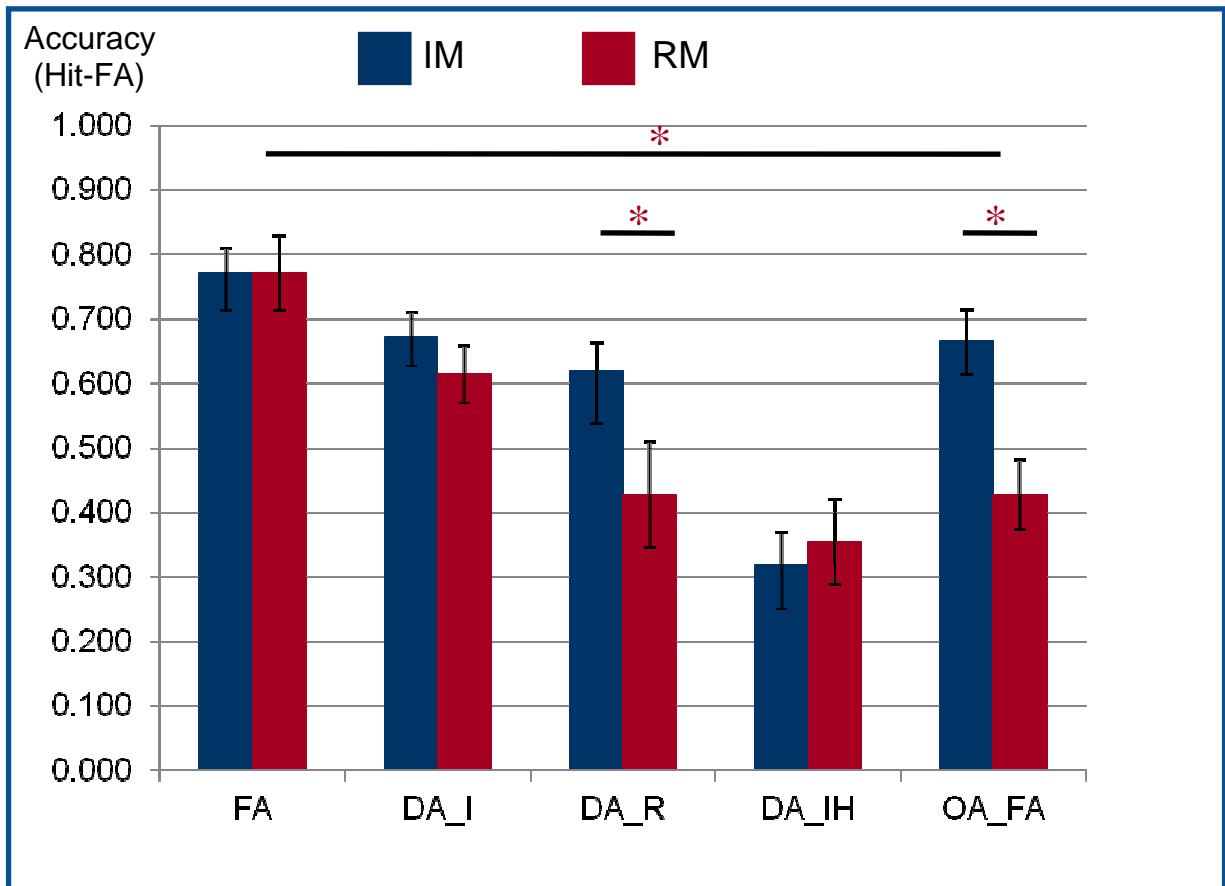le face in each trial while memorizing words and word pairs. In the divided attention with relation condition (b), participants were instructed to compare ages of two faces and detect an older face in each trial during encoding of words and word pairs.

FIGURE 2.

Proportion of Hit minus Proportion of False Alarm Rates in each memory test in each group in Experiment 1.
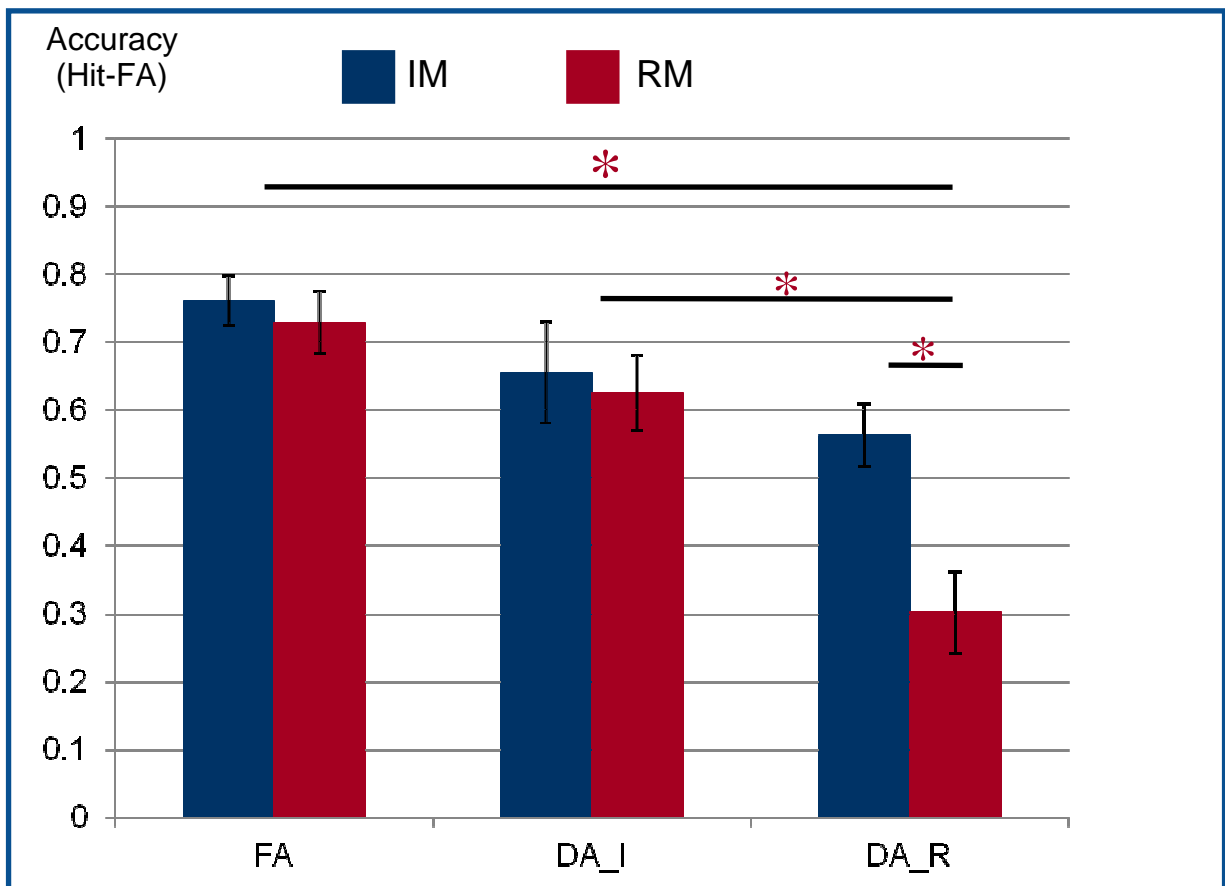
*Note: * indicates the significant effect at p<.05. IM, Item memory; RM, Relational memory; FA, Full attention, DA_I, Divided attention with item detection; DA_R, Divided attention with relation detection.*

FIGURE 3.
Trial sequence for each condition in Experiment 2.
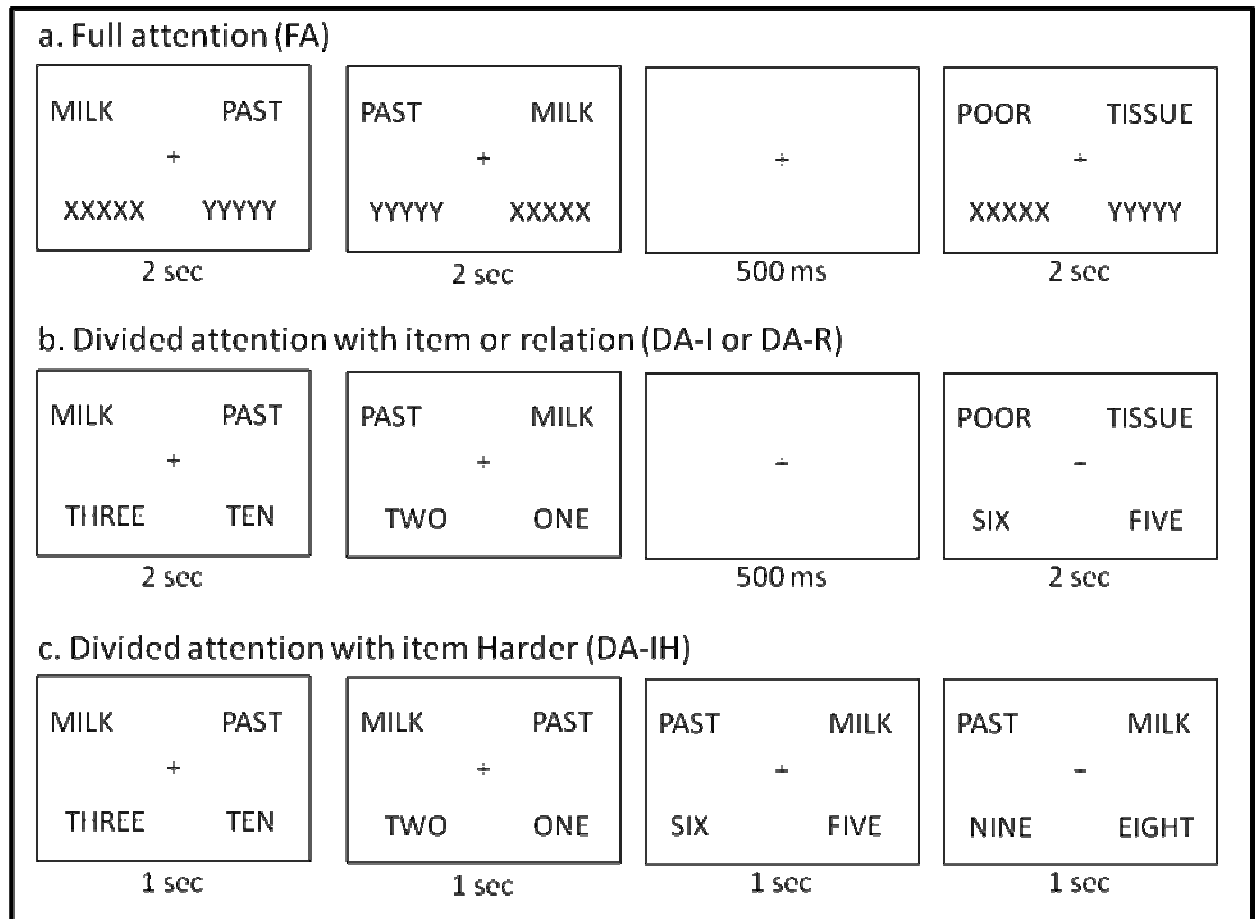
Note: In the full attention condition, participants were told to memorize both words and word pairs ignoring strings presented below the word pairs (a). In the divided attention with item condition (b), participants were instructed to detect an odd number in each trial while memorizing words and word pairs. In the divided attention with relation condition (b), participants were instructed to compare two numbers and detect a numerically bigger number in each trial during encoding of words and word pairs. In the divided attention with item, harder condition (c), participants were instructed to detect an odd number every 1 second while memorizing words and word pairs.

FIGURE 4.

Proportion of Hit minus Proportion of False Alarm Rates in each memory test in each group in Experiment 2.

*Note: * indicates the significant effect at p<.05. IM, Item memory; RM, Relational memory; FA, Full attention, DA_I, Divided attention with item detection; DA_R, Divided attention with relation detection; DA_IH, Divided attention with item detection, harder; OA, Older adults.*
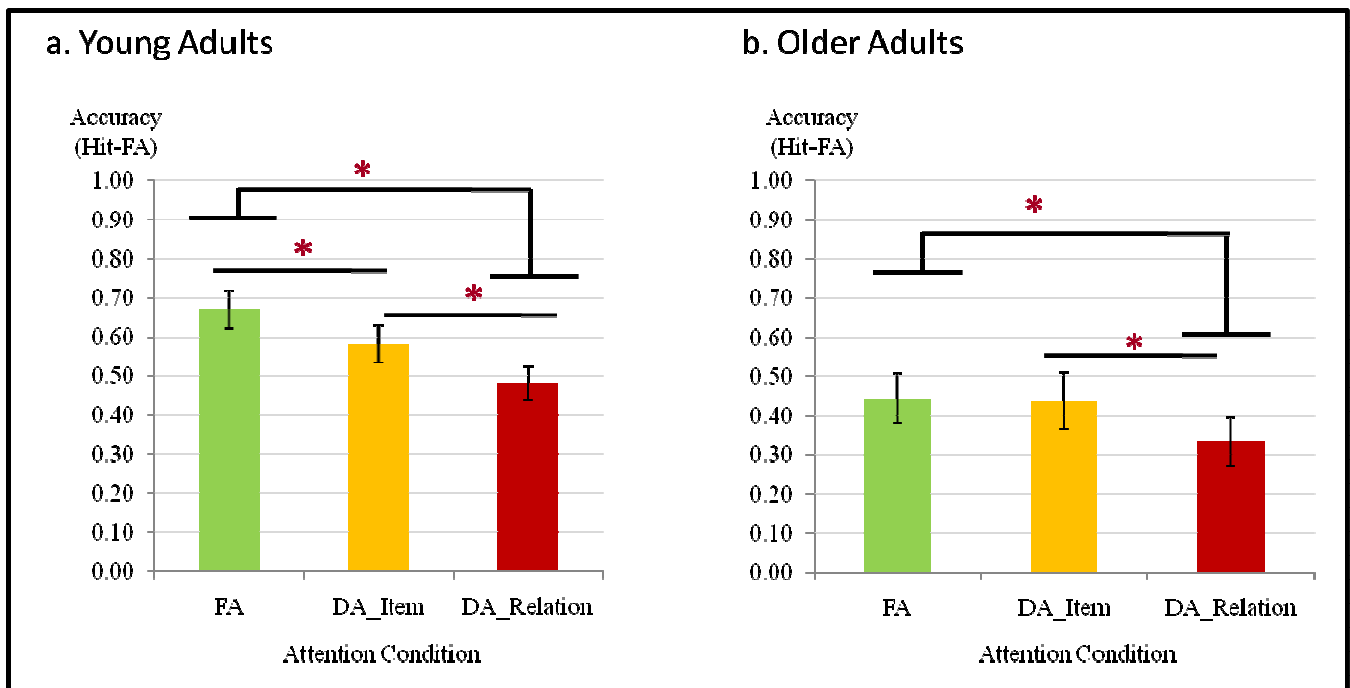
FIGURE 5.
Trial sequence for each condition in Experiment 3.
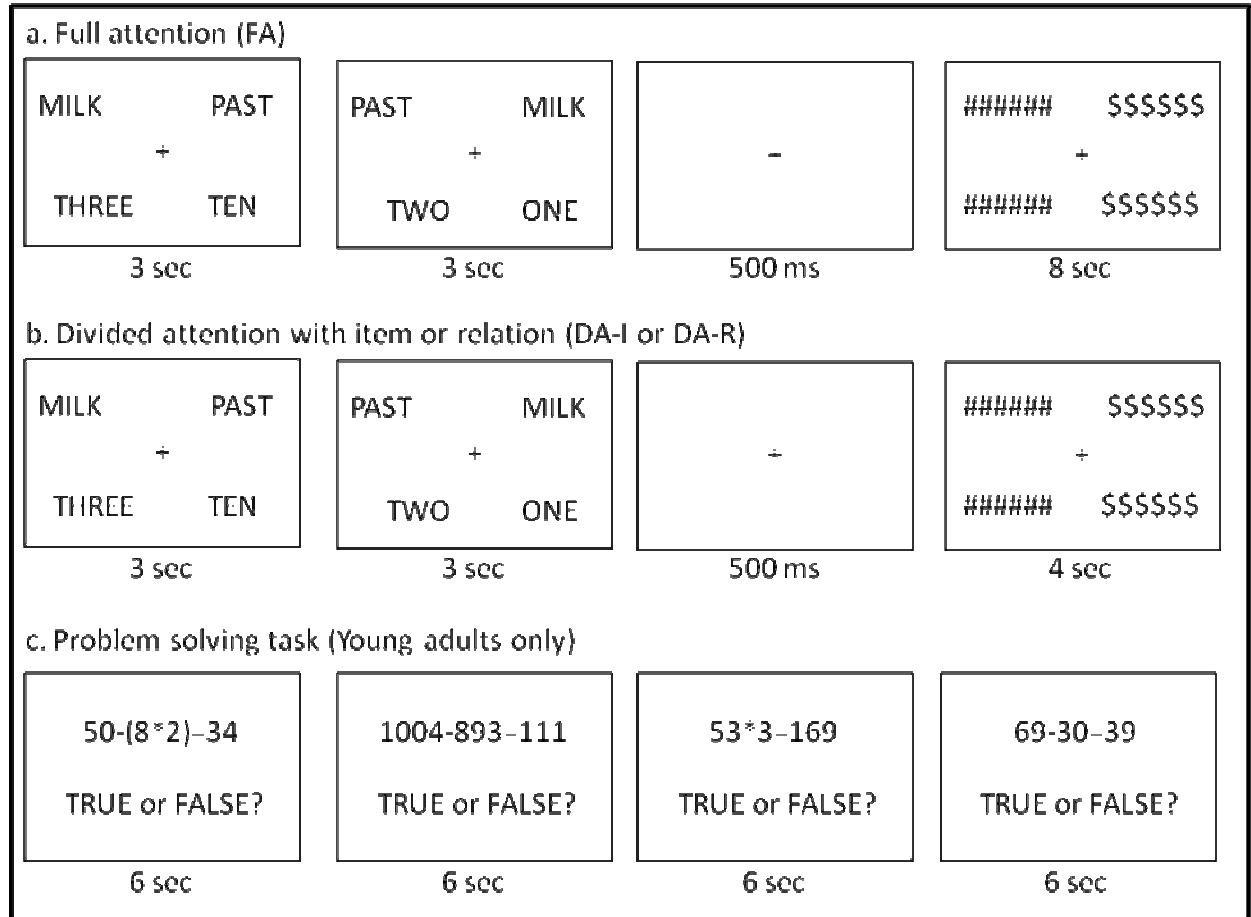
Note: In the full attention condition, participants were told to memorize both words and word pairs ignoring strings presented below the word pairs (a). In the divided attention with item condition (b), participants were instructed to detect an odd number in each trial while memorizing words and word pairs. In the divided attention with relation condition (b), participants were instructed to compare two numbers and detect a numerically bigger number in each trial during encoding of words and word pairs. The control trials containing strings of "$" and "#" were inserted in each of encoding phase to increase power to detect hemodynamic responses (1/3 of the total trials in each run was control trials). After each of encoding run, only young adults performed a problem solving task block (c). In the problem solving task block, young adults were asked to solve each math problem as accurately as possible and to indicate whether each equation is true or false.

FIGURE 6.

Proportion of Hit minus Proportion of False Alarm Rates in Relational memory test in each Attention condition in Young adults in Experiment 3.

*Note: * indicates the significant effect at p<.05. IM, Item memory; RM, Relational memory; FA, Full attention, DA_Item, Divided attention with item detection; DA_Relation, Divided attention with relation detection.*
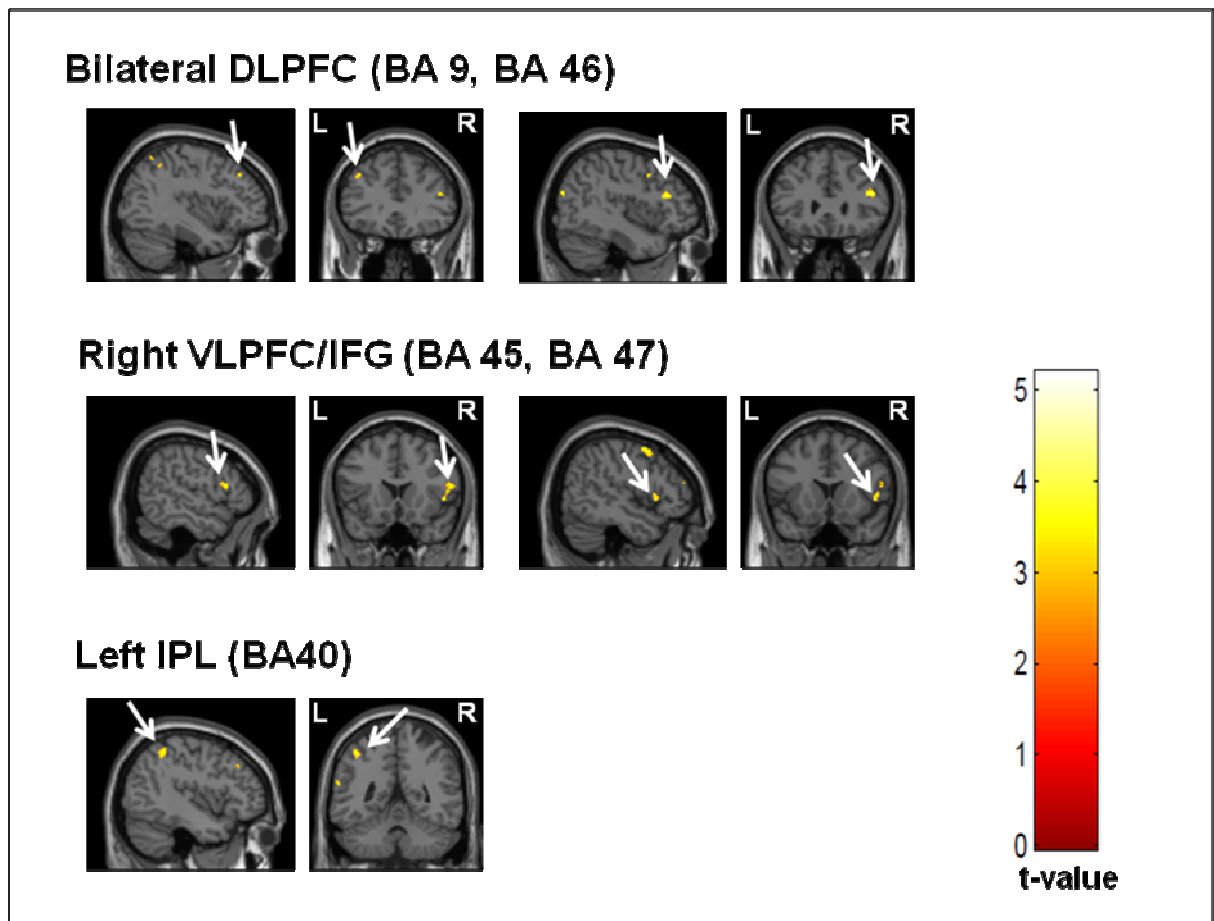
FIGURE 7.
The neural correlates of successful relational memory encoding in young adults with full attention.
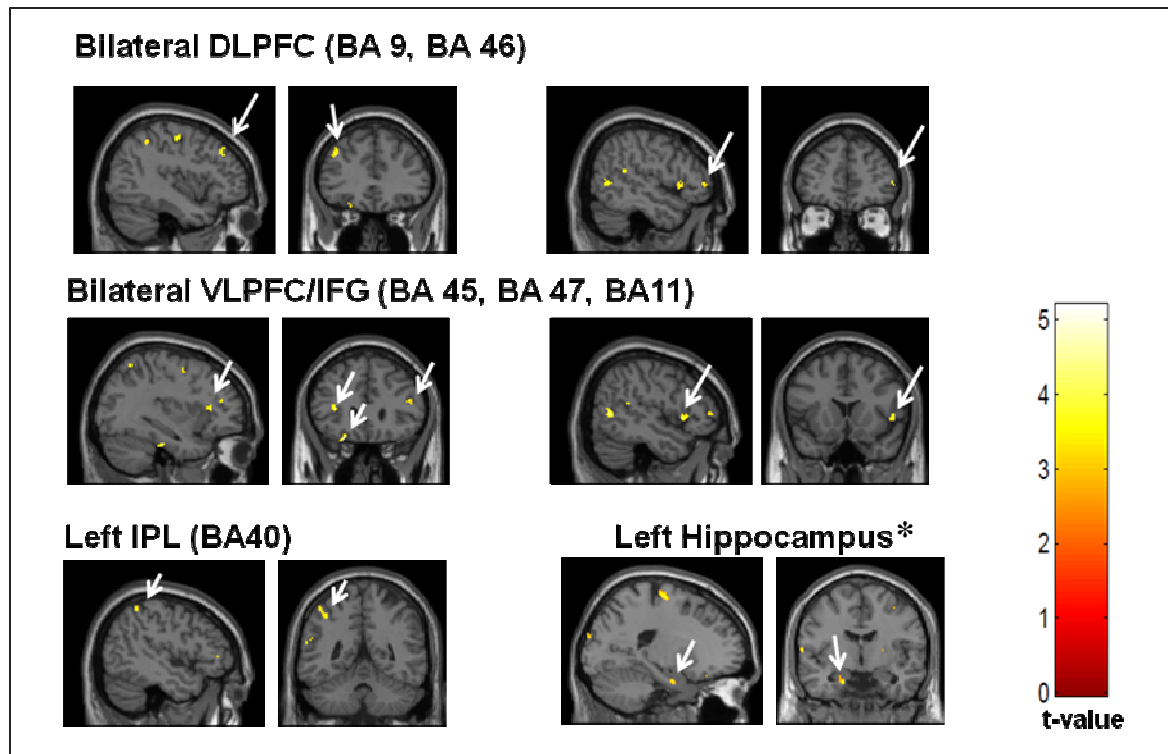
Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>10 (Note: * indicates k>5). DLPFC, Dorsolateral prefrontal cortex; VLPFC, Ventrolateral prefrontal cortex; IFG, Inferior frontal gyrus; IPS, Inferior parietal lobule; BA, approximate Brodmann area based on coordinates.
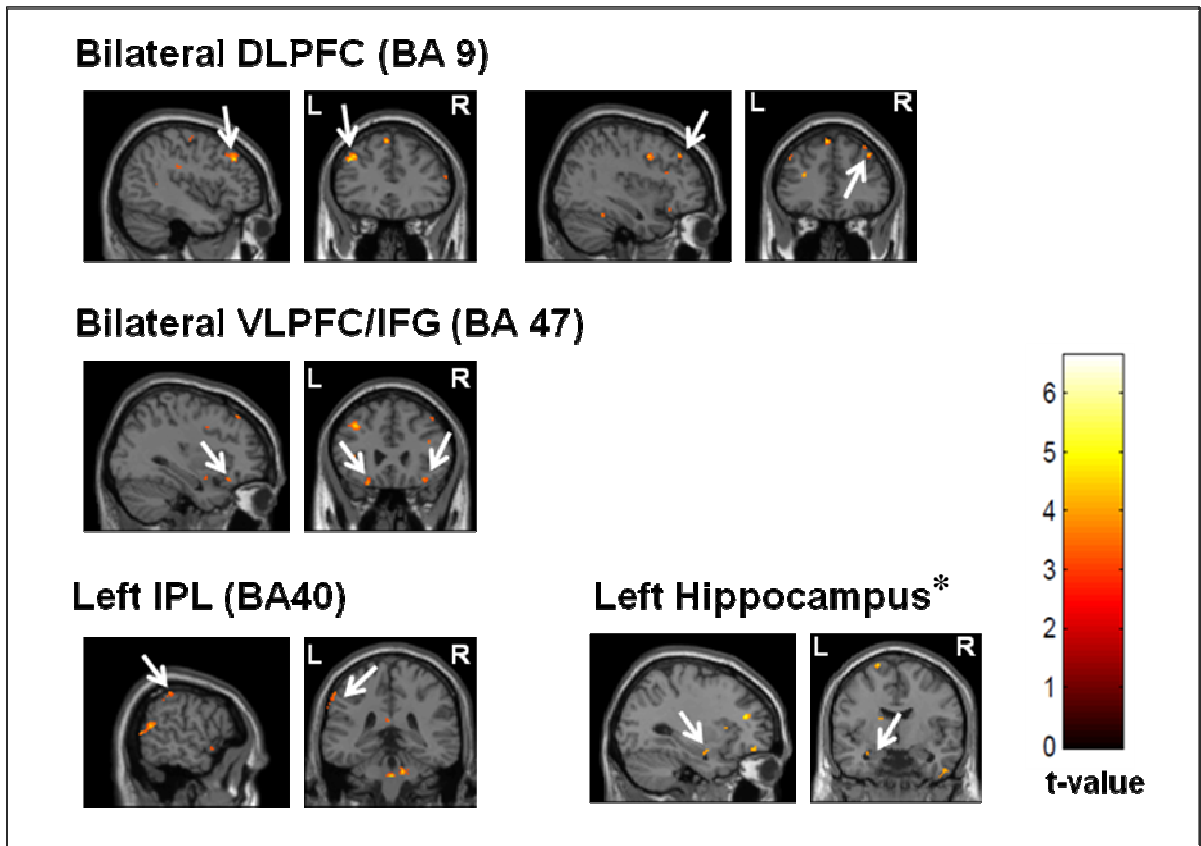
FIGURE 8.
Neural regions for successful relational memory encoding showing significant attenuations
with increased aging.

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>10. DLPFC,
Dorsolateral prefrontal cortex; VLPFC, Ventrolateral prefrontal cortex; IFG, Inferior frontal gyrus;
IPS, Inferior parietal lobule; BA, approximate Brodmann area based on coordinates.

FIGURE 9.
Neural regions for successful relational memory encoding showing significant attenuations with the reduction in relational attention in young adults.

Note: Regions significant at uncorrected p<.005 with a cluster extent threshold of k>10 (Note: * indicates k>5). DLPFC, Dorsolateral prefrontal cortex; VLPFC, Ventrolateral prefrontal cortex; IFG, Inferior frontal gyrus; IPS, Inferior parietal lobule; BA, approximate Brodmann area based on coordinates.

FIGURE 10.
Neural regions for successful relational memory encoding showing significant attenuations both by aging and by the reduction in relational attention in young adults.
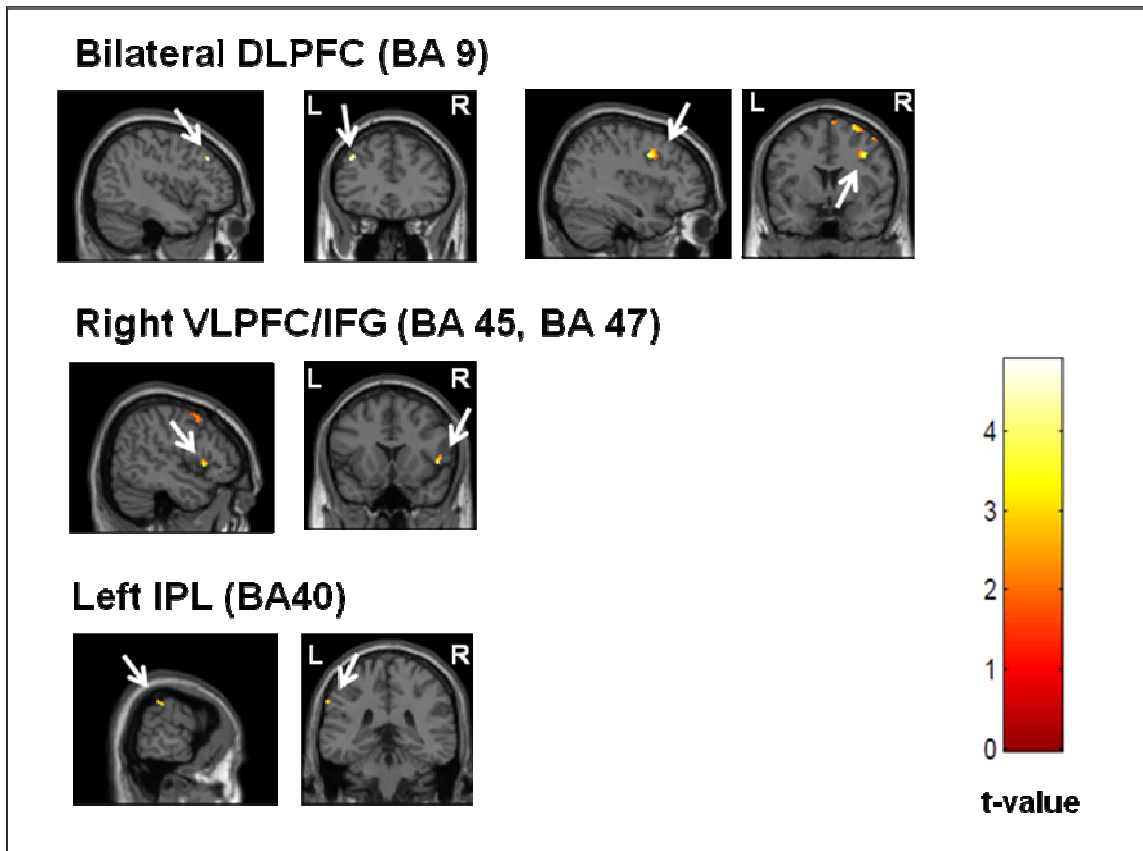
Note: Regions significant at the conjoint probability of p < .00025 (k>5) following inclusive masking (please see the text for more details on the procedure). DLPFC, Dorsolateral prefrontal cortex; VLPFC, Ventrolateral prefrontal cortex; IFG, Inferior frontal gyrus; IPS, Inferior parietal lobule; BA, approximate Brodmann area based on coordinates.

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