# Cognitive and Neural Correlates of Memory Retrieval in Young and Older Adults

by

Gail O'Kane

B.A., Political Science
Boston College, 1987

Submitted to the Department of Brain & Cognitive Sciences in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY IN NEUROSCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2004

Signature of Author ____________________
Gail O'Kane
Department of Brain & Cognitive Sciences
September 13, 2004

Certified by: ____________________
Suzanne Corkin
Professor of Behavioral Neuroscience
Thesis Supervisor

Accepted by: ____________________
Earl K. Miller
Picower Professor of Neuroscience
Chairman, Department Graduate Committee

# Cognitive and Neural Correlates of Memory Retrieval in Young and Older Adults

by

Gail O'Kane

Submitted to the Department of Brain & Cognitive Sciences
On September X, 2004 in partial fulfillment of the
Requirements for the Degree of Doctor of Philosophy
in Neuroscience

## Abstract

Older adults are impaired in episodic and semantic retrieval but the extent of these deficits and their neural correlates is unknown. In episodic memory, older adults appear particularly impaired in retrieving bound information, such as conjunctions of items or of an item and its context. These retrieval deficits, however, may be merely the downstream effects of poor encoding. **Chapter 1** presents a series of studies that test the theory that age-related recollection deficits are due to encoding failures. Results revealed that older adults were impaired in associative recognition when self-initiated processes were required at acquisition. Additional encoding support eliminated age differences, however, even when the retrieval task was made more difficult. The results support the hypothesis that recollection deficits are primarily due to poor encoding.

Although older adults with encoding support can retrieve information as well as young adults, it is an open question whether brain activity supporting retrieval is identical in the two groups. In past studies, greater left prefrontal activity has been observed in older adults even when their performance does not differ from young adults. However, the circumstances under which this pattern arises and its functional significance are still unknown. **Chapter 2** presents a functional magnetic resonance imaging (fMRI) study of associative recognition by young and older adults who performed equally well but who showed different patterns of recollection-related activity. Young adults exhibited greater activity in left inferior prefrontal cortex (LIPC) and inferior temporal/fusiform gyri for retrieval based on recollection relative to retrieval based on familiarity. In the same regions, older adults exhibit increased activity whenever recollection was attempted, independent of the level of recollection success. The results are consistent with the hypothesis that increased left-lateralized retrieval activity in older adults supports recollection attempt.

Age deficits in semantic memory are more subtle than in episodic memory. However, older adults are impaired when automatic, data-driven processes are not sufficient to support the retrieval of conceptual knowledge. The fMRI study described in **Chapter 3** used semantic repetition priming to test two theories of the role LIPC plays in semantic retrieval. Young adults exhibited repetition-related BOLD response reductions in LIPC that were specific to the particular semantic task engaged, consistent with the hypothesis that LIPC supports controlled semantic retrieval. Older adults, in contrast, exhibited repetition-related signal reductions even when the semantic judgment made about a word differed across the two exposures, consistent with the hypothesis that older adults fail to gate irrelevant semantic information from working memory during initial presentation of the word.

Thesis Supervisor: Dr. Suzanne Corkin
Title: Professor of Behavioral Neuroscience
Department of Brain & Cognitive Sciences

## Acknowledgements

Since entering the field of neuroscience six years ago, I have been awed by the kindness and generosity of friends and strangers in the scientific community. Busy lab mates were always willing to lend a hand whether for an early weekend morning scan or an evening of babysitting. Friends in Anthony Wagner's lab took me in as one of their own and shared their rich knowledge with me. Utter strangers responded to emails asking for help with technical problems or for clarification on fine points of theory.

I wish to thank the members of my thesis committee. In particular, I would like to thank my thesis adviser Suzanne Corkin, for giving me her constant support and the intellectual freedom to pursue the questions that inspired me. I thank her for collaborating with me on the first two chapters of this dissertation. I will always be grateful to her.

I also wish to express my appreciation for Anthony Wagner. In particular, I would like to thank him for giving me the opportunity to collaborate with him on the experiment described in Chapter 3. In the time I have known him, he has shared his wealth of knowledge and challenged me to be a better scientist on every level. I will always be grateful his intelligence, generosity, and patience.

Current and former colleagues have been a constant source of support and inspiration. I am particularly indebted to Elizabeth Kensinger for her keen insights on theory, methodology, and life. I also am incredibly grateful for Itamar Kahn, who lifted me over technical and programming hurdles on countless occasions. For the past two years, I was fortunate to have the support and friendship of Anne Krendl, who proved herself to be one of the kindest people I have ever met. Again and again, Keyma Prince went above and beyond the call of duty for me. I also appreciate the counsel and friendship of Olivier Piguet, Sarah Steinvorth, Silvia Bunge, Lila Davachi, and David Badre. I am grateful to Ellen Goodman for always being willing to help. And I thank Pat Tun of Brandeis University for being a mentor in work and in life.

Through MIT's UROP program, I was fortunate to be assisted over the years by some of the most talented young women I have ever met. I thank Christina Fuentes, Sarojani Sammy, Irit Rappley, Erica Richardson, Courtney Esinhart, Megan Lumb, and Ijeoma Ezeofor for their many contributions to the projects described in this dissertation.

I could not have completed any of my research without the selfless older adults who volunteered to participate in my experiments. They braved inner-city traffic, sometimes walking with canes, often suffering through arthritis and other ailments. They are the unspoken heroes of aging research.

Completing a dissertation with a baby in tow takes a village. More precisely, it takes a family. In my case, this includes my parents and brothers, and my husband's family, who have graciously made me a full-fledged member of their loving clan. In particular, I thank my mother, Millie Marion, and my sisters-in-law Corinne and Mary O'Kane for their missions of mercy, their love, and their kindness. I am grateful every day for my son, Jack: The hours of sleep lost were more than made up for by all the joy and laughter. Most importantly, my partner and best friend in every step has been my loving and talented husband, Dan O'Kane. He helped me in every way he could think of, and in more ways than I could ever say. He and Jack are the lights of my life.

**Table of Contents**

# Introduction

Memory retrieval failures are among the most prevalent cognitive deficits reported by older adults. While deficits in retrieval are often attributed to poor encoding (e.g., Anderson et al., 2000; Glisky et al., 2001; Mark & Rugg, 1998; Perfect, Williams, & Anderton-Brown, 1995), several lines of evidence suggest that older adults also may be impaired in the processes that support retrieval itself. For example, while divided attention at retrieval affects older and young adults' retrieval performance equally, older adults experience a greater cost in the secondary task, suggesting retrieval is more effortful for them (Anderson, 1998). Moreover, age-related retrieval deficits increase as environmental support decreases, with age gaps growing from recognition to cued recall to free recall (Ceci & Tabor, 1981; Craik, Byrd, & Swanson, 1987; Craik & McDowd, 1987; Schonfield & Robertson, 1966; reviewed in Craik & Jennings, 1992; but see Naveh-Benjamin, 2000, Experiment 4). While such a pattern could result from encoding failures (e.g., if older adults are creating impoverished memory traces sufficient to support recognition but not recall), it remains an open question whether there are retrieval-specific deficits in aging. At a neural level, older adults frequently exhibits patterns of retrieval-related activity that are different from those exhibited by young adults (Anderson et al., 2000; Bäckman et al., 1997; Grady et al., 1995, 2000; Madden et al., 1999; Schacter et al., 1996), even when performance is equated across the two age groups (Daselaar et al., 2003; Cabeza et al., 2002; but see Mark & Rugg, 1998).

Evidence also suggests that older adults experience deficits in semantic memory, even when the targeted knowledge was acquired before the onset of age-related encoding impairments. The pattern of deficits in this domain is even more subtle than in episodic memory. For example, while access to the names of even well-known people and objects is impaired, older adults nevertheless retain the meaning associated with even infrequently encountered words (e.g., Horn & Cattell, 1967). In fact, deficits seem to arise only when cognitive control processes are needed to constrain or facilitate retrieval. For example, when older adults are restricted by task requirements to list exemplars of a specific semantic category, such as animals, age differences arise in both strategies employed and overall output. Even when making classification decisions that don't rely on self-initiated recall, older adults are slower and less accurate than young adults to access the semantic features of named objects when automatic, data-driven processes are not sufficient to support retrieval (Badre & Wagner, 2002). Further, across a wide variety of tasks, older adults have been shown to access irrelevant semantic information to a greater extent than young adults (for review, see Hasher, Zacks, & May, 1999).

Age-related impairments in semantic and episodic retrieval observed in the laboratory have functional consequences for older adults. Deficits in linking the memory of a stimulus to a particular context can result in minor aggravations, such as forgetting where one last saw one's car keys, or more serious errors, such as mistaken identifications in eyewitness testimony (Memon et al., 2003). Impairments in filtering irrelevant semantic information from entering working memory spill over into other domains of cognition, resulting in impaired performance on such everyday tasks as language comprehension (Hartman & Hasher, 1991), reading (Connelly, Hasher & Zacks, 1999) and free recall (Tun, O'Kane, & Wingfield, 2002). Inhibitory deficits also have been shown to predict older adults' self reports of such cognitive failures as forgetting appointments, having difficulty making decisions, and being unable to find what one wants in a supermarket (Kramer et al., 1994).

A common feature of the deficits observed in episodic and semantic recall is their common reliance on cognitive processes mediated by prefrontal cortex. Neuroimaging studies have demonstrated age differences in patterns of prefrontal activation in episodic retrieval (e.g., Anderson et al., 2000; Cabeza et al., 2002; Daselaar et al., 2003) and semantic interference tasks (Milham et al., 2003; Langenecker et al., 2003). The most prevalent pattern of age differences that has been observed is increased bilaterality in prefrontal activations in older adults, though the functional significance of these activations is still not known. Neuropsychological studies also have tied frontal lobe dysfunction in older adults to a variety of impairments, such as category fluency (Tröster et al., 1989) and memory for the source or context in which an item was encountered (Craik et al., 1990; Schacter et al., 1991; Spencer & Raz, 1994).

The present series of studies aim to further characterize patterns of preservation and loss in episodic and semantic retrieval in normal healthy aging, and to identify patterns of age-related neural differences that occur independent of differences in task performance. Taken as a whole, these studies are more about how older adults succeed in retrieval than how they fail.

Specifically, the goals of the four experiments reported in this dissertation are: (1) determine the extent to which episodic retrieval failures are an emergent property of poor encoding or are due to failures in retrieval processes per se (Specific Aim 1); (2) investigate whether patterns of success in episodic retrieval differ across older and young adults when encoding procedures and performance are equated across age groups (Specific Aim 2); and (3) to investigate age-related differences in neural processes that support semantic retrieval, and possible sources of failures to gate irrelevant information during semantic retrieval (Specific Aim 3). These objectives are described more fully below.

Specific Aim 1: To determine the extent to which episodic retrieval failures are an emergent property of poor encoding or are due to failures in retrieval processes per se.

Specific Aim 1a (Experiments 1a and 1b): to develop encoding methods that allow older and young adults to perform equally well in associative recognition, a retrieval task that relies on recollection but does not require self-initiated target production.

Specific Aim 1b (Experiment 2): to determine whether retrieval impairments are revealed as task requirements are made more difficult. Encoding procedures developed in Experiment 1b were used to ensure material was well encoded by both young and older adults.

Specific Aim 2 (Experiment 3): To investigate whether older adults recruit different neural circuitry to support episodic retrieval when performance is equated across age groups. Functional MRI (fMRI) was used to determine which patterns of neural activation subserve success in high-performing older adults (i.e., those who achieve the same level of performance as young adults).

Specific Aim 3 (Experiment 4): To shed light on the role of prefrontal cortex in semantic retrieval and to test the hypothesis that older adults, through failures in inhibitory processes, show reduced specificity when accessing semantic information, as revealed by fMRI.

## References

Anderson, N. D., Craik, F. I. M., & Naveh-Benjamin, M. (1998). The attentional demands of encoding and retrieval: 1. Evidence from divided attention costs. Psychology and Aging, 13, 405-423.

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

Bäckman, L., Almkvist, O., Andersson, J., Nordbert, A., Winblad, B., Reineck, R., & Langström, B. (1997). Brain activation in young and older adults during implicit and explicit retrieval. Journal of Cognitive Neuroscience, 9, 378-391.

Badre, D., & Wagner, A. D. (2002). Prefrontal and medial temporal contributions to controlled semantic retrieval in cognitive aging. Proceedings of the Ninth Annual Meeting of the Cognitive Neuroscience Society.

Cabeza, R., Anderson, N. D., Locantore, J. K., McIntosh, A. R. (2002). Aging gracefully: Compensatory brain activity in high-performing older adults. NeuroImage, 17, 1394-1402.

Ceci, S. J., & Tabor, L. (1981). Flexibility and memory: Are the elderly really less flexible? Experimental Aging Research, 7, 147-158.

Connelly, S. L., Hasher, L., & Zacks, R. T. (1991). Age and reading: The impact of distraction. Psychology and Aging, 6, 533-541.

Craik, F. I. M., Byrd, M., & Swanson, J. M .(1987). Patterns of memory loss in three elderly samples. Psychology and Aging, 2, 79-86.

Craik, F. I. M. & McDowd, J. M. (1987). Age differences in recall and recognition. Journal of Experimental Psychology: Learning, Memory, and Cognition, 13, 474-479.

Craik, F. I. M., Morris, L. W., Morris, R. G., & Loewen, E. R. (1990). Relations between source amnesia and frontal lobe functioning in older adults. Psychology and Aging, 5, 148-151.

Craik, F. I. M., & Jennings, J. M. (1992). Human memory. In F.I.M. Craik, T.A. Salthouse (Eds.), The handbook of aging and cognition (pp. 51-110). Hillsdale, NJ: Erlbaum.

Daselaar, S. M., Veltman, D. J., Rombouts, S. A. R. B., Raaijmakers, J. G. W., Jonker, C. (2003). Neuroanatomical correlates of episodic encoding and retrieval in young and elderly subjects. Brain, 126, 43-56.

Glisky, E. L., Rubin, S. R., Davidson, P. S. R. (2001). Source memory in older adults: An encoding or retrieval problem? Journal of Experimental Psychology: Learning, Memory, and Cognition, 27, 1131-1146.

Grady, C. L., Bernstein, L. J., Beig, S., Siegenthaler, A. L. (2002). The effects of encoding task on age-related differences in the functional neuroanatomy of face memory. Psychology and Aging, 17, 7-23.

Grady, C. L., McIntosh, A. R., Horwitz, V., Maisog, J. M., Ungerleider, L. G., Mentis, M. J., et al (1995). Age-related reductions in human recognition memory due to impaired encoding. Science, 269, 218-221.

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

Hasher, L., Zacks, R. T., May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D Gopher & A Koriat (Eds.), Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application (pp. 653-675). Cambridge: MIT Press.

Horn, H. L., & Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. Acta Psychologica, 26, 107-129.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: beyond a unitary view of inhibitory processing in attention. Psychology and Aging, 9, 491-512.

Langenecker, S. A., Nielson, K. A., & Rao, S. M. (2003). FMRI of healthy older adults during Stroop interference. NeuroImage, 21, 192-200.

Madden, D. J., Turkington, T. G., Provenzale, J. M., Denny, L. L., Hawk, T. C., Gottlob, L. R., Coleman R. E. (1999). Adult age differences in the functional neuroanatomy of verbal recognition memory. Human Brain Mapping, 7, 115-135.

Mark, R. E., & Rugg, M. D. (1998). Age effects on brain activity associated with episodic memory retrieval: an electrophysiological study. Brain, 121, 861-873.

Memon, A., Bartlett, J. Rose, R., Gray, C. (2003). The aging eyewitness: effects of age on face, delay, and source memory ability. Journals of Gerontology B, Psychological Science, 58, P338-345.

Milham, M. P., Erickson, K. I., Banich, M. T., Kramer A. F., Webb A., Wszalek, T., Cohen, N. J. (2002). Brain and Cognition, 49, 277-296.

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: Tests of an Associative Deficit Hypothesis. Journal of Experimental Psychology: Learning, Memory, and Cognition, 26, 1170-1187.

Perfect, T. J., Williams, R. B., & Anderton-Brown, C. (1995). Age differences in reported recollective experience are due to encoding effects, not response bias. Memory, 3, 169-186.

Schacter, D. L., Kaszniak, A. W., Kihlstrom, J. F., & Valdiserri, M. (1991). The relations between source memory and aging. Psychology and Aging, 6, 559-568.

Schacter, D. L., Savage, C. R., Alpert, N. M., Rauch, S. L., & Albert, M. S. (1996). The role of the hippocampus and frontal cortex in age-related memory changes: a PET study. Neuroreport, 7, 1165-1169.

Schonfield, D., Robertson, B. A. (1966). Memory storage and aging. Canadian Journal of Psychology, 20, 228-236.

Spencer, W. E., & Raz, N. (1994). Memory for facts, source, and context: Can frontal lobe dysfunction explain age-related differences? Psychology and Aging, 9, 149-159.

Tröster, A. I., Salmon, D. P., McCullough, D., Butters, N. (1989). A comparison of the category fluency deficits associated with Alzheimer's and Huntington's disease. Brain and Language, 37, 500-513.

Tun, P. A., O'Kane, G., Wingfield, A. (2002). Distraction by competing speech in young and older adults listeners. Psychology and Aging, 17, 453-467.

# Chapter 1

# Recollection Impairments in Older Adults: A Memory Binding or Memory Search Deficit?

## Abstract

Age deficits in source recognition are frequently attributed to encoding failures. However, recollective tasks with greater memory search demands than source recognition may reveal age-related deficits in retrieval. In Experiment 1A, older adults' associative recognition performance benefited from imagery training but they still performed worse than young participants. In Experiment 1B, when imagery-inducing sentences were provided to increase support at acquisition, older and young adults did not differ in associative recognition, suggesting that age differences in this task primarily reflect encoding impairments. In Experiment 2 older adults who received encoding support performed as well as young adults in paired-associate cued recall, as well as associative recognition, suggesting that age-related impairments in recollection, even in tasks with heavy search demands, reflect failures in encoding rather than retrieval.

## Introduction

Older adults exhibit deficits when performing memory tasks that rely on controlled recollection, but are unimpaired on tasks that can be accomplished with relatively automatic familiarity-based processes. Recollection-specific age differences have now been observed in virtually every task that has been used to distinguish familiarity from recollection, including associative recognition (Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000), source recognition (Glisky et al.,1995; McIntyre & Craik, 1987; Schacter, Harbluk, & McLachlan, 1984), process dissociation (e.g., Caldwell & Masson, 2001; Jennings & Jacoby, 1993; Rybash & Hoyer, 1996), and remember/know (e.g., Parkin & Walter, 1992; Java, 1996, Norman & Schacter, 1997; Friedman & Trott, 2000). Despite this extensive research, however, it has yet to be determined whether the age deficit in recollection reflects a failure of encoding, retrieval, or both.

A critical characteristic of tasks that depend on recollection is that they require participants to acquire and retrieve connections between items or between items and their context. In a simple recognition task, which can be accomplished with familiarity alone, a participant need only remember whether an item, such as a word, was presented in the study set. In a typical source recognition task, in contrast, participants must remember the context in which each word appeared, such as the color of typeface in which it was printed. In an associative recognition task, participants study pairs of items, such as words, and then must determine whether pairs of old words presented at test are in the same or a different combination from that seen at study (Humphreys, 1976).

Accordingly, it has been hypothesized that the declarative memory deficit experienced by older adults is due at least in part to a failure to process information that must be bound (e.g., Chalfonte & Johnson, 1996; Mitchell et al., 2000a, 2000b; Naveh-Benjamin, 2000). To test this theory, Chalfonte & Johnson (1996) asked participants to study arrays of colored line drawings of objects. Even when older and young adults were equated on memory for the specific objects and the specific colors used in the study set (i.e., item memory), they were nevertheless impaired in an associative recognition task that required them to endorse pictures of objects only when shown in their studied color. Similarly, Naveh-Benjamin (2000) demonstrated that older adults were impaired at distinguishing intact from recombined word pairs, even when memory for the individual items was intact. These findings led Naveh-Benjamin to hypothesize that older adults' declarative memory deficit can be attributed to "their decreased ability to encode and retrieve associations among units of information or attributes within events" (Naveh-Benjamin, 2000, p. 1183). Because both of these studies failed to distinguish encoding from retrieval failures, however, it is equally plausible that age-related differences in associative recognition tasks, as with source recognition, reflect solely an encoding failure. That is, age differences in retrieval may occur because older adults never formed the associations from the outset.

A study by Glisky and colleagues (2001) concluded that age-associated impairments in one type of recollective task, source memory, are the result of encoding failures. In that study, age-related differences in source memory retrieval were eliminated when incidental encoding instructions were used to encourage participants to attend to the relation between study items and their context at the time of acquisition. The finding was consistent with the more general theory that older adults benefit disproportionately from environmental support because they engage self-initiated processes less efficiently than young adults, as the result of a deficiency in available processing resources, (Craik, 1986, 1994).

According to several dual-process models, however, recollection is distinguished from familiarity by differential processing demands during retrieval. In particular, tasks that depend on recollection, unlike those that can be accomplished by familiarity-based processes alone, engage active search processes during retrieval (Atkinson & Juola, 1973, 1974; Mandler, 1980). In the case of source recognition, search requirements are highly constrained, because such tasks are posed as multiple-choice problems, with participants choosing between as few as two response options. This type of construct has been referred to as a many-to-few mapping, with many items mapped to only a few possible contexts. In the task used by Glisky and colleagues (2001), for example, participants decided which of two rooms a chair had been pictured in at study. Although participants may have had to search their memory for details to aid in selecting a response, the response options themselves were provided to them. Thus, while age differences in source recognition appeared to results from impaired encoding, recollective tasks with more demanding search requirements could still reveal deficiencies in retrieval.

Associative recognition, like source memory, depends on recollective processes (Hockley & Consoli, 1999; Westerman, 2001; Yonelinas, 1997) and tests participants' ability to create and retrieve associations. Unlike the many-to-few mappings of source memory tasks, associative recognition tasks use unique one-to-one mappings. At study, participants view uniquely paired items, such as words (e.g., TIGER-LEAF and FLOOR-CLOUD). At test, participants must decide whether pairs presented to them are either intact (e.g., TIGER-LEAF) or recombined (e.g., TIGER-CLOUD). Participants can reject recombined pairs on the basis of a lack of recollection: They don't remember encountering the words paired as such, so by "default" they deem the pair recombined (Yonelinas, 1997). Past research has shown, however, that participants frequently use a recall-to-reject strategy when faced with recombined pairs (Rotello, Macmillan, & Van Tassel, 2000). That is, rather than simply rejecting TIGER-CLOUD because it is an unfamiliar pairing, they *recall* which word(s) TIGER and/or CLOUD were paired with at study. If different than the pair presented, they will *reject* the presented pair as being intact and identify it instead as recombined. Because the criterial target information (i.e., the word(s) initially paired with the words that now constitute the test pair) is not provided to participants as an answer option, they must initiate an extended search of memory if they are to use the recall-to-reject strategy.

A recent study compared associative recognition performance in older adults, young adults retrieving under full attention, and (in an attempt to mimic the attentional deficits associated with aging) young adults retrieving under divided attention (Castel & Craik, 2003). Older adults operating under full attention performed similarly to young participants under divided attention, and both groups performed worse than young adults performing under full attention. However, it is unknown whether the traces acquired at encoding were equivalent across the two age groups. Thus, the rationale of the current study was to examine whether it was possible to boost older adults' performance to the level of young adults' by providing encoding support.

The goal of the current study was to determine the extent to which the age deficit in recollection reflects impairments in encoding or, alternatively, retrieval. First, using the rationale employed by Glisky and colleagues (2001), we examined the effects of encoding support. If encoding support were to eliminate age differences in associative recognition, we would conclude that the differences were due to older adults' failure to fully engage those cognitive and/or neural processes capable of supporting acquisition. Second, if encoding support were to eliminate age differences in paired-associate recognition, we would then examine the effect of boosting retrieval demands by employing a paired-associate recall task, in which an extended search of memory would be obligatory for successful performance.

Several measures were used to assist older adults at the time of encoding. First, they were encouraged to use visual mediation to link the words in each study pair. Imagery is an effective technique for paired-associate learning (Paivio, 1971). Older adults benefit disproportionately from instructions to use imagery to bind pairs, although even with this advantage age differences may remain (e.g., Hulicka and Grossman, 1967).

Second, we used incidental as opposed to intentional encoding instructions. In previous studies that used visual mediation as a study aid, participants received traditional intentional encoding instructions. That is, at study, they were told to try to memorize the material for a subsequent test. An alternative method is incidental encoding, in which participants perform a task that supports acquisition but are unaware that they will later be tested on their memory for the studied material. A recent functional magnetic resonance imaging (fMRI) study found that BOLD responses in regions that support deep semantic encoding were more similar in young and older adults when incidental instructions were used (Logan et al., 2002). Thus, the imagery task was described to older adults through incidental encoding instructions, in an attempt to further close the gap in performance between older and young adults.

In addition, because older adults experience cognitive slowing (Cerella, 1985; Myerson et al., 1990; Salthouse, 1991, 1996), they can benefit when they receive additional time to perform a task, or when the task is self-paced (Canestrari, 1968; Craik & Rabinowitz, 1985; Treat & Reese, 1976). Thus, unpaced study trials or long study trial durations were used to ensure that age deficits did not reflect lack of time to complete processes that support successful performance.

The present study aimed to determine whether encoding support was sufficient to eliminate age differences in recollection, even when retrieval required an extended search of memory. Experiment 1A compared associative recognition performance by young and older adults who received encoding support through incidental encoding instructions, coupled with imagery training, to a control group that received standard intentional encoding instructions, with no guidance on encoding techniques. Experiment 1B compared the performance of older and young adults who received additional encoding support through incidental encoding instructions and reading imagery-inducing sentences. Experiment 2 tested whether older adults would perform worse than young adults on a paired-associate cued recall task, which required a self-initiated search of memory, even when equivalent performance on the associative recognition task suggested to-be-recalled word pairs had been successfully bound.

## Experiment 1A:

## The Effect of Encoding Support on Associative Recognition Performance in Young and Older Adults

The design used in Experiment 1A was similar to that used by Glisky and colleagues in their source memory study (2001) to help older adults attend to conjunctive information in to-be-learned stimuli. Specifically, (a) participants received instruction on how to create images that bound information from the two words in the to-be-studied pair, and (b) no mention was made of a subsequent memory test. A separate, control group of young and older adults received no imagery training and were simply told to study the pairs for a later test.

## Methods

Participants. We enrolled 40 young adults and 40 healthy, community-dwelling older adults in accordance with procedures approved by the MIT Committee on the Use of Humans as Experimental Subjects (Table 1). An equal number of young and older adults were assigned randomly to one of two experimental groups: a supported-encoding group and an unsupported-encoding group.

Table 1. Experiment 1A Participant Characteristics.

| | **Young Adults** | | **Older Adults** | |
|---|---|---|---|---|
| | Supported Encoding M(SE) | Unsupported Encoding M(SE) | Supported Encoding M(SE) | Unsupported Encoding M(SE) |
| Age | 21.8(0.7) | 21.4(0.9) | 72.5(1.1) | 70.7(1.1) |
| Education | 15.0(0.4) | 15.6(0.3) | 17.3(0.5) | 17.6(0.4) |
| Vocabulary | 56.1(1.4) | 55.0(1.6) | 58.4(1.4) | 59.0(1.4) |
| Forward digit span | 7.5(0.3) | 7.4(0.3) | 7.2(0.3) | 7.1(0.3) |
| Backward digit span | 6.2 (0.3) | 5.8(0.4) | 5.3(0.3) | 5.7(0.4) |

Materials and design. The experiment was a 2 X 2 X 3 factorial design with age (Young, Old) and encoding condition (Supported, Unsupported) as between-participants factors, and pair type (Intact, Recombined, New) as a within-participants factor. Participants were tested individually at the Massachusetts Institute of Technology with sessions lasting approximately 90 to 135 min, depending on how much time each participant spent on the encoding task.

We used 20 unique study and test lists, such that only one participant in each of the age groups and encoding groups received each list. A large number of encoding items —108 pairs presented in 3 blocks of 36 pairs — were presented to each participant to avoid ceiling effects in young adults.

Procedure. Because pilot testing revealed attentional fatigue from the imagery task when the encoding blocks proceeded uninterrupted, a distractor task (i.e., judging the familiarity of celebrities depicted in photographs) was introduced during rest periods presented after each third of the encoding trials. This procedure also ensured that a filled delay of 3-5 min would separate the end of the encoding phase and the beginning of the test phase.

The assistance provided to the supported-encoding group included training on the creation of interactive images and the use of incidental encoding instructions, in which participants were given a task that supports encoding but were not informed there will be a subsequent memory test. Participants in the supported-encoding group were told that they were participating in an experiment that investigated the relation between imagination and assessment of familiarity of celebrity faces. In the famous faces distractor task, after each of the three blocks of 36 encoding trials, participants rated the familiarity of 24 actors or politicians using a 5-point scale. For the encoding task, participants were instructed about how to generate interactive images, and how to rate the quality of the resulting images using a 3-point rating system. Participants were told they would not have to draw the images but rather just mentally visualize them. Training began with the presentation of three word pairs, and drawings of potential images that participants could create from them. For example, in training, participants were given the pair "GEESE-LIMOUSINE". They were then shown three images. The first portrayed a goose standing apart from a limousine, not interacting. They were told this image would represent the failure to create an interactive image and should be rated as a "1". They were then shown a picture of a limousine with geese standing on top of it, and told that this would be rated as a "2," reflecting a weak or awkward image. They were then shown a picture of a limousine driven by a goose, with a gaggle of geese as passengers. This version they were told would be rated a "3." After viewing two other example pairs, participants described images for six practice pairs. The experimenter recorded the description of each image in writing and provided participants with a rating for each response, to help calibrate their rating scale to that of the experimenter, and thus to other participants' as well. After these practice pairs, participants received 12 additional word pairs. They described the images and independently rated them. The images and rating were recorded by the experimenter, who gave feedback to the participants on the appropriateness of the rating for each image described. These 12 images and ratings were later submitted to independent raters who were blind to the age of the participants who generated them. These reliability ratings were obtained to ensure that older and young adults could consistently produce interactive images, and to verify that participants could rate images accurately. To limit the amount of time required to complete the encoding block, none of the images produced during the encoding trials was recorded: Participants visualized images silently and recorded ratings unobserved.

Participants in the unsupported-encoding group were told that they would be studying word pairs in preparation for a memory test that would follow immediately. The nature of the associative recognition task was also explained to them. As with the supported-encoding group, they completed the famous faces distractor task during three break periods. In addition, they also produced a rating at the end of each encoding trial, but the ratings were based on their confidence that they would correctly recognize pairs at test, with "1" representing low confidence, "2" moderate confidence, and "3" high confidence.

The encoding trials were self-paced, with the constraint that a minimum study time was imposed for each of the two unsupported-encoding groups (i.e., the young and older groups) based on the average time required for each age group to create an image under incidental encoding conditions in pilot testing. These minimum study times ensured that if the supported-encoding group outperformed the unsupported-encoding group, it would not be due to mere differences in encoding time. Because pilot testing showed that it took older adults much longer than young adults to create an image, the young supported-encoding group was required to study each item for at least 12 sec, and the older group for at least 21 sec.

During the recognition phase, participants were shown 108 test pairs, with equal numbers of intact, recombined and new items. They pressed one of three keys to indicate whether each pair was intact, recombined, or new. They were told that intact pairs would include two studied words paired exactly as they were at study, recombined pairs would contain two studied words presented in a pairing not shown at study, and new pairs would consist of two new words, neither of which had been presented during the study phase.

At both encoding and test, words were presented in uppercase white text on a black computer screen in 40-point font; words within a pair were presented in a vertical column separated by a plus sign. Each word retained its position above or below the plus sign at both study and test.

## Results

Differences were considered reliable if significant at the $\underline{p}<.05$ alpha level (two-tailed).

### Encoding Results

Supported-encoding group. The average time used by older adults in the supported-encoding group to form and rate an image was 19.8 sec, compared with 10.0 sec for young adults. The mean rating for the quality of images generated during encoding was slightly higher for young adults (2.77 out of 3) than older adults (2.62), $F(1,38)=4.12$, $p<.05$.

Because the scale used by participants was subjective, it is possible that the two age groups were differentially biased to give their images higher or lower scores. Thus, to verify the reliability of the self-reported ratings, descriptions of the images generated from 12 practice word pairs by each participant were rated independently by three raters. To determine whether the participants' ratings conformed to those given by the independent raters, an ANOVA was conducted with Source of Rating (Participant, Rater) as a within-subjects variable and age group (Young, Older) as a between-subjects variable. The average rating assigned by the independent raters did not differ from the participants' self-reported ratings for those same practice items, $F(1,38)=2.41$, $p>.10$. Moreover, the ratings assigned by the raters and participants did not differ as a function of Age Group, $F(1,38)=0.18$,$p>.60$. Further, Age Group did not interact with the Source of Rating, $F(1,38)=0.74$, $p>.30$, indicating that the difference between the blind raters' and participants' ratings was no greater for older adults than young adults. Thus, this analysis suggests that young and older participants were using the same relative scale to assess the quality of their images.

## Unsupported-encoding group

Chi-square tests compared the distribution of confidence ratings within participants and across the two age groups. Overall, participants were more likely to express moderate confidence that they would remember items at test, than they were to express either high or low confidence, both p<.05, but young and older adults did not differ in the distribution of their confidence ratings across the three categories, F(2)=2.03, p>.10 (Table 2).

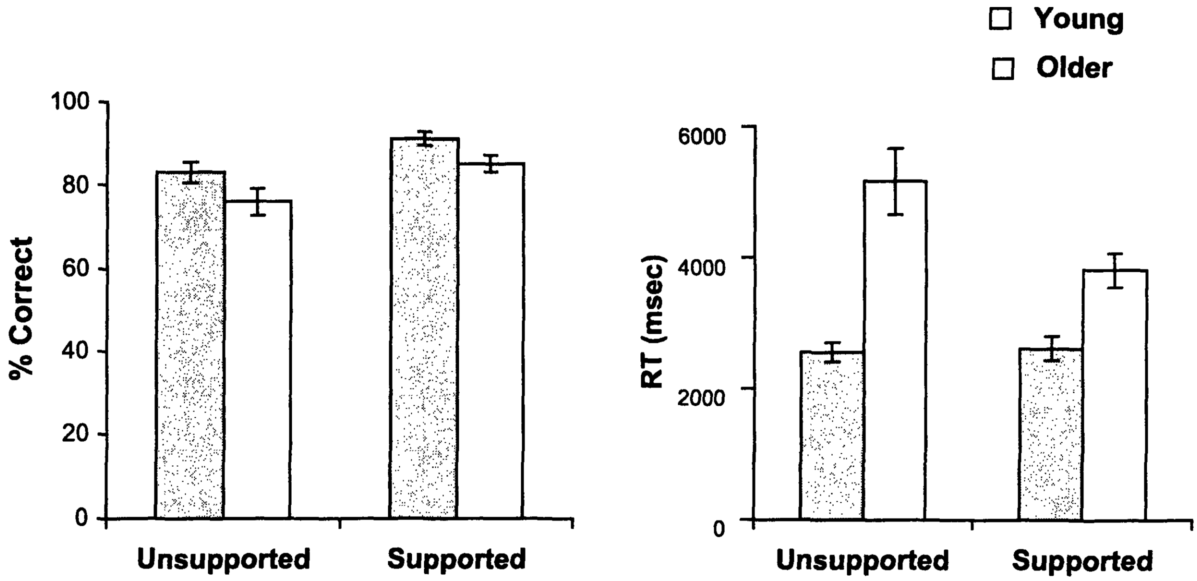
Table 2. Experiment 1A. Mean Number of Pairs Allocated to Each Rating Category During Study in Each Age and Encoding Group.

| **Group** | **No. Ratings Received in Each Category** | | |
|---|---|---|---|
| **Supported Encoding** | **Poor/No Image** | **Good Image** | **Very Good Image** |
| Young | 1.3 | 22.45 | 84.15 |
| Older | 6.4 | 28 | 73.55 |
| **Unsupported Encoding** | **Low Confidence** | **Moderate Confidence** | **High Confidence** |
| Young | 36.75 | 40.95 | 30.15 |
| Older | 50.35 | 37.25 | 20.3 |

Retrieval Results

Accuracy. Participants showed a slight bias to identify pairs as recombined items, as shown by a nonsignificant trend, F(2,38)=2.64, p=.08, but this trend did not differ as a function of Age Group, F(2,38)=1.66, p>.10, or Encoding Group, F(2,38)=.74, p>.40. Thus, accuracy was scored as the raw percentage correct across all pair types. An ANOVA was conducted with Encoding Group (Supported, Unsupported) as a random-effects variable and Age Group (Young, Older) as a fixed-effects variable. Overall, accuracy was marginally higher in young relative to older adults, F(1,38)=132.64, p=.06, and significantly higher in the supported encoding group relative to the unsupported group, F(1,38)=236.91, p<.05 (Figure 1A). These factors, however, did not interact, F(1,76)=0.06, p>.80, indicating that accuracy in young adults and older adults benefited equally from the encoding manipulation. However, while the age difference was only marginal in the intentional encoding group, F(1,38)=3.32, p=.08, in the incidental encoding group, the young adults were significantly more accurate than the older adults, F(1,38)=5.69, p<.05.

**Figure 1.** (A) Percentage correct in associative recognition averaged across intact, recombined, and new trials (±SEs) by age and encoding group in Experiment 1A. (B) Response latencies.



Not surprisingly, the older adults were slower to respond at test than were the young participants (Figure 1B). Unlike with accuracy, there was a significant interaction between Age Group and Encoding Group, F(1,76)=5.37, p<.05, reflecting the fact that older adults in the incidental encoding group responded more quickly than their age counterparts in the intentional encoding group, F(1,38)=5.37, p<.05, while response times were equivalent for young adults across the two encoding groups, F(1,38)=0.08, p>.70. Nevertheless, young adults were faster than the older participants to respond in both the intentional, F(1,38)=109.08, p<.001, and incidental encoding groups, F(1,38)=13.68, p<.002.

## Discussion

Older and young adults benefited from support provided at encoding. As a result, young adults outperformed older adults in both the supported and unsupported encoding conditions. While the accuracy benefit afforded by encoding support was equivalent in young and older adults, the response time difference between the two encoding groups was larger for older adults than young adults. This result suggests that encoding support disproportionately reduced the amount of effort required for successful performance at test for the older individuals.

Nevertheless, unlike the results obtained by Glisky and colleagues (2001) in a source recognition task, the encoding support provided in this associative recognition task did not eliminate age differences in retrieval accuracy. While one must be circumspect about drawing conclusions across different studies, it is worth considering what the source of the discrepant findings may be. One possibility is that the different results are due to differences in the *retrieval* demands of the two tasks. The redundancy in encoding contexts across trials could potentially result in cue overload, making source memory retrieval more complex than associative recognition. The redundancy, however, also could serve to constrain and simplify retrieval strategy. During a source recognition task, participants are exposed to an item in one of a handful of situations (e.g. a word printed in red or blue type, or in the case of Glisky et al., 2001, a chair pictured in one of two possible rooms). Thus, the context response options that participants must weigh are explicitly stated in the task. In contrast, the words with which a word may have been re-paired in our associative recognition test numbered in the hundreds and were semantically unconstrained. If participants were using a "recall-to-reject" strategy to determine which word pairs were recombined (Rotello et al., 2000), the search of memory may have demanded the type of self-initiated processing believed to be problematic for older adults (Craik, 1983, 1986).

Alternatively, the difference in result between the current task and the findings of Glisky et al. (2001) may have reflected differences in the *encoding* demands between associative and source recognition tasks. Specifically, the encoding support provided in the present experiment may not have been as successful as Glisky and colleagues' in equating encoding processes between young and older adults, because of differences in the demands of the two tasks. While performance in both tasks relied on successful acquisition of conjunctions of information, the possible conjunctions to be acquired were much more constrained in the source recognition task (Glisky et al., 2001). Thus, once provided with the heuristic of judging the degree to which each chair belonged in the room shown in the study picture, one could use that heuristic successfully on each trial. In contrast, creating a salient conjunction between randomly paired words relies much more on self-initiated, trial-specific solutions, which could prove difficult for older adults (Craik, 1983, 1986). Older adults took approximately twice as long as young adults in the supported encoding group to generate salient interactive images, suggesting that they had greater difficulty performing the encoding task. The wide gap in latencies suggests that the overall experience in the current study may have been qualitatively different for young and older adults. First, the task may have demanded more cognitive resources for elaboration, potentially leaving fewer resources available to consolidate and bind the two words. Second, due to encoding time differences, older adults may have been more fatigued at test than were young adults. Consistent with this, the images generated by older adults in the supported encoding group during the practice session were as vivid as images generated by younger adults, as judged and rated both by the participants and by blind raters. However, older adults gave lower ratings to the images generated during the encoding session, perhaps because they were less successful in generating images as they became more fatigued. Third, because the encoding session was longer for older than young adults, the former experienced a greater delay between initial encoding and test for many of the words in the study set. Fourth, based on the participants' own ratings, the images generated by older adults during the encoding trials were perhaps not as rich as those generated by the young adults.

To address these problems, in Experiment 1B, only supportive encoding was used and rather than requiring participants to develop a concept to link the two words on each trial, the concept was provided to them in the form of a sentence. Past research has shown that older adults benefit disproportionately when enriched encoding cues are provided to them at study (Park, Puglisi, & Smith, 1986; Rankin & Collins, 1985). Further, this approach made it possible to (a) equate the two age groups more closely in encoding time and (b) ensure that the image being elaborated on did not differ between young and older adults. To preclude the possibility of ceiling effects in this enriched encoding environment, the task was made more difficult by more than doubling the number of items studied and by imposing a 45-min delay between study and test. In addition, no new-word test pairs were included so that a corrected recognition score could be computed (i.e., by subtracting false alarms to recombined pairs from intact hits) to control for possible differences in response bias among older and young adults.

## Experiment 1B:

## Comparison of Young and Older Adults in Associative Recognition Under Reduced Encoding Demands

## Methods

Participants. We enrolled 18 young adults (age 18-28, M=21.3, SE=0.8) and 18 older adults (age 60-82, M=74.5, SE=1.9), all of whom were recruited according to procedures approved by the MIT Committee on the Use of Humans as Experimental Subjects. The older adults had completed more years of schooling (M=17.4) than the young adults (M=15.4), many of whom were still undergraduate students at the time of testing, $F(1,34)=11.99$, $p<.01$.

Materials and Design. We developed a study list of 240 word pairs. All of the words were highly imageable concrete nouns. Words were paired randomly, and sentences were constructed that used the two words to elicit an interactive image. Of the 240 encoding pairs, 80 were presented intact at test, and one word from each of the remaining 160 were re-paired to create 80 recombined test pairs.

Procedure. As in Experiment 1A, participants performed blocks of encoding trials followed by the famous faces task described above. In that experiment, however, participants rated 24 faces after each of three 36-word pair encoding blocks, while the participants in this experiment rated 12 faces after each of six 40-word pair encoding blocks.

In each encoding trial, the two study words were presented in the center of the screen in a vertical column separated by a fixation cross. Below the pair, the corresponding imagery sentence was displayed simultaneously. This display was shown for 6 sec, followed by an enforced visualization period of 6 s for young adults and 8.5 sec for older adults. Additional time was allotted to older adults for visualization because past research has shown that although older adults can generate a complex image as well as young adults, the process of creating it takes older adults longer (Dror & Kosslyn, 1994). At the end of each word-pair presentation, participants were prompted to rate how successful they were at generating a visual image from the sentence using a 1 to 5 scale. They were also told that the goal was to generate as high a score as possible for each word pair by working to create a vivid image and holding it online until they received the prompt to provide a rating. The intertrial interval was 2 sec.

A 45-min unfilled delay period followed. After the delay, participants performed the surprise associative recognition test. Unlike Experiment 1A, all word pairs presented at test were either intact or recombined pairs; no new-word pairs were presented. In addition to identifying whether a test pair was intact or recombined, participants indicated the basis for their decision using a remember/know (R/K) distinction. Instructions regarding this distinction were identical to those used by Gardiner and Java (1990, p. 25), except for minor changes made to reflect the use of test pairs rather than individual words. Specifically, participants were told that test pairs should receive "remember" responses if the participant remembered the original image learned at study. Additionally, for recombined items, participants were instructed to respond "remember" only if they recalled the original word with which either of the two test words was paired. Each participant performed two practice trials with feedback to further clarify the difference between "remember" and "know" responses. Participants pressed one of four keys to indicate their response as (1) Intact-Remember, (2) Intact-Know, (3) Recombined-Remember, or (4) Recombined-Know. We imposed no time limit for responding.

## Results

Because new pairs were not used, we were able to calculate accuracy by adopting the method traditionally used to correct for response bias in tests of associative recognition (i.e., intact hits minus recombined false alarms). The results revealed that older and young adults did not differ in accuracy, F(1,17)=1.63, p>.20 (Figure 2).

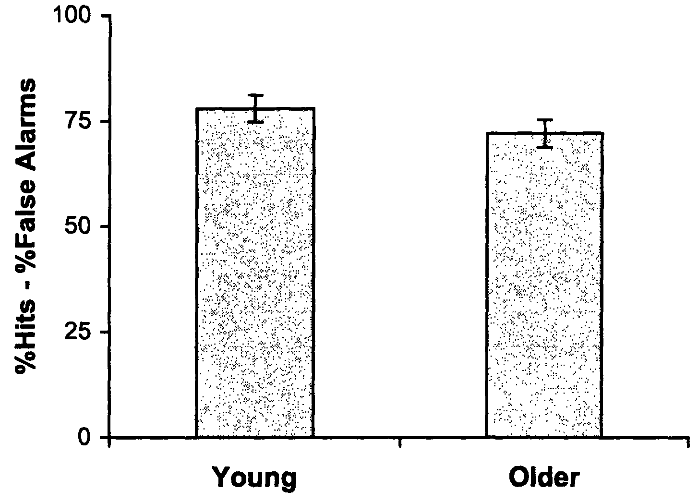


**Figure 2.** Experiment 1B. Corrected associative recognition scores (±SEs) by age group.

It is possible that older and young adults did not differ in associative recognition performance, but still based their responses on qualitatively different information. Thus, we analyzed accurate associative recognition trials to determine whether the pattern of "remember" and "know" responses differed as a function of age group for either intact or recombined pairs. A mixed-effects ANOVA was conducted with Response Type (Remember, Know) as a within-participants variable and Age Group (Young, Older) as a between-participants variable for intact and recombined pairs. The number of items based on "remembering" did not differ as a function of age group for either intact or recombined pairs, both F<1 (Table 3).

We did not analyze reaction times because it could not be determined how much time was allotted to deciding whether the pair was intact or recombined versus how much to the remember/know distinction.

Table 3. Experiments 1B and 2. Proportion of Correct Associative Recognition Responses Designated as "Remembered."

| | Young Adults M(SE) | Older Adults M(SE) |
|---|---|---|
| **Experiment 1B** | | |
| Intact | .87(.06) | .86(.04) |
| Recombined | .56(.06) | .50(.10) |
| **Experiment 2** | | |
| Intact | .92(.02) | .95(.02) |
| Recombined | .57(.05) | .48(.06) |

## Discussion

In Exeriment 1B, when participants received a high degree of encoding support that simultaneously used incidental encoding and eliminated the need for self-initiated study strategies, older adults performed as well as young adults in an associative recognition task. These results lend support to the finding by Glisky et al. (2001) that age differences on some recognition tasks that rely on recollection reflect age-related encoding deficits resulting from older adults' failure to initiate successful encoding strategies. While instruction to attend to contextual information was sufficient to eliminate age differences in a source recognition task, however, directing participants to attend to item-item information alone was not sufficient to eliminate age differences in associative recognition, as shown in Experiment 1A. Thus, the failure to attend to conjunctive information is not the only barrier older adults experience in binding information that supports recollecting; older adults also appear to have difficulty initiating processes that help bind disparate item-item information.

Although older adults can perform simple source and associative recognition tasks well when encoding support is provided, it remains an open question whether age-associated impairments in retrieval would be revealed if requirements for memory search were made even more demanding. We conducted Experiment 2 to address this question.

## Experiment 2:

## Comparison of Cued Recall and Associative Recognition Performance in Young and Older Adults

Past studies have shown that age deficits are greater in recall than recognition (Craik, 1986; Craik, Byrd, & Swanson, 1987; Craik & McDowd, 1987; Rabinowitz, 1984, 1986; Schonfield & Robertson, 1966). Thus, encoding support may allow older adults to perform even the most difficult of recognition tasks well, but deficits in retrieval processing may, nevertheless, be revealed when self-initiated access is obligatory, as is the case with recall. In Experiment 2, we compared the performance of young and older adults in two tasks: associative recognition and paired-associate cued recall. In one prior study in which older adults had been coached to use imagery, older adults had performed a paired-associate cued recall task as well as young adults in trials where increased study time was allowed (Treat & Reese, 1976). The critical question in the current study was whether the gap between associative recognition and cued recall performance would be greater for older than young adults. The rationale was that if the age groups performed equally well on the associative recognition task, as in Experiment 1B, it would demonstrate that they had succeeded in binding the word pairs; any age difference observed in cued recall could then be attributed to difficulties in retrieving those bound representations.

In addition to the associative recognition and paired-associate recall tasks, participants completed a number of standardized cognitive tasks during the delay between encoding and retrieval. The rationale for administering these tests was (a) to use a filled delay to further ensure that ceiling effects were not obtained; and (b) to demonstrate that the older adults did perform worse than the young on some tests of memory and cognition, so that a failure to find age differences in associative recognition and/or paired-associate recall could not be attributed to the possibility that the older adults were super-performers.

## Methods

Participants. We enrolled 20 young adults (age 18-28, M=21.5, SE=0.7) and 23 older adults (age 61-82, M=70.6, SE=1.3), using the same recruitment procedures as for the earlier experiments. The older adults had completed more years of schooling (M=17.7) than the young adults (M=14.5), F(1,38)=25.74, $p<.001$, but the older (M=58.9, SE=1.2) and young adults (M=59.0, SE=1.1) did not differ in verbal intelligence as estimated by the Vocabulary subtest of the WAIS-III (Wechsler, 1997), F(1,38)<1. Only participants with a Mini-Mental Status Examination score of 26 or above were eligible for inclusion. Of the 23 older participants, 3 were excluded because they were unable to understand or follow instructions.

Materials and Design. We developed study list using five sets of 24 word pairs. The five sets did not differ in word frequency, imageability, concreteness, or word length. Participants viewed the resulting 120 word pairs in randomized order at study.

We created five versions of the test list of 96 word pairs using the five sets of word pairs from the study session. In each test list, 48 of the study pairs were re-used as paired-associate recall items; 24 were used as intact associative recognition items; and one word from each of the remaining 48 studied pairs was used to form 24 recombined associative recognition items. Across participants, each word was shown equally often in either an intact associative recognition pair, a recombined associative recognition pair, or a cued recall pair. Test trials were presented in two blocks with half of participants in each group receiving the paired-associate recall block first, and the other half receiving it last.

In addition to the word lists, the same pictures of famous faces were once again used in the distractor familiarity-rating task between study blocks.

Procedure. Encoding procedures were similar to those used in Experiment 1B, with a few exceptions. Unlike Experiment 1B, older participants had the same amount of time as young adults to study each word pair because many older participants in Experiment 1B reported that the encoding trial duration was too long. Thus, each word pair was shown for 6 sec, the last 5 sec of which it was accompanied by a sentence. A 5-sec imagery period followed, then a prompt instructed participants to rate imagery success on a 1 to 5 scale, as in Experiment 1B.

The presentation of associative recognition test trials was identical to Experiment 1B. In the cued recall trials, a single word appeared on the screen and participants were instructed to say aloud the word they had studied with it. The experimenter then recorded the response in writing. To ensure that differences in performance across the two types of task were not due to differences in the amount of time participants performed the two tasks, a maximum of 15 sec was allowed for each response.

Unlike Experiment 1B, which used a 45-min unfilled delay, the current experiment used a 1-hour filled delay, during which a series of standardized cognitive tests was administered. This series was slightly modified from that used by Glisky and colleagues to measure frontal and temporal lobe function in healthy older adults (1995, 2001). Measures of frontal lobe capacities included the total number of words generated on a letter fluency task using the letters *F*, *A*, and *S* (Spreen and Benton, 1977), Mental Arithmetic from the Wechsler Adult Intelligence Scale—Revised (WAIS-R: Wechsler, 1981), Mental Control from the Wechsler Memory Scale—Revised (WMS-R; Wechsler, 1987), and Backward Digit Span from the WMS-R. In place of the modified Wisconsin Card Sorting Test (Hart et al., 1988) used by Glisky and colleagues (1995, 2001), we used a computerized set-shifting task that was analogous to card sorting (Owen et al., 1991), the score of which reflected the total number of trials required to learn eight different shift rules. Tests of temporal lobe capacities included Logical Memory I and Visual Paired Associates II from the WMS-R and the Long-Delay Cued Recall measure from the California Verbal Learning Test (Delis et al., 1987). Participants also completed the Vocabulary subtest of the WAIS-III (Wechsler, 1997).

## Results

Associative Recognition and Cued Recall. As in Experiment 1B, we computed a corrected recognition score for the associative recognition trials by subtracting false positives to recombined trials (those incorrectly deemed intact by participants) from intact hits (those correctly deemed intact). The two scores computed for the cued recall task were a verbatim score was computed in which participants received credit for a correct response only if their answer was identical to the target word, and a semantic score in which participants received credit if their response was identical to or synonymous with the target word (e.g., "SEA" instead of "OCEAN").

Overall, participants were more accurate on the associative recognition task than the paired-associate recall task, $F(1,38)=905.51$, $p<.001$, confirming that the latter task was more difficult than the former despite equivalent encoding opportunities. Older and young adults were equally accurate on the associative recognition task, F(1,38)=0.18, p>.80, replicating the findings of Experiment 1B (Figure 3). Critically, the two groups also did not differ in cued recall performance. This result held whether the method of scoring was verbatim, F(1,38)<1, p>.40, or semantic, F(1,38)<1, p>.50. Further, the gap in performance between the two tests was no greater for older than for young adults, and there was no interaction between Age Group and Test Type, whether the verbatim, F(1,38)<1, p>.90, or the semantic, F(1,38)<1, p>.90, score was used, confirming that the gap in performance between the two types of test was equivalent for the two age groups.

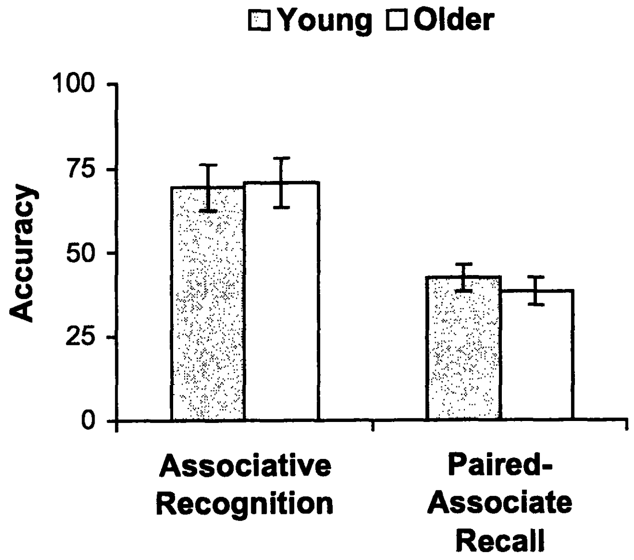


**Figure 3.** Experiment 2. Corrected recognition (%hits - % false alarms) for associative recognition and percent correct for paired-associate cued recall trials (±SEs).

An ANOVA was conducted to determine whether the pattern of "remember" and "know" responses differed as a function of age group for either intact or recombined items in the associative recognition task. Results revealed that the proportion of responses based on remembering did not differ as a function of age group for either intact, F(1,36)=1.23, p>.20, or recombined pairs, F(1,36)<1 (Table 3)[1].

Standardized cognitive tests. The older adults in the present sample performed better than the normative scores for older adults aged 65 to 75 on all tests for which normative data was not available (Table 4). Young and older participants did not differ in letter fluency, Mental Control, Backward Digit Span, and Logical Memory I. The young adults, however, outperformed older adults in set-shifting, Visual Paired Associates II, and the Long-Delay Cued Recall portion of the CVLT.

Table 4. Performance on Neuropsychological Tests by Young and Older Participants in Experiment 2 and Estimates of Published Normative Data for Adults Aged 65 to 75 Years[a].

| | **Norm**<br>M(SD) | **Young Adults**<br>M(SD) | **Older Adults**<br>M(SD) |
|---|---|---|---|
| Intradimensional/Extradimensional Set Shifting | na | 120.5(3.4) | 149.8 (22.1)* |
| Total Number of Words in Letter Fluency | 39.2 (11.9) | 52.1 (13.6) | 51.5(10.8) |
| Mental Control, WMS-R | 5.0 (1.5) | 5.7 (0.6) | 5.7 (0.6) |
| Backward Digit Span, WMS-R | 7.6 (2.0) | 6.5 (1.5) | 6.1 (1.1) |
| Visual Paired Associates II (Delayed Recall), WMS-R | 4.0 (2.5) | 6 (0.0) | 5.7 (0.7)* |
| Logical Memory I (Immediate Recall), WMS-R | 24.0 (7.5) | 31.9 (5.1) | 30.6 (5.1) |
| California Verbal Learning Test, Long-Delay Cued Recall (Delis, Kramer, Kaplan & Ober, 1987) | 10.3 (3.7) | 14.4 (1.8) | 13.1 (2.1)* |

[a] From Glisky, Polster, & Routhieaux, 2001.
*p<.05
**p<.01

---

[1] There were only 36 degrees of freedom in calculating "remember"/"know" data because two of the older adults were tested before a "remember"/"know" distinction was added to the task requirements.

## Discussion

Young and older adults performed similarly on the associative recognition task. Scores were low enough (~70% corrected recognition for both groups) that the lack of a difference could not be attributed to a ceiling effect. The results suggest that older adults were just as capable as young adults of acquiring bound representations when input was equivalent at encoding.

Interestingly, the older adults also performed as well as young adults in the paired-associate cued recall task. Thus, increasing processing demands at the time of retrieval did not reveal a retrieval deficit in older adults. On the contrary, the results suggest that once the information had been acquired, older and young adults were equally capable of searching for and retrieving specific bound representations.

The failure to find age differences in the two memory tasks cannot be attributed to the possibility that the older adults enrolled in the current study were atypical super-performers who would behave like young adults on all cognitive tests. Although the older adults tested were high functioning and highly educated, they performed worse than the young adults on a number of standardized cognitive tests, including two that, like the experimental tasks, were delayed memory tests (Visual Paired Associates II of WMS-R, and the Long-Delay Recall portion of the California Verbal Learning Test).

The absence of age-related differences in the paired-associate recall task also suggests that older adults' successful retrieval cannot be attributed simply to the recruitment of familiarity-based processes. Despite extensive evidence that young adults use recollection to support associative recognition (Hockley & Consoli, 1999; Westerman, 2001; Yonelinas, 1997), it is still possible to imagine that participants could succeed in this task simply by judging whether a particular word pairing presented at test seemed familiar (and therefore, intact) or not (therefore, recombined). It seems unlikely, however, that familiarity would allow them to generate a missing target word in a paired-associate cued recall task.

## General Discussion

Past research has suggested that the deficit older adults experience in recollecting detailed information from memory reflects a failure to encode, store, and/or retrieve bound information (Chalfonte and Johnson, 1996; Naveh-Benjamin, 2000). The results of the current study indicate that this failure can be attributed primarily to impaired encoding processes.

Older adults were slower and less efficient than young adults in binding random pieces of information, such as the disparate words that made up the to-be-remembered pairs in this study's retrieval tasks. Older participants required on average 20 sec to generate an image linking the word pairs -- approximately twice as long as their young counterparts. This extended imagery time calls into question whether in past associative learning studies -- which often allowed no more than 4 sec to encode each pair --- older adults failed to retrieve associates because they did not have the time to link the items together (e.g., Dunlosky & Hertzog, 1998; Naveh-Benjamin, 2000, 2002). Given the present results, it is interesting to note that in one prior study of paired-associate learning (Dunlosky & Hertzog, 1998), young adults reported success in using imagery more often when study time was 8 sec than when it was 4 sec, whereas older adults did not benefit from the extra time. The current results suggest that 8 sec may have been enough time for young, but not older, adults to develop a productive image to bind unrelated word pairs.

Importantly, when encoding support provided older adults with the structure for binding disparate pieces of information at encoding, they were able to do so as well as young adults. This pattern is consistent with past findings that gaps in performance between young and older adults tend to narrow as additional levels of encoding support are provided (Craik & Jennings, 1992; Naveh-Benjamin, 2002). The extensive encoding support provided to older participants in the form of imagery-inducing sentences is not normally available in their environment. Without such assistance, older adults typically do not bind information as well as young adults. Even though the encoding environment in the present study was artificial, the current findings are important because they suggest that older adults retain the cognitive resources that support the binding of disparate information once attended.

The present results suggest that older adults' ability to retrieve bound information is preserved when strong connections are formed during encoding. The strength of these connections may reduce demands on control processes required to achieve successful retrieval (Glisky et al., 2001). Thus, while older adults may not be impaired in retrieval processing when deep encoding is successful, retrieval problems may occur when weak links between items in memory force them to rely more on self-initiated search strategies at retrieval (Craik, 1983, 1986). For example, a recent study showed that older adults benefited more than young adults from a letter-cue provided to help them retrieve semantically related items in a paired-associate recall task that used intentional encoding instructions (Naveh-Benjamin, 2002). Older adults did not benefit as much as young adults in retrieving unrelated pairs, which were more difficult to encode, perhaps indicating that the older participants did not acquire the associations at the outset. Interestingly, only 5-8 sec were allowed for participants to learn each pairing, which based on the findings of Experiment 1A is perhaps not enough time for older adults to create associations between unrelated items.

An open question is whether age-associated deficits in free recall (e.g., Perlmutter, 1979; Craik & McDowd, 1987) can also be attributed primarily to encoding failures. Within-participants studies showing that age differences are smaller in recognition than free recall would seem to suggest that older adults, in fact, are disproportionately affected by the greater retrieval demands of the latter task (Craik, 1986; Craik & McDowd, 1987; Rabinowitz, 1984, 1986; Schonfield & Robertson, 1966). On the other hand, some studies have observed equivalent or lesser performance differences in free recall relative to cued recall (Drachman & Leavitt, 1972; Naveh-Benjamin, 2000, Experiment 4). Such findings are inconsistent with the existence of a retrieval deficit in older adults because memory search demands are presumably greater in free than cued recall. Further, the pattern of impaired free recall and intact recognition also could be accounted for by encoding failures. For example, it has been argued that partial acquisition may be sufficient to support recognition but not free recall (Perlmutter, 1979). In addition, binding is also likely critical for successful free recall performance – specifically, binding pre-experimental semantic knowledge such as words to a particular context (i.e. the study episode; Raajimakers & Shiffrin, 1981). By this view, age-associated impairments in free recall, as in source recognition, may reflect at least in part a failure to attend to features of the study context (e.g., the room in which the items were learned, or the experimenter who presented them) that could act as cues for later recall. If so, encoding support which prompts older adults to attend to such contextual details may help reduce or eliminate age differences in free recall, as in source recognition, associative recognition, and paired-associate recall.

## References

Atkinson, R. C., & Juola, J. F. (1974). Search and decision processes in recognition memory. In D.H. Krantz, R.C. Atkinson, R.D. Luce, & P. Suppes (Eds.), Contenporary developments in mathematical psychology: Vol. 1. Learning, memory & thinking. San Francisco: Freeman.

Caldwell, J. I., & Masson, M. E. J. (2001). Conscious and unconscious influenes of memory for object location. Memory & Cognition, 29, 285-295.

Canestrari, R. E. (1968). Age changes in acquisition. In G.A. Talland (Ed.), Human aging and behavior (pp. 169-188). New York: Academic Press.

Castel, A. D., & Craik, F. I. M. (2003). The effects of aging and divided attention on memory for item and associative information. Psychology and Aging, 18, 873-885.

Ceci, S. J., & Tabor, L. (1981). Flexibility and memory: Are the elderly really less flexible? Experimental Aging Research, 7, 147-158.

Cerella, L. (1985). Information processing rates in the elderly. Psychological Bulletin, 98, 67-83.

Chalfonte, B. L., & Johnson, M. K. (1996). Feature memory and binding in young and older adults. Memory & Cognition, 24, 403-416.

Craik, F. I. M. (1986). A functional account of age differences in memory. In F. Klix & H. Hagendorf (Eds.), Human memory and cognitive capabilities, mechanisms and performance (pp. 409-422). Amsterdam: Elsevier.

Craik, F. I. M. (1994). Memory changes in normal aging. Current Directions in Psychological Science, 3, 155-158.

Craik, F. I. M., Byrd, M., & Swanson, J. M .(1987). Patterns of memory loss in three elderly samples. Psychology and Aging, 2, 79-86.

Craik, F. I. M. & McDowd, J. M. (1987). Age differences in recall and recognition. Journal of Experimental Psychology: Learning, Memory, and Cognition, 13, 474-479.

Craik, F. I. M., & Jennings, J. M. (1992). Human memory. In F.I.M. Craik, T.A. Salthouse (Eds.), The handbook of aging and cognition (pp. 51-110). Hillsdale, NJ: Erlbaum.

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

Delis, D. C., Kramer, J., Kaplan, E., & Ober, B. A. (1987). The California Verbal Learning Test. San Antonio, TX: Psychological Corp.

Drachman, D. A., & Leavitt, J. (1972). Memory impairment in the aged: Storage versus retrieval deficit. Journal of Experimental Psychology, 93, 302-308.

Dror, I. E., & Kosslyn, S. M. (1994). Mental imagery and aging. Psychology and Aging, 9, 90-102.

Dunlosky, J., & Hertzog, C. (1998). Aging and deficits in associative memory: What is the role of strategy production? Psychology and Aging, 13, 597-607.

Friedman, D., & Trott, C. (2000). An event-related potential study of encoding in young and older adults. Neuropsychologia, 38, 542-557.

Gardiner, J. M., & Java, R. I. (1990). Recollective experience in word and nonword recognition. Memory & Cognition, 18, 23-30.

Glisky, E. L., Polster, M. R., & Routhieaux, B. C. (1995). Double dissociation between item and source memory. Neuropsychology, 9, 229-235.

Glisky, E. L., Rubin, S. R., & Davidson, P. S. R. (2001). Source memory in older adults: An encoding or retrieval problem? Journal of Experimental Psychology: Learning, Memory, and Cognition, 27, 1131-1146.

Hart, R. P., Kwentus, J. A., Wade, J. B., & Taylor, J. R. (1988). Modified Wisconsin Card Sorting in elderly normal, depressed, and demented patients. Clinical Neuropsychologist, 2, 49-56.

Hockley, W. E., & Consoli, A. (1999). Familiarity and recollection in item and associative recognition. Memory & Cognition, 27, 657-664.

Hulicka, I. M., & Grossman, J. L. (1967). Age-group comparisons for the use of mediators in paired associate learning. Journal of Gerontology, 22, 46-57.

Humphreys, M. S. (1976). Relational information and the context effect in recognition memory. Memory & Cognition, 4, 221-232.

Java, R. I. (1996). Effects of age on state of awareness following implicit and explicit word-association tasks. Psychology and Aging, 11, 108-111.

Jennings, J. M., & Jacoby, L. L. (1993). Automatic versus intentional uses of memory: Aging, attention, and control. Psychology and Aging, 8, 283-293.

Logan, J. M., Sanders, A. L., Snyder, S. Z., Morris, J. C., Buckner, R. L. (2002). Under-recruitment and nonselective recruitment: Dissociable neural mechanisms associated with aging. Neuron, 33, 827-840.

Mandler, G. (1980). Recognizing: The judgment of previous occurrence. Psychological Review, 87, 252-271.

Mitchell, K. J., Johnson, M. K., Raye, C. L., & D'Esposito, M. (2000a). fMRI evidence of age-related hippocampal dysfunction in feature binding in working memory. Cognitive Brain Research, 10, 197-206.

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

McIntyre, J. S., & Craik, F.I . M. (1987). Age differences in memory for item and source information. Canadian Journal of Psychology, 41, 175-192.

Myerson, J., Hale, S., Wagstaff, D., Poon, L., & Smith, G. A. (1990). The information-loss model: A mathematical theory of age-related cognitive slowing. Psychological Review, 97, 475-487.

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: tests of an associative deficit hypothesis. Journal of Experimental Psychology: Learning, Memory, and Cognition, 26, 1170-1187.

Naveh-Benjamin, M., Craik, F. I. M., & Ben-Shaul, L. (2002). Age-related differences in cued recall: Effects of support at encoding and retrieval. Aging, Neuropsychology and Cognition, 9, 276-287.

Norman, K. A., & Schacter, D. L. (1997). False recognition in younger and older adults: Exploring the characteristics of illusory memories. Memory & Cognition, 25, 838-848.

Owen, A. M., Roberts, A. C., Polkey, C. E., Sahakian, B. J., Robbins, T. J. (1991). Extra-dimensional versus intra-dimensional set shifting performance following frontal lobe excisions, temporal lobe excisions or amygdalo-hippocampectomy in man. Neuropsychologia, 29, 993-1006.

Park, D. D., Puglisi, J. T., & Smith, A. D. (1986). Memory for pictures: Does an age-related decline exist? Psychology and Aging, 1, 11-17.

Parkin, A. J., & Walter, B. M. (1992). Recollective experience, normal aging, and frontal dysfunction. Psychology and Aging, 7, 290-298.

Perfect, T. J., Williams, R. B., & Anderton-Brown, C. (1995). Age differences in reported recollective experience are due to encoding effects, not response bias. Memory, 3, 169-186.

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

Raaijmakers, J. G .W., & Shiffrin, R. M. (1981). Search of Associative Memory. Psychological Review, 88, 93-134.

Rabinowitz, J. C. (1984). Aging and recognition failure. Journal of Gerontology, 39, 65-71.

Rabinowitz, J. C. (1986). Priming in episodic memory. Journal of Gerontology, 41, 204-213.

Rankin, J. L., & Collins, M. (1985). Adult age differences in memory elaboration. Journal of Gerontology, 30, 451-458.

Rotello, C. M., Macmillan, N.A., & Van Tassel, G. (2000). Recall-to-reject in recognition: Evidence from ROC curves. Journal of Memory and Language, 43, 67-88.

Rybash, J. M., & Hoyer, W. J. (1996). Process Dissociation Procedure reveals age differences in unconscious influences on memory for possible and impossible objects. Aging, Neuropsychology, and Cognition, 3, 251-263.

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

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

Schacter, D. L., Harbluk, J. L., & McLachlan, D. R. (1984). Retrieval without recollection: An experimental analysis of source amnesia. Journal of Verbal Learning and Verbal Behavior, 23, 593-611.

Schonfield, A. E. D., & Robertson, B. A. (1966). Memory storage and aging. Canadian Journal of Aging, 20, 228-236.

Spreen, O., & Benton, A. L. (1977). Neurosensory Center Comprehensive Examination for Aphasia (Rev. ed.). Victoria, British Columbia: University of Victoria Neuropsychology Laboratory.

Treat, N. J., & Reese, H. W. (1976). Age, pacing, and imagery in paired-associate learning. Developmental Psychology, 12, 119-124.

Wechsler, D. (1981). Wechsler Adult Intelligence Scale—Revised. New York: Psychological Corp.

Wechsler, D. (1987). Wechsler Memory Scale—Revised. New York: Psychological Corp.

Wechsler, D. (1997). Wechsler Adult Intelligence Scale—III. New York: Psychological Corp.

Westerman, D. L. (2001). The role of familiarity in item recognition, associative recognition, and plurality recognition on self-paced and speeded tests. Journal of Experimental Psychology: Learning, Memory, and Cognition, 27, 723-732.

Yonelinas, A. P. (1997). Recognition memory ROCs for item and associative information: The contribution of recollection and familiarity. Memory & Cognition, 25, 747-763.

# Chapter 2

# Age Differences in Patterns of BOLD Response During Recollection Success and Recollection Attempt

## Abstract

Neuroimaging studies of episodic retrieval in young and older adults have uncovered a pattern of increased left prefrontal activity in the latter group. This pattern is not always observed, however, and its functional significance remains an open question. In the present study, event-related functional MRI (fMRI) was used to investigate patterns of blood-oxygen level dependent (BOLD) response as participants performed an associative recognition task with intact, recombined, and new pairs. Critically, participants were required to make remember/know decisions when pairs were judged as intact or recombined, allowing trials to be sorted based on recollection success. The results revealed contrasting activation patterns for young and older adults. Young adults showed increased activity in left inferior frontal gyrus (~BA 44/6) and left fusiform/inferior temporal gyri (~BA 37) for successful recollection, as indicated by correct "remember" responses, relative to all other conditions. In the same regions, older adults exhibited increased activation for all retrieval hits, independent of whether responses were based on recollection or familiarity, as well as false alarms. The results constrain the conditions under which age differences in lateralization patterns can be expected to be observed and suggest that potentially compensatory recollection attempts by older adults recruit the same regions that support recollection success in young adults.

## Introduction

Older adults can retrieve bound information as well as young adults once they acquire the associative information (Glisky et al., 2001; Experiments 1B and 2). An open question, however, is whether the same neural processes underlie retrieval in young and older adults.

A relatively small number of studies have examined age differences in episodic retrieval (Anderson et al., 2000; Bäckman et al., 1997; Cabeza et al., 1997, 2000, 2002, 2004; Daselaar et al, 2003; Grady et al., 1995, 2002; Madden, 1999; Schacter et al., 1996). The most consistent finding across these studies was increased activity in left prefrontal cortex (PFC) among older relative to young adults. In general, the episodic retrieval tasks elicited primarily right-lateralized activity in PFC among young adults, while in older adults PFC activity was either left-lateralized (e.g., Anderson et al., 2000) or bilateral (e.g., Cabeza et al., 1997; Bäckman et al., 1997; Madden et al., 1999; Grady et al., 2002). Investigators have hypothesized that the increased left PFC activations in older adults reflect compensatory processing (e.g., Cabeza et al., 2002; Grady et al., 2002), perhaps through increased retrieval of semantic associates as episodic retrieval cues.

Many of these investigations of episodic retrieval in aging, however, employed blocked designs because they were PET studies or were undertaken before the advent of event-related fMRI (e.g., Backman et al., 1997; Cabeza et al., 2002; Grady et al., 2002; Schacter et al., 1996). As a result, they were not able to ascertain whether the results reflected the successful recovery of information from episodic memory or, alternatively, retrieval attempt. Studies of retrieval in young adults indicated that these elements of retrieval processing have different neural correlates (Rugg and Wilding, 2000). Some studies have found retrieval success to be associated with activity in left inferior prefrontal cortex (LIPC), left lateral parietal cortex, and bilateral medial parietal cortex (e.g., Nolde et al., 1998; Konishi et al., 2000; Maril et al., 2003). These studies do not differentiate between processes that lead to successful retrieval versus those that reflect the outcome of successful retrieval. A recent study, however, found that regions associated with the successful recapitulation of episodic memory are related to the type of representations acquired at encoding (Kahn et al., 2004). Recollection attempt, in contrast, has been associated with activations in left inferior parietal cortex and dorsal/frontopolar PFC (Dobbins et al., 2003; Kahn et al., 2004).

Only one neuroimaging study of age-associated differences in retrieval has attempted to isolate the neural correlates of retrieval success using an event-related design that allowed contrasts between successfully identified old and new items (Daselaar et al., 2003). That study failed to find differential activation for retrieval success across young and older adults. Because it used a yes/no item recognition task, however, that study did not address possible differences in the quality of the information recovered (i.e. recollection versus familiarity-based success). This distinction is critical because older adults have frequently been found to have little or no impairment in item recognition, but are significantly impaired on most tasks that rely on recollection (see Introduction to Chapter 1; for review, see Yonelinas, 2002). Thus, while Daselaar and colleagues (2003) did not find age differences in patterns of brain activity supporting item memory success, age differences may be apparent in patterns of brain activity supporting successful recollection.

In the present study, we used fMRI to scan participants as they performed an associative recognition task, similar to the one used in Experiment 1B. As in the previous experiment, when participants judged a pair to be old, they were required to distinguish between intact and recombined old items and to indicate whether their judgments were based on "remembering" the studied pair(s) or on "knowing" that the item was intact or recombined without remembering the original study episode(s). Additionally, unlike Experiment 1B, we included novel pairs among the intact and recombined test pairs. Thus, participants had five response choices: Intact-Remember, Intact-Know, Recombined-Remember, Recombined-Know, and New.

Previous studies of associative recognition in young adults have found ambiguous response patterns for intact relative to recombined items. Two studies that used event-related potentials (Donaldson and Rugg, 1998, 1999) observed greater "old/new" ERP effects in right PFC and left parietal cortex for intact relative to recombined items. They attributed this result to participants' use of a default strategy for rejecting recombined items. According to this hypothesis, recombined pairs are identified by a failure of recollection: "If I don't remember seeing this pair, then it must be recombined." In contrast, a recent fMRI study found increased activation for recombined relative to intact items in left middle frontal gyrus, inferior temporal gyrus, and inferior parietal lobule (Lepage et al., 2003). The authors interpreted the increased PFC response as reflecting the use of active recollection to reject recombined pairs. Specifically, they assumed participants were actively recalling the words that had been paired at study with the recombined items, a "recall-to-reject" strategy. Past behavioral research suggests that either a "default" process (Yonelinas, 1997) or a recall-to-reject process (Rotello et al., 2000) may be used to identify recombined pairs. By requiring participants to indicate whether their recombined responses were based on "remembering" or "knowing," we could determine whether participants' responses were based on recollection or a lack or recollection, respectively.

The combination of intact/recombined/new and remember/know judgments provided for a unique pattern of BOLD-related responses that could identify regions showing a pattern of recollection success, as opposed to attempt or effort. Recollection success would be characterized by regions where BOLD responses were greater for "remember" relative to "know" hits independent of trial type (i.e., intact vs.

recombined). In the current study, this pattern could not be attributed to retrieval effort because reaction times (RTs) for "know" hits exceeded RTs for "remember" hits (see Behavioral Results below). It also could not easily be attributed to recollection attempt, because attempt would predict equivalent activation for any item judged to be old and thus in need of categorization as either intact or recombined.[2]

In addition to identifying regions that exhibited age differences related to recollection success, the current study differed from most prior neuroimaging investigations comparing episodic retrieval in young and older adults because of the steps taken to equate encoding processes the two groups. With the exception of Daselaar et al. (2003), most aging studies of episodic retrieval have used intentional encoding procedures, such that prior to encoding, participants are informed that a memory test will follow. A recent fMRI experiment (Logan et al., 2002) showed that, at acquisition, older adults who are given intentional instructions exhibit reduced activation relative to young adults in LIPC regions known to support subsequent episodic memory for words (e.g., Wagner et al., 1998). In contrast, when participants were given incidental encoding instructions (i.e., they performed a semantic retrieval task that supports subsequent memory but were not told they would later be tested), LIPC activations in older adults were similar to those in young adults. To ensure that age-associated differences in activation seen at retrieval were not the inevitable result of cognitive and neural differences in the way the stimulus material was encoded, the present study took several measures to equate encoding processes between groups.

---

[2] One could argue that participants do not attempt to recollect information when they reject recombined pairs based on a default strategy (i.e., a lack of recollection). However, receiver operating characteristics (ROCs) for associative recognition judgments suggest that participants opt for a recall-to-reject strategy when they are told that this strategy is appropriate and have a long time (i.e., more than 2.5 sec) to respond (Rotello et al., 2000), as in the present study.

These measures, which included incidental encoding instructions, are identical to those outlined in Experiment 1B.

The steps taken to equate encoding processes engaged by young and older adults also were intended to elicit equivalent retrieval performance in the two groups. In studies that fail to equate retrieval performance, ostensible age differences in BOLD response patterns could reflect differences in performance not specific to age. In other words, differences in BOLD-dependent activation may be observed between any two groups who differed in accuracy, regardless of age (for discussion, see Rugg & Morcom, in press).[3]

One study (Cabeza et al., 2002) equated cued recall and source memory accuracy between young adults and a subset of high-performing older adults through careful subject selection. The older adults who performed worse than young adults recruited similar right-lateralized dorsolateral and anterior PFC regions as did young adults in the source memory task. The high-functioning older adults, in contrast, recruited anterior PFC *bilaterally*. These results were interpreted as evidence that bilateral activations seen in older adults reflect productive, compensatory processes rather than a breakdown in selectivity that signifies ineffective neural activity. A limitation of this study, however, is that no steps were taken to ensure that older adults were recruiting

---

[3] It may seem circular to equate performance in older and young adults when the ultimate goal in aging studies is to understand the sources of differences in performance between the two groups. Rugg and colleagues, nevertheless, argue that this approach is a necessary first step (Rugg & Morcom, in press). In short, until cognitive neuroscientists identify the brain activity patterns that differ between young and older adults even when they perform at the same level, it will be impossible to interpret differences that emerge when performance differs.

the same processes at encoding: Only 5 sec were allowed for encoding, and participants received intentional encoding instructions with no guidance about strategies that could help them learn the word pairs. The results of Experiment 1A suggest that it may take older adults longer than 5 sec to link unrelated study items. Thus, the patterns of compensatory retrieval activity in high-performing older adults observed by Cabeza et al. (2002) may have reflected compensation for failures that occurred at encoding.

The current study compared patterns of recollection success across young and older adults following strictly controlled encoding procedures that resulted in equivalent performance between the two age groups in terms of both accuracy and RT. The results revealed that regions engaged by young adults only when recollection was successful were recruited by older adults whenever recollection was attempted, regardless of the level of success or the true memory status of the test stimulus.

## Methods

Participants. We enrolled 14 young and 20 older participants in accordance with procedures approved by the institutional review boards of MIT and Massachusetts General Hospital. The young participants were recruited from a database of research volunteers maintained by the MIT Department of Brain and Cognitive Sciences that includes primarily MIT undergraduate and graduate students. Older participants included MIT alumni, MIT retirees, and other community-dwelling, healthy older adults. No participants were using psychoactive medications. Older adults were pre-screened to ensure they did not have diabetes, cardiac illness, or neurological disorders. We excluded the data from 10 participants (2 young, 8 older) for the following reasons: difficulty fitting comfortably into the small-sized head coil, spiking by the scanner that contaminated the data, the detection of a brain anomaly in one participant, failure to follow task instructions, and poor performance (the accuracy of one older adult was more than 2 SD below the mean of the other older adults, and two others failed to report "remembering" enough recombined items to model this condition). The remaining 12 older adults ranged in age from 60 to 80 (M=69.7, SD=5.8), and the remaining 12 young adults ranged in age from 18-34 (*M*=21.8, *SD*=4.6). The older adults had more years of education (*M*=17.5, *SD*=1.9) than the young adults (*M*=14.8, *SD*=3.5), *F*(1, 23)=5.65, *p*<.05, but did not differ in verbal intelligence as estimated by the Vocabulary subtest of the Wechsler Adult Intelligence Scale (WAIS-III, Wechsler, 1997), *F*(1,23)=2.82, *p*>.10. All older adults whose data were included in the analyses had a Mini-Mental Status Examination (Folstein et al., 1975) score of 28 or greater.

*Materials and design*. We created four stimulus sets of 80 word pairs, such that the words constituting each set did not differ in concreteness (*M*=585), familiarity (*M*=506), imageability (*M*=579), word frequency (*M*=23) or word length (*M*=5). For each word pair, we created a sentence linking the two words (Appendix A). Three of the study sets were studied by each participant, with one set left unstudied for use as novel test pairs. Four versions of the test list were compiled such that, in each, one set of 80 pairs was presented intact at test, two sets of 80 pairs were used to form 80 recombined pairs (by using one word from each test pair to form the rearranged pairs), and the remaining set included 80 novel pairs, each composed of two unstudied words. Using this method, four study-test list combinations were created such that each word pair was seen equally often in the intact, recombined, and novel condition.

In addition to the critical pairs, 24 word pairs and associated sentences were created for use in two buffer encoding trials at the beginning and end of each of the six study blocks, so that long-term primacy and recency effects (Bjork & Whitten, 1974) would not affect performance on the critical pairs. These primacy and recency pairs also were used in practice test trials.

Behavioral procedures. Encoding procedures for each trial were identical to those used in Experiment 2. Each study session comprised six blocks of 40 critical trials, 2 primacy trials, and 2 recency trials. Encoding was conducted outside the scanner.

The test trials differed from those in Experiment 2 in several ways. First, despite equivalent performance obtained by young and older adults in Experiments 1B and 2, pilot testing showed that in the scanning environment, young participants outperformed the older participants. Thus, the young adults were given an unfilled delay of approximately 2 hours between study and test, and older participants were allotted approximately 45 min, the minimum time needed for a rest break and to obtain structural scans before the test trials began. In addition, so that stimulus presentation could be synchronized with the MRI scans (TR=2), each trial was 6 sec in duration. At the start of each trial, the two words, separated by a fixation cross, were presented for 4.5 sec. Then, a small filled circle appeared for 1.5 sec warning participants that the 6-sec trial was about to end. They were told that the circle was only a warning and that responses would be recorded if made while either the word pair or circle was present. To encourage participants to allow sufficient time to retrieve recollective information (Footnote 1), they also were instructed that accuracy was important and that response time was not,

Stimuli were presented visually on a projection screen reflected on a mirror attached to the head coil. Responses were recorded by right-hand finger presses on a 5-button magnet-compatible button box. The buttons were assigned in order from the thumb to the fifth finger as (1) new; (2) intact based on remembering; (3) intact based on knowing; (4) recombined based on remembering; (5) recombined based on knowing.

Instructions for describing the remember/know distinction were identical to those used in Experiments 1B and 2. To ensure that participants understood each task, example trials were presented at the beginning of the encoding and the retrieval sessions.

MRI acquisition procedure. We acquired the MIR data using a gradient-echo echo-planar sequence (repetition time = 2000 msec, echo time = 40 msec, 21 axial slices aligned parallel to the AC-PC plane, 3.125 X 3.125 X 5 mm, 1-mm interslice skip, 240 volumes per run) in a 3T Siemens Trio whole-body scanner with an 8-channel domed head array (MRI Devices Corp., http://www.mridevices.com/RFcoils/HRH/HRH.asp). We collected high-resolution T1-weighted (MP-RAGE) structural images for anatomical visualization. Cushions were placed around each participant's head to minimize head movement.

MRI analysis procedures. Data were analyzed with SPM99 (Wellcome Department of Cognitive Neurology, London), using standard preprocessing procedures. The first four functional scans from each of the four runs were discarded because of spin saturation effect. Structural and functional images were normalized to EPI and T1-weighted anatomical templates based on the MNI305 stereotaxic space. Images were resampled into 3-mm cubic voxels and spatially smoothed with an 8-mm full-width half maximum isotropic Gaussian kernel.

Statistical analyses were performed using the general linear model. Trials from each condition were modeled using a canonical hemodynamic response and its first-order temporal derivative. Each trial was modeled as a mini-epoch, which provides a more accurate estimate of the BOLD response in trials of long duration (Russell A. Poldrack, personal communication). Effects were estimated using a subject-specific fixed-effects model, with session-specific effects and head motion treated as confounds. Linear contrasts were used to obtain subject-specific estimates for each effect. The resulting estimates were entered into a second-level analysis treating participants as a random effect, using a one-sample t test against a contrast value of zero at each voxel. The resulting regions of activation were considered reliable if they comprised at least five contiguous voxels that exceeded an uncorrected threshold of $p<.001$. Group X condition interactions were computed using two-sample t tests and a threshold of $p<.005$, following Cabeza et al. (2002). An inclusive mask was used by thresholding a contrast of all retrieval trials > fixation at $p<.05$. This mask was applied to all voxel-based contrasts to ensure that differences between conditions were due to activations rather than deactivations. Thus, voxel-based results could be compared directly to ROI results, which included only above-baseline activations because the ROI definition used was based on all retrieval trials > fixation.

Region-of-interest (ROI) analyses further characterized the degree to which neural responses differed across conditions and age groups in functionally defined, and a priori predicted, prefrontal, temporal, and parietal regions. For these analyses, spherical ROIs were identified by selecting all significant voxels within a 10-mm radius of the maxima defined by the contrast of all retrieval trials minus fixation trials across the two subject groups. Signal within each ROI was calculated for each subject by selectively averaging the data with respect to peristimulus time for trials in each condition. The time point representing the peak signal change was determined by averaging the signal change relative to fixation baseline across all conditions and all participants within each participant group. The ROI analyses focused on regions where a significant age X condition interaction was observed in relevant contrasts. In regions where a main effect of condition was found in only one of two groups in the absence of an interaction, the null effect in only one group could reflect a lack of statistical power and should be interpreted with caution (Buckner et al., 2000).

# Results

## Behavioral Results

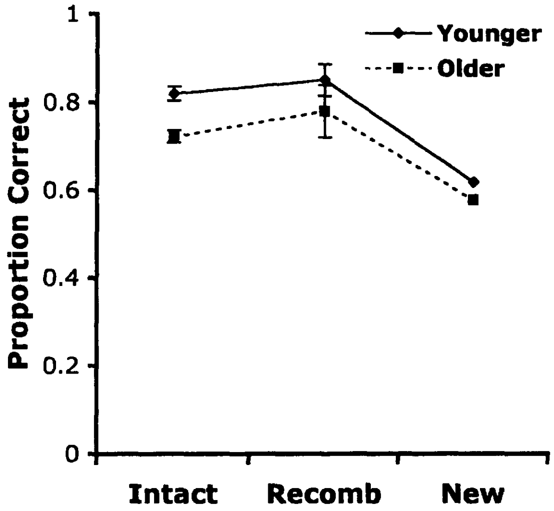


**Figure 1**: Proportion of correct responses in each test pair category (±SE).

We analyzed five critical response categories: (1) Intact-Remember (IR), correctly recognized intact pairs that received a "remember" response; (2) Recombined-Remember (RR), correctly recognized recombined pairs that received an "remember" response; (3) Recombined-Know (RK), correctly recognized recombined pairs that received a "know" response; (4) correct rejections (CR), correctly rejected new pairs; (5) false alarms (FA) to new pairs (i.e., new pairs incorrectly identified as recombined or intact).

Accuracy. To compare accuracy in apportioning responses correctly to the Intact, Recombined, and New conditions, a 2X3 mixed factorial ANOVA was conducted with percentage of hits in each of the three trial types as a within-participants factor and age group (Young, Older) as a between-participants factor. Hit rate differed significantly across the three conditions, F(2,44)=14.85, p<.001, with reduced accuracy for novel pairs as compared to intact, t(23)=3.62, p<.002, and recombined pairs, t(23)=4.78, p<.001 (Figure 1). We found no main effect of age group, F(1,22)=2.51, p>.10, and no age X condition interaction, F(2,44)<1.

To determine whether patterns of "remember"/"know" responses differed across the two age groups, a 2X2 ANOVA was conducted to analyze the percentage of correct intact and recombined trials that received "remember" responses as a function of age group. A main effect of condition demonstrated that a greater percentage of correct intact than recombined trials was based on recollection, F(1,22)=8.09, p<.01 (Figure 2). We found no main effect of age group, F(1,22)<1, indicating that the portion of correctly identified old (i.e., intact and recombined) pairs that received "remember" responses did not differ between young and older adults. Moreover, the lack of an age group X condition interaction, F(1,22)<1, indicated that the distribution of "remember" and "know" responses across conditions did not differ between young and older adults. Because of the small number of Intact-Know items among most participants (~5% on average), there were too few trials to model this condition in the fMRI analysis. In addition, 3 of the older adults had fewer than 12 correct Recombined-Know responses; as a result, there were too few trials to model this condition in these 3 individuals. Thus, in fMRI analyses that used the RK bin, only 9 older participants were included in the analysis, compared to 12 young adults.[4] A re-analysis of the hit and remember/know

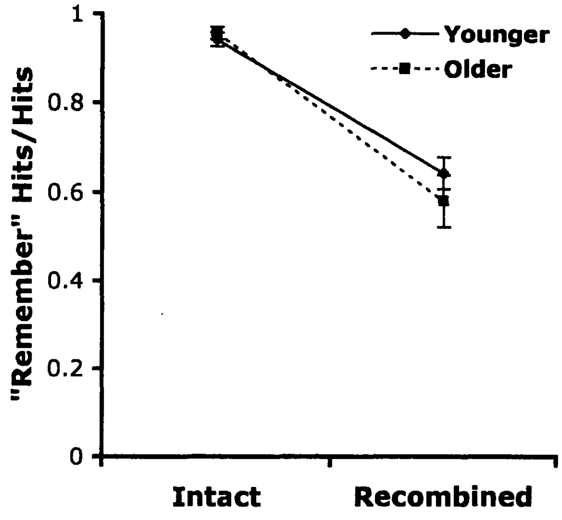


**Figure 2:** Proportion of correct responses to old pairs that were based on recollection, as indicated by a "remember" response (±SE).

---

[4] There is precedent in the aging neuroimaging literature for using an unequal number of older and young participants, given the difficulty in recruiting older participants willing and eligible to participate in neuroimaging studies. Cabeza et al. (2002), which used PET, compared groups of

data showed that the patterns of behavioral results did not change when these 3 older participants were excluded.

We also examined behavioral response patterns for false alarms to new pairs. The vast majority of these false alarms were identified as recombined (93% in each group). Older adults, however, gave a larger portion of false alarms a "remember" rating (46% in old vs. 22% in young), $\underline{F}(1,22)=11.95$, $\underline{p}<.005$.

We analyzed RTs by conducting a 2X5 mixed factorial ANOVA with Age Group (Young, Older) as a between-participants factor and Retrieval Condition (IR, RR, RK, CR, FA) as a within-participants factor. The results revealed that RTs differed as a function of condition, $\underline{F}(4,88)=44.83$, $\underline{p}<.001$, but not group, $\underline{F}(1,22)<1$, and the two factors did not interact, $\underline{F}(4,88)<1$ (Figure 3). Collapsing across the two participant groups, RTs increased from IR to CR to RR to RK, and FA did not differ from RK.

---

12 young participants with 8 high-performing older participants and 8 low-performing young participants.

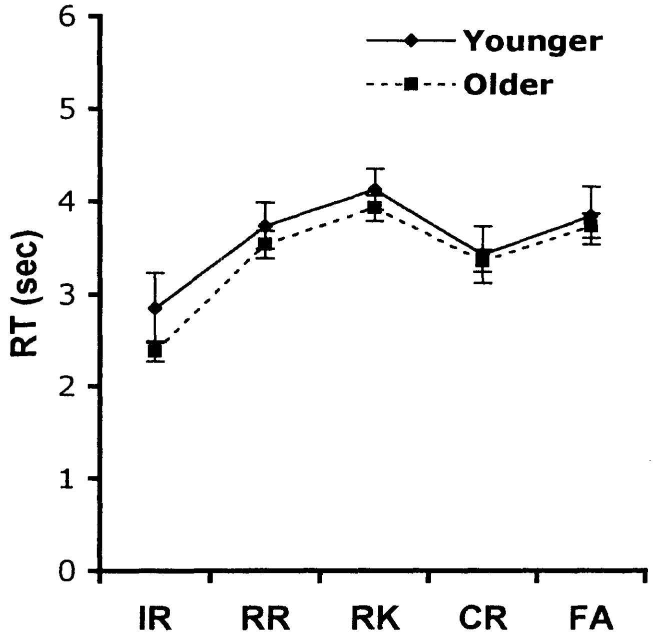


**Figure 3:** RTs as a function of age group and retrieval condition (±SE).

fMRI Results

Voxel-based analyses. Analyses were conducted at the voxel level to identify regions across the brain that reflected successful differentiation of old vs. new items (old-new effect), irrespective of recollection outcome (i.e., "remember" vs. "know" response). To compare successful responses to old vs. new items, correct rejections were subtracted from correctly identified intact and recombined pairs, (i.e., [IR + RR + RK] – CR). This contrast identified similar areas of activation in young and older participants that were consistent with previously observed observations of old/new effects in episodic retrieval in primarily left-lateralized PFC and parietal regions (Table 1). In addition, we found areas of differential activation across the two groups, as revealed by age X condition interactions (Figure 4A). Young adults exhibited greater activation for successful old relative to new recognition in left anterior superior parietal cortex, while old/new effects were greater in older adults in a number of areas including inferior parietal cortex bilaterally, right posterior-dorsolateral PFC, left insula, and medial frontal superior frontal cortex.

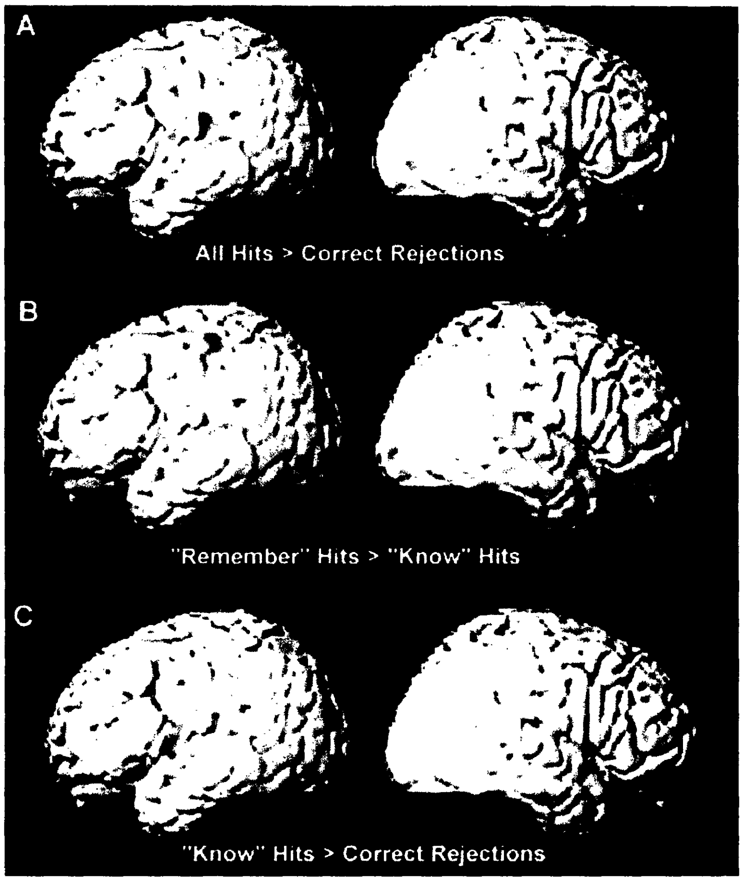


**Figure 4.** Renderings depicting brain regions where young and older adults' BOLD responses differed across conditions, as indicated by age X condition interactions in voxel-based analyses. Regions of Older > Young activation are shown in red, and Young > Older in green. (A) All hits (Intact-Remember + Recombined-Remember + Recombined-Know) > Correct Rejections. (B) "Remember" hits (Intact-Remember + Recombined-Remember) > Recombined Know. (C) "Know" hits (Recombined-Know) > Correct Rejections.

To identify regions that were differentially active as a function of recollection success, a voxel-wise analysis of remember hits (i.e., IR + RR) minus know hits (i.e., RK) was conducted (Table 2). In young adults, this contrast revealed differential activation for remember hits relative to know hits in posterior left inferior frontal cortex (MNI coordinates of -48, 0, 6 and -51, 9, 3; BA 44/6) and posterior middle temporal gyrus (-57, -42, -3). In older adults, no areas exhibited greater activation for "remember" than "know" hits at a threshold of $\underline{p}<.001$, though this null result may have been due to low statistical power and should be interpreted with caution. An age X condition interaction revealed differentially increased activation for recollection hits among young adults in left inferior frontal cortex (approximately BA 44/6; coordinates of -45, 0, 3) in a region overlapping that identified in the young-only contrast (Figure 4B). In older adults, greater activation for "remember" hits than "know" hits was observed in the left pre- and postcentral gyri, medial frontal cortex, cerebellum and occipital cortex.

Table 1. Regions demonstrating differential activation during correctly recognized old items (Intact and Recombined pairs) relative to correctly rejected new items (New Pairs).

| | | **MNI Coordinates** | | | |
|---|---|---|---|---|---|
| **Region** | **Left/ Right** | **x** | **y** | **z** | **~BA** |
| **Young Adults** | | | | | |
| Lateral parietal | | | | | |
| Inferior parietal | L | -39 | -57 | 45 | 40 |
| | L | -39 | -63 | 51 | 40 |
| | L | 36 | -60 | 42 | 40 |
| Post. superior parietal | L | -33 | -69 | 45 | 7/19 |
| Ant. superior parietal | L | -42 | -36 | 57 | 5 |
| Lateral prefrontal | | | | | |
| Ant. inferior frontal | L | -54 | 27 | 15 | 45 |
| Ant. inferior/middle frontal | L | -42 | 42 | 0 | 45/10 |
| Sup. middle frontal | L | -42 | 6 | 42 | 9 |
| | R | 54 | 15 | 42 | 6 |
| | R | 42 | 27 | 27 | 9 |
| Middle frontal | R | 36 | 6 | 57 | 8/6 |
| | R | 42 | 3 | 48 | 8/6 |
| Medial superior frontal | L | -6 | 21 | 42 | 6 |
| | L | -6 | 27 | 51 | 6 |
| | L | -9 | 18 | 54 | 6 |
| Lateral temporal | | | | | |
| Inferior temporal | L | -54 | -57 | -18 | 20/37 |
| Middle temporal | L | -51 | -45 | -12 | 21 |
| | L | -51 | -36 | -9 | 21 |
| Superior temporal | L | -57 | -42 | 0 | 22 |
| Lingual gyrus | R | 18 | -72 | -3 | 17 |
| Post. cingulate | L | -3 | -30 | 30 | 23 |
| | L | -6 | -36 | 21 | 23 |
| Cerebellum | R | 33 | -63 | -36 | |
| | R | 15 | -69 | -33 | |
| Basal ganglia | | | | | |
| Caudate | L | -9 | 12 | 0 | |
| | L | -15 | -3 | 15 | |
| | R | 12 | 12 | 0 | |
| | R | 15 | 6 | 9 | |
| Putamen | L | -27 | 21 | -3 | |
| Thalamus | L | -18 | -33 | -6 | |

Table 1 (continued).

| Region | Left/ Right | MNI Coordinates x | y | z | ~BA |
|---|---|---|---|---|---|
| **Older Adults** | | | | | |
| Lateral parietal | | | | | |
| Inferior parietal | L | -45 | -51 | 48 | 40/7 |
| | R | 36 | -42 | 36 | 39 |
| Post. superior parietal | L | -30 | -66 | 48 | 7 |
| | L | -36 | -63 | 36 | 39 |
| | R | 33 | -75 | 36 | 19/7 |
| | R | 24 | -69 | 42 | 7 |
| Lateral prefrontal | | | | | |
| Inferior frontal | L | -51 | 15 | -3 | 47 |
| | R | 57 | 24 | 15 | 45 |
| | R | 36 | 27 | 18 | 45 |
| Post. inferior frontal | R | 60 | 15 | 27 | 44 |
| | R | 51 | 6 | 30 | 44/6 |
| Post. inferior/middle frontal | R | 45 | 9 | 42 | 8 |
| Middle frontal | L | -48 | 21 | 33 | 9/8 |
| | R | 48 | 33 | 21 | 46/9 |
| Superior frontal | L | -24 | 3 | 57 | 4/6 |
| | R | 30 | 6 | 54 | 8/6 |
| Occipitotemporal | L | -54 | -54 | -15 | 37 |
| Post. cingulate | R | 6 | -27 | 30 | 23 |
| Basal ganglia | | | | | |
| Caudate | L | -6 | -3 | 6 | |
| | L | -9 | 3 | -3 | |
| | R | 18 | 3 | 15 | |
| | R | 15 | 15 | 0 | |
| Cerebellum | R | 30 | -57 | -36 | |
| | R | 18 | -66 | -36 | |
| **Young > Older Adults** | | | | | |
| Lateral parietal | | | | | |
| Postcentral | L | -42 | -42 | 63 | 5 |
| **Older>Young Adults** | | | | | |
| Lateral parietal | | | | | |
| Inferior parietal | L | -63 | -24 | 21 | 40 |
| | L | -21 | -81 | 36 | 39 |
| | R | 39 | -39 | 33 | 39/40 |
| Lateral prefrontal | | | | | |
| Post. Inferior/middle frontal | R | 51 | 6 | 27 | 9/44 |

Table 1 (continued).

| | | MNI Coordinates | | | |
|---|---|---|---|---|---|
| **Region** | **Left/ Right** | **x** | **y** | **z** | **~BA** |
| **Older>Young Adults (continued)** | | | | | |
| Medial frontal | L | -9 | -9 | 48 | 6 |
| | L | -15 | 6 | 48 | 6 |
| Insula / subcentral gyrus | L | -42 | -6 | 15 | 43 |
| Precentral gyrus | L | -27 | -36 | 39 | 5 |
| | L | -39 | -9 | 36 | 4 |
| Middle occipital gyrus | R | 42 | -75 | -3 | 19 |
| | R | 39 | -84 | -3 | 19 |

A further analysis identified regions where "know" hits (RK) elicited greater activation than correct rejections (CR; Table 3). Young adults showed activation in numerous regions including left parietal cortex, lateral PFC bilaterally, left frontopolar cortex, and posterior cingulate gyrus. Significant increases in activation were revealed in older adults in left parietal cortex, PFC, and precuneus. An age X condition interaction revealed that this contrast uncovered significantly greater activation in young adults in left superior parietal cortex and right cerebellum (Figure 4C). Older adults, on the other hand, exhibited differentially greater activation in left inferior parietal cortex and in left inferior frontal cortex, in or near the region where young adults exhibited increased activation for "remember" relative to "know" hits.

Table 2. Regions demonstrating differential activation during "Remember" hits relative to "Know" hits.

| | | MNI Coordinates | | | |
|---|---|---|---|---|---|
| **Region** | **Left/ Right** | x | y | z | **~BA** |
| **Young Adults** | | | | | |
| Lateral frontal | | | | | |
| Post. inferior frontal | L | -51 | -9 | -3 | 44/6 |
| | L | -48 | 0 | 6 | 44/6 |
| Middle temporal | L | -57 | -42 | -3 | 21 |
| **Young > Older Adults** | | | | | |
| Lateral frontal | | | | | |
| Post. inferior frontal | L | -45 | 0 | 3 | 44/6 |
| **Older>Young Adults** | | | | | |
| Medial frontal | R | 6 | 6 | 54 | 6 |
| Lateral parietal | | | | | |
| Postcentral gyrus | L | -36 | -27 | 60 | 5 |
| | L | -45 | -18 | 48 | 5 |
| Middle occipital gyrus | L | -24 | -96 | -6 | 17 |
| | R | 33 | -93 | -3 | 17 |
| Cerebellum | R | 30 | -45 | -24 | |
| | R | 18 | -72 | -30 | |
| | R | 9 | -69 | -30 | |

Table 3. Regions demonstrating differential activation during "know" hits to Recombined pairs (RK) relative to correctly rejected New pairs (CR).

| Region | Left/ Right | MNI Coordinates x | y | z | ~BA |
|---|---|---|---|---|---|
| **Young Adults** | | | | | |
| Lateral parietal | | | | | |
| Inferior parietal | L | -36 | -54 | 48 | 40/7 |
| Post. Superior parietal | L | -30 | -72 | 48 | 7/19 |
| | L | -27 | -66 | 57 | 7 |
| Lateral prefrontal | | | | | |
| Inferior prefrontal | L | -48 | 18 | 18 | 45 |
| Middle frontal gyrus | R | 42 | 27 | 27 | 9/46 |
| | R | 45 | 27 | 39 | 9 |
| Middle frontal | L | -39 | 3 | 39 | 6 |
| | R | 36 | 3 | 57 | 6 |
| | R | 42 | 3 | 45 | 6 |
| Superior frontal | L | -18 | 0 | 57 | 4/6 |
| | L | -27 | 24 | -6 | 6 |
| | L | -27 | -3 | 63 | 8/6 |
| Frontopolar | L | -27 | 54 | 9 | 10 |
| | L | -42 | 48 | 0 | 10 |
| Medial superior frontal | L | -6 | 21 | 42 | 32 |
| | L | -6 | 12 | 54 | 32/6 |
| | L | -3 | 3 | 60 | 32/6 |
| Precentral gyrus | L | -33 | -21 | 60 | 4 |
| Post. cingulate | L/R | 0 | -33 | 27 | 23 |
| | L/R | 0 | -21 | 27 | 23 |
| Lingual gyrus | L | 18 | -72 | -3 | 18 |
| Cerebellum | L | -27 | -60 | -39 | |
| | R | 9 | -72 | -30 | |
| | R | 33 | -63 | -36 | |
| | R | 12 | -66 | -36 | |
| Thalamus | L | -15 | 0 | 12 | |
| | L | -12 | 9 | 6 | |

Table 3 (continued).

| | | MNI Coordinates | | | |
|---|---|---|---|---|---|
| **Region** | **Left/ Right** | **x** | **y** | **z** | **~BA** |
| **Older Adults** | | | | | |
| Lateral parietal | | | | | |
| Post. superior parietal | L | -24 | -69 | 39 | 7 |
| Inferior parietal | L | -36 | -63 | 45 | 40/7 |
| | L | -30 | -48 | 42 | 40/7 |
| Precuneus | L | -6 | -69 | 60 | 7 |
| | L | -9 | -75 | 54 | 7 |
| Lateral prefrontal | | | | | |
| Post. inferior frontal | L | -51 | 0 | 33 | 44/6 |
| Post. inferior/middle frontal | L | -42 | 15 | 30 | 9/8/44 |
| Precentral | L | -45 | -6 | 42 | 6 |
| **Young > Older Adults** | | | | | |
| Lateral parietal | | | | | |
| Post. superior parietal | L | -24 | -63 | 60 | 7 |
| Cerebellum | R | 12 | -69 | -30 | |
| **Older>Young Adults** | | | | | |
| Lateral parietal | | | | | |
| Inferior parietal | L | -60 | -24 | 21 | 40 |
| Lateral prefrontal | | | | | |
| Post. inferior frontal | L | -48 | -3 | 12 | 44/6 |
| | L | -51 | 3 | 0 | 44/6 |

Region-of Interest Analyses. ROI analyses characterized the pattern of results across relevant retrieval conditions in temporal, parietal and prefrontal regions. To identify regions associated with recollection success (i.e., "remember" hits > "know" hits), a 3 X 2 mixed factorial ANOVA was conducted with Hit Condition (IR, RR, RK) as a within-participants variable and Age group (Older, Young) as a between-participants factor on clusters in these a priori defined regions of interest. A significant Age X

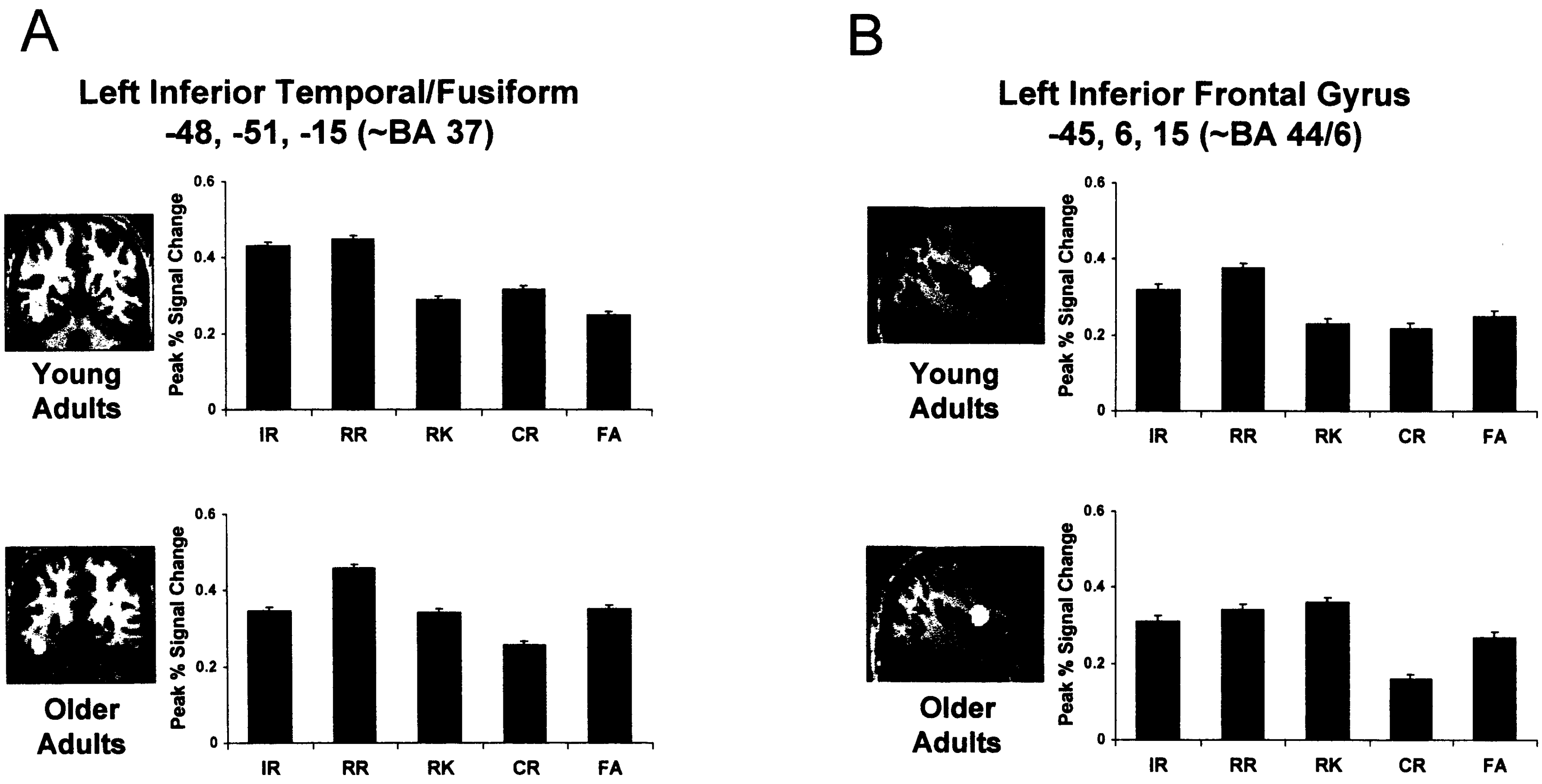


**Figure 5:** At left of A and B above, brain slices depicting ROI cluster in representative young and older participants. At right of each, peak percentage signal change for Intact-Remember hits (IR), Recombined-Remember hits (RR), Recombined-Know hits (RK), correct rejections of New pairs (CR), and false alarms to New pairs for young (top) and older (bottom) adults (±SE).

Condition interaction was observed in the left inferior temporal (IT)/fusiform gyri (MNI coordinates, -48, -51, -5, ~BA37; Figure 5A), F(4, 64)=3.97, p<.05. Among young adults, the levels of BOLD responses differed across the three hit conditions, F(2,22)=10.94, p=.001. Specifically, post hoc tests revealed RK was reduced relative to IR t(11)=3.81, p<.005 and RR, t(11)=3.95, p<.005; moreover, RK did not differ from CR, t(11)<1, p>.60. BOLD responses for IR trials did not differ from RR, t(11)<1, p>.70. In older adults, there was also a difference across the three hit conditions, F(2,16)=6.53, p<.01. The pattern of BOLD responses, however, was not consistent with recollection success: IR did not differ from RK, t(8)<1, p>.80, although the two conditions differed in recollection success, as measured by "remember" / "know" ratings, and effort, as measured by RT. Moreover, RK elicited greater activation than CR, though the difference was only marginal t(8), p=.06. This pattern is consistent with retrieval attempt, with one exception: RR trials elicited greater activation than either IR, t(11)=2.40, p<.05, or RK, t(8)=2.70, p<.05.

A trend for an Age X Hit Condition interaction also was observed in posterior LIPC (-45, 6, 15, BA 44/6), F(2,38)=2.86, p=.07 (Figure 5B). Post hoc analyses revealed that, similar to the observations in fusiform/IT cortex, young adults showed a pattern consistent with recollection success, while the pattern in older adults again was consistent with recollection attempt. In young adults, the three hit conditions significantly differed from each other, F(2,22)=7.18, p=.005. BOLD responses to the two "remember" conditions — IR and RR — did not differ, t(11)=1.31, p>.20, and each elicited increased activation relative to RK, though the difference between IR and RK was only marginal, t(11)=2.02, p=.07. As in the IT cluster, RK did not differ from CR, t(11)<1, p>.80. Among older adults, the three types of hit trials did not differ from each other, F(2,16)<1, p>.70. Post hoc tests revealed that the only differences among the five conditions were reductions in BOLD activation for CR relative to each other trial type, a pattern consistent with equivalent recollection attempt for pairs composed of words judged "old."

There were no other ROI clusters in either group that met the stringent criteria set for the pattern of recollection success, i.e. activation for RK trials that was reduced relative to both IR and RR. To confirm that no other regions showed a pattern consistent with retrieval success, a second less stringent analysis was conducted: A 2-way ANOVA identified any regions where activations for RK were significantly lower than for IR. The rationale was that in regions sensitive to recollection success, IR trials should engender greater activation than RK even though IR trials required less effort, as indicated by their lower RTs relative to RK. This pattern (i.e., IR>RK) was not observed in any clusters other than those mentioned above. Although this null result could have been due to a lack of power in either group, it is interesting to note that there were a number of areas, including left inferior parietal cortex and right dorsolateral and frontopolar cortex, in which activation for RK trials was greater than for IR trials. These signal increases may have signified greater recollection effort, although they also may reflect increased time on task, rather than qualitative differences in the cognitive operations that were engaged by the task.

## Discussion

Numerous neuroimaging studies have observed increased left PFC activation in older adults relative to young adults during performance of episodic retrieval tasks. The functional significance of this pattern is not known, although evidence suggests that the increased activation is productive and compensatory (Cabeza et al., 2002). In the current study, voxel-based analyses revealed increased left PFC activation in *young* adults in a contrast comparing recollection-based hits (i.e., correct "remember" responses) relative to familiarity-based hits (i.e., correct "know" responses), in an apparent contradiction of the previously observed findings. In the same LIPC region (~BA 44/6), however, greater activity was observed in *older* adults when familiarity hits were compared to correct rejections (RK-CR).

ROI analyses for young adults confirmed that levels of activity in left PFC, as well as in another ROI in IT/fusiform cortex, were correlated with recollection success. Two different trial types with dissimilar levels of difficulty as measured by RTs (IR and RR trials) elicited equivalent levels of BOLD response in each of these regions. Activation levels were lower for word pairs that were correctly recognized without accompanying recollective information (i.e., RK), even though these trials were more effortful, as indicated by increased RTs relative to the "remember" hits (i.e., IR and RR). Older adults, in contrast, exhibited equivalent levels of BOLD response for IR and RK trials in each of these regions, despite having different levels of recollection success and effort. Moreover, in this group, responses in this region were greater for RK than for correct rejections (i.e., CR). In young adults, in contrast, activation was equivalent for RK and CR. Thus older adults recruited these PFC and IT/fusiform regions whenever recollection was attempted, while young adults engaged them only when recollection was successful.

An alternative interpretation of the current results is that the pattern of increased activation for "remember" and "know" hits relative to CRs in older adults may reflect successful item retrieval of the words that constituted all hits trials, regardless of recollection status. The older participants rated nearly half of the FAs as "remember," however, consistent with the interpretation that they attempted recollection for this category of stimuli. Thus, a more parsimonious interpretation of the results is these regions in LIPC/premotor cortex and left IT/fusiform gyri were engaged by older adults in the service of recollection attempt, irrespective of the true memory status of the test pairs or the words that constituted them.

The current findings contribute to a growing body of evidence that left-lateralized activity observed in older adults during episodic retrieval may be associated with processes engaged in the service of recollection attempt. Several PET studies that used blocked designs found increased activation in left PFC regions, including LIPC, in older adults, despite overall poorer performance than young adults (Anderson et al., 2000; Grady et al., 2002; Madden et al., 1999). In one such study that investigated face recognition, retrieval success was not correlated with regional cerebral blood flow (rCBF) in this left PFC region but instead correlated with rCBF in temporal and occipital regions, as well as right PFC (Grady et al., 2002). Confirming this pattern of results, in the only other study to use event-related procedures to dissociate retrieval attempt from retrieval success, the former was associated with greater LIPC activation in older adults compared to young (Daselaar et al., 2003).

In another study that attributed increased left-lateralized activation in older adults to differences in patterns of attempt, greater left PFC activity in older adults was observed in a source recognition task relative to a cued recall task (Cabeza et al., 2002). These two tasks were compared because in young adults, greater right PFC activity had been observed during source recognition than during cued recall (Cabeza et al., 2001). The blocked design of this study precluded a clear separation of retrieval success and attempt. The authors, however, interpreted the increased left-lateralized source recognition activity observed in high-performing older adults as an indication that they were recruiting additional cue production or search processes from semantic retrieval networks during source retrieval, consistent with a retrieval attempt explanation.

Because of the complexity of the task performed in the present study, several older participants did not understand the task or perform well enough to contribute to the analysis, but there were not enough of these low-performing participants to form a group of their own. Thus, the older participants who were included may have formed a self-selected group of high performers. In future research, it will be important to compare patterns of activation in older adults who exhibit different levels of recognition success, to determine whether the patterns of attempt observed in the present study form a compensatory response unique to high-performing older adults.

Further light may be shed on the nature of the attempt effects observed in older adults if one considers what may account for BOLD activity associated with recollection success in young adults. Activations that correlated with recollection success could in principle stem from processes that are either the cause or the effect of recollection success. Specifically, increased activation for correctly recollected information may signify the engagement of processes that lead to successful information recovery or, alternatively, processes that reflect the outcome of successful retrieval, i.e. the recapitulation of the previously encoded episode. The present study, in isolation, cannot distinguish which of these two possibilities was driving the recollection success effects seen in young but not older adults. A recent fMRI study, however, isolated recollection success effects associated specifically with the recapitulation of previously encoded information, as distinct from those that reflected differences in processes leading to recollection success. Using event-related fMRI, Kahn and colleagues (2004) compared retrieval activation patterns for words that had been encoded phonologically versus words encoded by visualizing a scene called to mind by the study words. They hypothesized that regions that were engaged to represent these two types of information would be recruited similarly at encoding and during successful recollection. Guided by this hypothesis, they focused their analyses on a priori defined regions previously shown to be engaged during scene imagery (O'Craven & Kanwisher, 2000) and phonological encoding (Davachi et al., 2003), respectively. They found that recollection success effects were task-specific: BOLD responses in the parahippocampal place area discriminated between source and item memory only for words encoded via scene imagery, whereas a premotor/posterior LIPC area (BA 44/6) overlapping Broca's area discriminated source from item memory only for words encoded phonologically.

Further, another recent fMRI study demonstrated that activity in material-specific IT regions (parahippocampal place area and fusiform face area) was associated with the active recall of associative target information (Ranganath et al., 2004).

Similarly, the two regions showing differential recollection success effects in the current study have been associated with maintaining, encoding, and retrieving the types of material that participants encountered at encoding. One such area was premotor/poserior LIPC (-45, 6, 15, ~BA44/6). Patients with lesions in this region (i.e. Broca's aphasics) have deficits in comprehending and producing grammatical speech and in word finding (Dronkers et al., 2000). In neuroimaging studies, activity in this region has been observed during working memory, semantic retrieval, and episodic encoding when task stimuli are verbal. For example, activity in posterior LIPC has been observed during verb generation, intentional word learning, semantic classification (Nyberg et al., 1996; Wagner, 2000, Chapter 3 of this dissertation), and in working memory paradigms LIPC activity has been associated with phonological rehearsal (e.g., Awh et al., 1996). Further, encoding activity in pLIPC has been shown to predict subsequent memory for words (Wagner et al., 1998) as well as accurate retrieval of previously encoded words during letter-cued recall (Buckner, 1996).

The second region showing unique recollection success effects in young adults was left inferior temporal(IT)/fusiform (MNI coordinates, -48, -51, -5, ~BA37. Patients with lesions in this region have deficits in comprehending and describing pictures of objects (Foundas et al., 1998; Mummery et al., 1999; Patterson & Hodges, 2000; Simons et al., 2002). In addition, activation in these regions has been observed during attempted recognition of new exemplars of previously studied everyday objects (Simons et al., 2001).

At encoding, participants in the current study were presented with sentences and asked to generate mental images from those sentences (e.g. "The pendulum swung in molasses" and "A brick smashed the rattle"; Appendix A). Many participants reported that the imagery task was successful in helping them recover both the image they visualized and the sentence that described it. It is, therefore, interesting to speculate that the success-related effects reported here in young adults may also reflect the successful recapitulation of studied sentences and the visualized objects described by those sentences. Whether or not these activations reflect processes leading to or resulting from retrieval, it would appear to be a productive response for older adults to recruit the same areas that young adults engage during successful recollection.

Interestingly, in two other studies where performance between young and older adults was matched at retrieval, the locus of differential activation in older adults was in regions that support the types of representations encoded and retrieved. In the study by Daselaar and colleagues (2003), pleasant/unpleasant judgments were made at encoding. High-performing adults exhibited significantly greater activation during retrieval attempt in anterior LIPC (BA 47), which has been associated with controlled semantic retrieval (Demb et al., 1995; Wagner et al., 2001; Dobbins et al., 2002; Gabrieli et al., 1998; Kapur et al., 1994; Petersen et al., 1988) and cue specification during episodic retrieval (Dobbins et al., 2002). In contrast, the attempt-related activity observed in older adults by Cabeza and colleagues (2002) was in left frontopolar cortex (-38, 50, 4, BA10), an area that has been associated with the attempt to recollect perceptual or contextual detail (Dobbins, 2002; Ranganath et al., 2000), a key requirement of source recognition.

In conclusion, the current study showed that increased left-lateralized activity (RK vs. CR) in older adults occurs in regions where young adults exhibited activity that was specific to recollection success, lending support to previous findings in which increased bilateral activity in older adults was believed to underlie compensatory mechanisms supporting retrieval attempt. The regions where age differences were observed have been shown in the past to support the types of representations encoded in the current study. A more stringent test is needed to confirm whether unique patterns of recollection attempt are material specific. In particular, it would be important to see whether the loci of age differences vary in a material-specific pattern in individual participants using a within-participants design, as did Kahn and colleagues (2004). One could also compare performance under conditions that bias participants either to attempt recollection or rely on familiarity.

## References

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

Awh, E., Jonides, J., Smith, E. E., Schumacher, E. H., Koeppe, R. A, & Katz, S. Dissociation of storage and rehearsal in verbal working memory (1996). Psychological Science, 7, 25-31.

Bäckman, L., Almkvist, O., Andersson, J., Nordbert, A., Winblad, B., Reineck, R., & Langström (1997). Brain activation in young and older adults during implicit and explicit retrieval. Journal of Cognitive Neuroscience, 9, 378-391.

Bjork, R. A., & Whitten, W. B. (1974). Recency-sensitive retrieval processes in long-term free recall. Cognitive Psychology, 6, 173-189.

Buckner, R. L. (1996). Beyond HERA: Contributions of specific prefrontal brain areas to long-term memory retrieval. Psychonomic Bulletin and Review, 3, 149-158.

Buckner, R. L., Snyder, A. Z., Sander, A. L., Raichle, M. E., & Morris, J. C. (2000). Functional brain imaging of young, nondemented, and demented older adults. Journal of Cognitive Neuroscience, 12, Supp 2, 24-34.

Cabeza, R., Anderson, N. D., Houle, S., Mangels, J. A., & Nyberg, L. (2000). Age-related differences in neural activity during item and temporal-order memory retrieval: A positron emission tomography study. Journal of Cognitive Neuroscience, 12, 197-206.

Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: Compensatory brain activity in high-performing older adults. NeuroImage, 17, 1394-1402.

Cabeza, R., Daselaar, S. M., Dolcos, F., Prince, S. E., Budde, M., & Nyberg, L. (2004). Task-independent and task-specific age effects on brain activity during working memory, visual attention, and episodic retrieval. Cerebral Cortex, 14, 364-375.

Cabeza, R., Grady, C., Nyberg., L., McIntosh, A. R., Tulving, E., Kapur, S., Jennings, J. M., Houle, S., Craik, F. I. M. (1997). Age-related differences in neural activity during memory encoding and retrieval: A positron emission tomography study. Journal of Neuroscience, 17, 391-400.

Daselaar, S. M., Veltman, D. J., Rombouts, S. A. R. B., Raaijmakers, J. G. W., Jonker, C. (2003). Neuroanatomical correlates of episodic encoding and retrieval in young and elderly subjects. Brain, 126, 43-56.

Davachi, L., Mitchell, J. P., Wagner, A. D. (2003). Multiple routes to memory: Distinct medial temporal lobe processes build item and source memory. Proceedings of the National Academy of Sciences USA, 100, 2157-2162.

Demb, J. B., Desmond, J. E., Wagner, A. D., Vaidya, C. J., Glover, G. H., & Gabrieli, J. D. E. (1995). Semantic encoding and retrieval in the left inferior prefrontal cortex: A functional MRI study of task difficulty and process specificity. Journal of Neuroscience, 15, 5870-5878.

Dobbins, I. G., Foley, H., Schacter, D. L., & Wagner, A. D. (2002). Executive control during episodic retrieval; Multiple prefrontal processes subserve source memory. Neuron, 35, 989-996.

Dobbins, R. G., Rice, H. J., & Wagner, A. D. (2003). Memory orientation and success: Separable neurocognitive components underlying episodic recognition. Neuropsychologia, 41, 318-333.

Donaldson, D. I., & Rugg, M. D. (1998). Recognition memory for new associations: electrophysiological evidence for the role of recollection. Neuropsychologia, 36, 377-395.

Donaldson, D. I., & Rugg, M. D (1999). Event-related potential studies of associative recognition and recall: electrophysiological evidence for context-dependent retrieval processes. Cognitive Brain Research, 8, 1-16.

Dronkers, N. F. (2000). The neural architecture of language. In M. S. Gazzaniga (Ed.), The New Cognitive Neurosciences (pp. 949-960), Cambridge, MA: MIT Press.

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

Foundas, A. L., Daniels, S. K., Vasterling, J. J. (1998). Anomia: case studies with lesion localization. Neurocase, 4, 35-43.

Gabrieli, J. D. E., Poldrack, R. A., & Desmond, J. E. (1998). The role of left prefrontal cortex in language and memory. Proceedings of the National Academy of Science (USA), 95, 906-913.

Glisky, E. L., Rubin, S. R., & Davidson, P. S. R. (2001). Source memory in older adults: An encoding or retrieval problem? Journal of Experimental Psychology: Learning, Memory, and Cognition, 27, 1131-1146.

Grady, C. L., Bernstein, L. J ., Beig, S ., Siegenthaler, A. L. (2002). The effects of encoding task on age-related differences in the functional neuroanatomy of face memory. Psychology and Aging, 17, 7-23.

Grady, C. L., McIntosh, A. R., Horwitz, V., Maisog, J. M., Ungerleider, L. G., Mentis, M. J., et al (1995). Age-related reductions in human recognition memory due to impaired encoding. Science, 269, 218-221.

Kahn, I., Davachi, L., & Wagner, A. D. (2004). Functional-neuroanatomic correlates of recollection: Implications for models of recognition memory. Journal of Neuroscience, 24, 4172-4180.

Kapur, S., Rose, R., Liddle, P. F., Zipurksy, R. B., Brown, G., M., Stuss, D., Houle, S., & Tulving, E. (1994). The role of left prefrontal cortex in verbal processing: Semantic processing or willed action. Neuroreport, 5, 2193-2196.

Konishi, S., Wheeler, M. E., Donaldson, D. I., & Buckner, R. L. (2000). Neural correlates of episodic retrieval success. NeuroImage, 12, 276-286.

Lepage, M., Brodeur, M., & Bourgouin, P. (2003). Prefrontal cortex contribution to associative recognition memory in humans: an event-related functional magnetic resonance imaging study. Neuroscience Letters, 346, 73-76.

Logan, J. M., Sanders, A. L., Snyder, S. Z., Morris, J. C., & Buckner, R. L. (2002). Under-recruitment and nonselective recruitment: Dissociable neural mechanisms associated with aging. Neuron, 33, 827-840.

Madden, D. J., Turkington, T. G., Provenzale, J. M., Denny, L. L., Hawk, T. C., Gottlob, L. R., & Coleman R. E. (1999). Adult age differences in the functional neuroanatomy of verbal recognition memory. Human Brain Mapping, 7, 115-135.

Maril, A., Simons, J. S., Mitchell, J. P., Schwartz, B. L., & Schacter, D. L. (2003). Feeling-of-knowing in episodic memory: an event-related fMRI study. NeuroImage, 18, 827-836.

Mummery, C. J., Patterson, K., Wise, R. J. S., Vandenberghe, R., Price, C. J., & Hodges, J. R. (1999). Disrupted temporal lobe connections in semantic dementia. Brain, 122, 61-73.

Nolde, S. F., Johnson, M. K., & D'Esposito, M. (1998). Left prefrontal activation during episodic remembering: an event-related fMRI study. Neuroreport, 9, 3509-3514.

Nyberg, L., Habib, R., McIntosh, A. R., & Tulving, E. (2000). Reactivation of encoding-related brain activity during memory retrieval. Proceedings of the National Academy of Sciences USA, 97, 11120-11124.

O'Craven, K. M., & Kanwisher, N. (2000). Mental imagery of faces and places activates corresponding stimulus-specific brain areas. Journal of Cognitive Neuroscience, 12, 1013-1023.

Patterson, K., & Hodges, J. R. (2000). Semantic dementia: one window on the structure and organization of semantic memory. In L. S. Cermak (Ed.), Handbook of neuropsychology, 2nd. Ed. (pp. 313-333), Amsterdam: Elsevier.

Petersen, S. E., Fox, P. T., Posner, M. E., Mintun, M., & Raichle, M. E. (1988). Positron emission tomographic studies of the cortical anatomy of single-word processing. Nature, 331, 585-589.

Ranganath, C., Cohen, M. X., Dam, C., & D'Esposito (2004). Inferior temporal, prefrontal, and hippocampal contributions to visual working memory maintenance and associative memory retrieval. Journal of Neuroscience, 24, 3917-3925.

Ranganath, C., Johnson, M. K., D'Esposito, M. (2000). Left anterior prefrontal activation increases with demands to recall specific perceptual information. Journal of Neuroscience, 20 (RC108), 1-5.

Rotello, C. M., Macmillan, N. A., & Van Tassel, G. (2000). Recall-to-reject in recognition: Evidence from ROC curves. Journal of Memory and Language, 43, 67-88.

Rugg, M., Morcom, A. (in press). The relationship between brain activity, cognitive performance and aging: The case of memory. In Cabeza, R., Nyberg L., & Park D. C. (Eds)., The Cognitive Neuroscience of Aging. New York: Oxford University Press.

Rugg, M. D., & Wilding, E. L. (2000). Retrieval processing and episodic memory. Trends in Cognitive Sciences, 4, 108-115.

Schacter, D. L., Savage, C. R., Alpert, N. M., Rauch, S. L., & Albert, M. S. (1996). The role of hippocampus and frontal cortex in age-related memory changes. Neuroreport, 7, 1165-1169.

Simons, J. S., Graham, K. S., & Hodges, J. R. (2002). Perceptual and semantic contributions to episodic memory: evidence from semantic dementia and Alzheimer's disease. Journal of Memory and Language, 47, 197-213.

Simons, J. S., Graham, K. S., Owen, A. M., Patterson, K., & Hodges, J. R. (2001). Perceptual and semantic components of memory for objects and faces: a PET study. Journal of Cognitive Neuroscience, 13, 430-443.

Wagner, A. D., Koutstaal, W., Maril, A., Schacter, D. L., & Buckner, R. L. (2000). Task-specific repetition priming in left inferior prefrontal cortex. Cerebral Cortex, 10, 1176-1184.

Wagner, A. D., Paré-Blagoev, E. J., Clark, J., & Poldrack, R.A. (2001). Recovering meaning: Left prefrontal cortex guides controlled semantic retrieval. Neuron, 31, 329-338.

Wagner, A. D., Schacter, D. L., Rotte, M., Koutstaal, W., Maril, A., Dale, A. M., Rose, B. R., & Buckner, R. L. (1998). Building memories: Remembering and forgetting of verbal experiences as predicted by brain activity. Science, 281, 1188-1191.

Yonelinas, A. P. (1997). Recognition memory ROCs for item and associative information: evidence for a dual process signal detection model. Memory and Cognition, 25, 747-763.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: a review of 30 years of research. Journal of Memory and Language, 46, 441-517.

Appendix A. Study pairs and sentence

| **Word Pair** | **Encoding sentence** |
|---|---|
| APE—DRIVER | The driver of the car was an ape. |
| BADGE—CARPET | The police badge lay on the carpet. |
| BANANA—MAGICIAN | The magician held up a banana. |
| BANK—CARNATION | The bank was decorated with carnations. |
| BEDROOM—DOLLAR | A dollar was found in the bedroom. |
| BLADE—HORSE | A horse was cut with a blade. |
| BOLT—NOODLE | The noodles were in the shape of bolts. |
| KISS—MULE | The mule gave me a kiss. |
| MEDICINE—COLUMN | The medicine was arranged in a column. |
| BREAD—BABY | The baby ate some bread. |
| BROOK—GAS | Gas spilled into the brook. |
| BROWNIE—QUEEN | The queen ate a brownie. |
| BUSH—RAKE | The rake removed the leaves from under a bush. |
| CARRIAGE—EMERALD | The carriage was studded with emeralds. |
| CART—ASPARAGUS | The cart was filled with asparagus. |
| CATFISH—BATH | A catfish takes a bath. |
| CHAPEL—ARMY | The army marched into the chapel. |
| CHEEK—GRANDMOTHER | The grandmother had a soft cheek. |
| CLOWN—HOOD | The clown wore a hood. |
| COUCH—CURB | A couch sat on the curb. |
| COW—OATMEAL | The cow ate warm oatmeal. |
| CROCODILE—CANOE | The crocodile tipped over the canoe. |
| DAFFODIL—MANURE | Daffodils grew out of a pile of manure. |
| DETECTIVE—POWDER | The detective used powder to test the scene. |
| DRILL—CROSS | He carved a cross with the drill. |
| DUST—HONEY | Dust fell into the honey. |
| EARTH—BELT | A big belt was cinched around the earth. |
| EASEL—CROWD | The crowd looked at the easel. |

| | |
|---|---|
| EYE—MAIL | An eye was delivered in the mail. |
| MARE—DUNGEON | The mare was in the dungeon. |
| FIDDLE—ORANGE | He played the fiddle with an orange. |
| LARD—PEPPER | The pepper was covered with lard. |
| FIREPLACE—BATON | The baton was thrown in the fireplace. |
| FORT—JUDGE | The judge defended the fort. |
| FROG—LETTER | The frog wrote a letter. |
| PEG—LANTERN | A peg stuck out of the lantern. |
| HAMMER—NECKLACE | He destroyed the necklace with a hammer. |
| HEDGE—PENNY | A penny was found under the hedge. |
| HIVE—OVERCOAT | An overcoat smothered the hive. |
| HORN—MAGNET | The magnet attracted the horn. |
| HOTEL—DOCK | There was a dock outside the hotel. |
| INFANT—FUDGE | An infant got fudge all over its face. |
| INSECT—JAIL | An insect flew into the jail. |
| JEWEL—FOAM | A jewel dropped into the foam. |
| KEG—CROOK | The crook stole the keg. |
| KEY—CANARY | A canary flies with a key in its beak. |
| KITE—RING | A kite was shaped like a ring. |
| KNEE—NEST | A bird nest sat on his knee. |
| LACE—LUNG | The lung had a texture like lace. |
| LAWN—MOSQUITO | Mosquitoes fly over the lawn. |
| LEG—FAN | He hit his leg on the fan. |
| LEMON—BEAVER | The beaver chewed a lemon. |
| LENS—CAKE | The lens was found in the cake. |
| LOTION—BEGGAR | The beggar rubbed lotion on himself. |
| MEASLES—RABBIT | The rabbit was covered in measles. |
| MONASTERY—BASIN | The monks at the monastery used a basin to wash. |
| MOTH—NECK | A moth landed on my neck. |
| MUG—PLANK | A mug sat on the plank. |
| MUSICIAN—PRISON | The musician performed at the prison. |
| MUSTARD—BONE | Mustard covered the bone. |
| MUZZLE—POOL | The dog muzzle fell in the pool. |

| | |
|---|---|
| NAVEL—MOLE | There was a mole in her navel. |
| OAR—BRASS | The oar was made of brass. |
| OBOE—BRANDY | Brandy was poured into the oboe. |
| OWL—BROOM | An owl swept with a broom. |
| PAINTER—ACCORDION | The painter painted an accordion. |
| PAN—RACQUET | The racquet stirred the soup in the pan. |
| PARK—GRANDFATHER | The grandfather walked in the park. |
| PEDAL—BUTTER | The bike pedal was covered in butter. |
| PILL—KEROSENE | The pill was soaked in kerosene. |
| PILLOW—FISHERMAN | A fisherman slept on a pillow. |
| PIPE—ALGAE | There was algae on the pipe. |
| PLATE—FLASK | The flask sat on the plate. |
| POCKET—ASH | The pocket was filled with ash. |
| POND—PIGEON | The pigeon splashed in the pond. |
| PORT—GIANT | A giant built the port. |
| PRUNE—PIE | The pie was filled with prunes. |
| COACH—HONEYMOON | The coach went on a honeymoon. |
| REFRIGERATOR—BIB | The bib was in the refrigerator. |
| REVOLVER—POSTER | The poster showed a revolver. |
| ARMOR—BASKET | The basket was made of armor. |
| ARROW—PANTS | An arrow pierced the soldier's pants. |
| BAY—MOVIE | A bay was shown in the movie scene. |
| ASPIRIN—BOOT | The aspirin was crushed under the boot. |
| AUNT—FLESH | The aunt has a lot of flesh. |
| BALL—CLAW | The claw gripped a ball. |
| CERTIFICATE—HUNTER | The hunter received a certificate. |
| BEAM—BLONDE | A blonde balanced on the beam. |
| BEEF—PORCH | The man ate a beef dinner on the porch. |
| BLOUSE—BARK | The blouse was ripped by the tree bark. |
| CAGE—BELL | The bell was inside a cage. |
| BOWL—MAP | A map was kept in the bowl. |
| CAMERA—HARP | The camera took a picture of the harp. |
| BRUSH—ANKLE | The ankle was scrubbed with a brush. |

| | |
|---|---|
| BUBBLE—JAM | Bubbles formed in the jam. |
| BUCKLE—BLOSSOM | The belt buckle was the shape of a blossom. |
| BULLET—CHIN | A bullet grazed his chin. |
| GIFT—BUREAU | The gift was hidden in the bureau. |
| CASKET—BEAR | A dead bear was in the casket. |
| CATERPILLAR—FLOOD | The caterpillar got caught in the flood. |
| CLOVER—CEILING | A green clover was painted on the ceiling. |
| CHICKEN—LEATHER | The chicken wore a leather coat. |
| CIDER—PEN | He stirred his cider with a pen. |
| COAT—BRA | She wore a bra on top of her coat. |
| CORAL—MAGAZINE | A magazine was found on the coral reef. |
| HURDLE—ARCH | There was an arch over the hurdle. |
| CREAM—CORN | Cream was poured on the corn. |
| CROWN—CANDY | The crown was made of candy. |
| DART—CLARINET | The dart was blown out of the clarinet. |
| DEW—GRAPE | The grape has drops of dew on it. |
| DOME—PARADE | The parade float had a dome. |
| DOUGH—BEETLE | A beetle was found in the dough. |
| EGG—MOUNTAIN | An egg rolled down the mountain. |
| HERMIT—BRANCH | The hermit hid under a branch. |
| FANG—DOLL | The fangs pierced the doll. |
| GALLERY—BERRY | A berry stained the gallery. |
| GEESE—OYSTER | The geese cracked open the oysters. |
| GIRDLE—POLICEMAN | The policeman wore a girdle. |
| HARBOR—POOL | A swimming pool was at the edge of the harbor. |
| HATCHET—CLOUD | The hatchet cut through the cloud. |
| LIQUOR—NUN | The nun drank some liquor. |
| HILL—DAISY | A field of daisies grew on the hill. |
| MERCURY—PLATFORM | The mercury spilled on the platform. |
| HOSE—BOMB | A hose was used to try cool the bomb. |
| HOSPITAL—BOUQUET | The bouquet was delivered to the hospital. |
| HUT—DUCK | The duck snuck into the hut to stay warm. |
| ICICLE—BLISTER | The blister was cooled by an icicle. |

| | |
|---|---|
| INK—PIN | He wrote with a pin dipped in ink. |
| JERSEY—KITTEN | The kitten wore a bright jersey. |
| LAKE—PEAR | A pear bobbed in the water of the lake. |
| LEMONADE—BED | The lemonade spilled on the bed. |
| LIP—GRAVY | He had gravy on his lip. |
| MACKEREL—RAILROAD | The mackerel was crushed on the railroad. |
| MANTLE—LEOPARD | A stuffed leopard was on the mantle. |
| MARBLE—LOCKER | A bag of marbles was in his locker. |
| MEADOW—LOBSTER | The lobster crawled through the meadow. |
| MENU—FOUNTAIN | The menu fell in the fountain. |
| MICROSCOPE—BISCUIT | A biscuit was seen under a microscope. |
| MIRROR—MECHANIC | The mechanic broke the mirror. |
| MOUTH—CABBAGE | He had cabbage on his mouth. |
| NAPKIN—MOOSE | The moose wiped his lips with a napkin. |
| NICKEL—EARTHWORM | The earthworm crawled over the nickel. |
| NOSE—DANCER | The dancer had a big nose. |
| OCEAN—MOSS | Moss grew along the ocean. |
| PAPER—BENCH | Papers covered the bench. |
| PEARL—DOG | The dog wore a pearl necklace. |
| PENCIL—HEEL | I stepped on a pencil with my heel. |
| PICKLE—CAMEL | A camel eats a pickle. |
| PILE—CAMP | There was a pile of dirt at the camp. |
| PIMPLE—MISTRESS | The mistress had a big pimple. |
| DOVE—FACTORY | A dove flew through the factory. |
| PINEAPPLE—JET | A jet slammed into a pineapple. |
| PONY—BUCKET | The pony drank from a bucket. |
| PRIEST—DANDELION | The priest wore a dandelion. |
| BANNER—ISLAND | A banner hung over the island. |
| PULPIT—HOSTAGE | The hostage hid behind the pulpit. |
| PUMP—EAGLE | An eagle was perched on the pump. |
| PYRAMID—POT | A pot was perched on top of the pyramid. |
| RATTLE—BRICK | A brick smashed the rattle. |
| RATTLESNAKE—FLUTE | The rattlesnake curled around the flute. |

| | |
|---|---|
| AISLE—MAT | A mat covered the floor of the aisle. |
| AMMONIA—COFFEE | The ammonia was poured in the coffee. |
| ARM—CANDLE | The candle was shaped like an arm. |
| ARMADILLO—COAL | An armadillo was grilled on the coals. |
| AVALANCHE—GATE | An avalanche destroyed the gate. |
| BEE—COTTON | A bee flew onto the cotton. |
| BEET—FENCE | A red beet was thrown against the white fence. |
| BIRD—FLOOR | A bird hopped across the floor. |
| BLANKET—CABINET | A blanket was in the cabinet. |
| BOX—GINGERBREAD | The gingerbread was in a box.. |
| BRACELET—PIANIST | The pianist's bracelet jingled on the piano keys. |
| BREEZE—DAWN | There was a breeze at dawn. |
| CALF—HELMET | The calf wore a helmet. |
| CANAL—LUMBER | The lumber floated down the canal. |
| CANTEEN—HAWK | A hawk grabbed the canteen. |
| CARROT—BRONZE | The carrot was caste in bronze. |
| CELLAR—BRAIN | The brain was hidden in the cellar. |
| CHAIN—BAGPIPE | The bagpipe hung from a chain. |
| CHAIR—HANDKERCHIEF | A handkerchief was used to wipe the chair. |
| CIGAR—COLLAR | The cigar burned a hole in his collar. |
| COCKTAIL—CLAM | There was a clam in the cocktail. |
| COIN—LAMB | The lamb carried a coin. |
| CUBE—GRAVE | The grave was the shape of a cube. |
| CUCUMBER—CHERRY | The salad was made of cherries and cucumbers. |
| DENTIST—GUN | The dentist held a gun. |
| DIRT—GOWN | The gown dragged in the dirt. |
| DITCH—POTATO | A potato rolled into the ditch. |
| DOT—GARLIC | There was a black dot on the garlic. |
| DRAIN—CAVE | There was a drain on the floor of the cave. |
| DRESS—OIL | Oil was spilled all over the dress. |
| ELEPHANT—CORPSE | The elephant carried the corpse. |
| FEAST—CATHEDRAL | There was a feast at the cathedral. |
| MAIDEN—BOOTH | The maiden sat in the booth. |

| | |
|---|---|
| FLAG—METAL | The flag was made of metal. |
| FLEA—FLOOD | A flea got caught in the flood. |
| FOOTBALL—EEL | The eel wrapped itself around a football. |
| GIN—CLOSET | The gin was kept in the closet. |
| GLACIER—FOOT | A frozen foot was found in the glacier. |
| GLOVE—ICE | The glove was covered with ice. |
| GNAT—MAZE | A gnat flew through the maze. |
| GOAT—AMBULANCE | An injured goat was put into an ambulance. |
| GORILLA—JADE | The statue of a gorilla was made of jade. |
| GRASS—INN | Grass grew in front of the inn. |
| GRAVEL—ORCHESTRA | The orchestra played on gravel. |
| HAIR—CORRIDOR | The long hair flowed down the corridor. |
| HAMSTER—FERRY | Hamsters on wheels powered the ferry. |
| MONSOON—CLAY | The clay was drenched in the monsoon. |
| HERRING—MONKEY | The monkey ate some herring. |
| IRON—COTTAGE | The cottage was made of iron. |
| IVORY—DAGGER | The dagger had an ivory handle. |
| IVY—CLIFF | Ivy clung to the side of the cliff. |
| JAW—BEAN | I hurt my jaw chewing an uncooked bean. |
| JOCKEY—FLANNEL | The jockey wore a flannel outfit. |
| JUGGLER—NOOSE | The juggler juggled as a noose was put on his neck. |
| KETTLE—ANCHOR | A tea kettle was used as an anchor. |
| KISS—MILK | The child with a milk mustache gave a sloppy kiss. |
| KNOB—CHIPMUNK | A chipmunk gnawed on the knob. |
| LIMB—PUPPY | The puppy was stuck on a limb. |
| LION—KERNEL | The lion liked to eat kernels of corn. |
| PURSE—COPPER | The purse was made of copper. |
| LOCK—MOON | The crater on the moon looked like the lock on a door. |
| MAST—DRIZZLE | Drizzle fell on the ship's mast. |
| MATTRESS—RASPBERRY | Raspberries were spilled on the mattress. |
| MOAT—CYMBAL | The cymbal hung over the moat. |
| MOLASSES—PENDULUM | The pendulum swung in molasses. |
| FABRIC—BEACH | The fabric was on the beach. |

| | |
|---|---|
| MOUSE—BOULDER | The mouse was crushed by a boulder. |
| NEWSPAPER—POISON | The poison was shown in the newspaper. |
| NURSE—ALLEY | The nurse walked in an alley. |
| NURSERY—PLANE | The plane has a baby nursery. |
| OX—EAR | The black ox has big droopy ears. |
| PACKAGE—PUDDLE | The package fell in a puddle. |
| PISTON—HEN | A hen got stuck in the piston. |
| PLIERS—BROTHER | The boy grabbed his brother with pliers. |
| POISON—CHROME | Poison spilled on the chrome. |
| POLLEN—CAPSULE | The capsule was filled with pollen. |
| PUDDING—JAR | The pudding was in a jar. |
| PUPIL—CRAB | The pupil brought a crab to school. |
| RAIN—CRUCIFIX | The crucifix was left in the rain. |
| RAT—FORK | A fork was stuck into the rat. |
| ANT—MUSCLE | The ant has a big muscle. |
| ARK—AXLE | The ark was wheeled out on an axle. |
| AXE—LETTUCE | The lettuce was chopped with an axe. |
| BAG—GRASSHOPPER | The bag was filled with grasshoppers. |
| BALLOON—CEREAL | A balloon landed in the cereal. |
| PROPELLER—NIGHTGOWN | The nightgown got caught in the propeller. |
| BARN—POLE | A pole held up the old barn. |
| BAYONET—RICE | The soldier ate rice with a bayonet. |
| BEAK—LAWYER | The lawyer has a nose like a beak. |
| GUARD—CIRCLE | The guard drew a circle. |
| BLOCK—JACKET | A block was on the jacket. |
| BUTCHER—CONE | A butcher put meat in a cone. |
| CAFE—ALUMINIUM | The café had an aluminum roof. |
| CAT—BLOOD | The cat was covered with blood. |
| CAULIFLOWER—RAM | The ram ate the cauliflower. |
| CAVERN—HOCKEY | They played hockey in the cavern. |
| CHALK—MOCCASIN | He drew on the moccasin with chalk. |
| COLONEL—MORGUE | The colonel visited the morgue |
| CIGARETTE—LEAF | The cigarette was made with a tobacco leaf. |

| | |
|---|---|
| CINNAMON—BUTTON | The button was made of a cinnamon stick. |
| CRUISER—RECTANGLE | A rectangle was painted on the cruiser. |
| CORD—HOOF | A cord was tied onto the hoof. |
| CORK—ORGAN | The organ was made out of cork. |
| CRADLE—DOCTOR | A doctor rocked the cradle. |
| CRANBERRY—FOREST | A cranberry bog was in the forest. |
| DESK—ELBOW | The elbow hit the side of the desk. |
| DIAMOND—MACHINE | The machine was used to make diamonds. |
| DIMPLE—BANDIT | The bandit has deep dimples. |
| DOORWAY—RANCH | The ranch had a huge doorway. |
| DRUM—PHONE | He hit the drum with a phone. |
| ENGINE—MANSION | There was a car engine in front of the mansion. |
| ENVELOPE—ARTIST | The artist drew on an envelope. |
| FISH—JUICE | The fish was squeezed to make fish juice. |
| FLAME—CABIN | A flame rose from the cabin. |
| FLOWER—QUILT | The quilt was covered with flowers. |
| FOG—DEER | The deer stood in the fog. |
| FOREHEAD—CANNON | The cannon ball struck him in the forehead. |
| FROST—LAMP | The lamp was covered with frost. |
| GLASS—PORK | The pork was under the glass. |
| GOLD—QUAIL | The quail had a beak made of gold. |
| HADDOCK—FURNACE | A haddock cooked on the furnace. |
| HAM—PURSE | The shoplifter hid a ham in her purse. |
| HAREM—PLANET | A harem lived on the planet. |
| HARPOON—KING | The king threw a harpoon. |
| HAT—DIME | The dime was hidden inside the hat. |
| HAY—APRICOT | Apricots were hidden in the hay. |
| NECTAR—BARREL | The barrel was filled with nectar. |
| HIGHWAY—CHOIR | The choir sang on the side of the highway. |
| HIVE—ABDOMEN | There were hives on the abdomen. |
| HURRICANE—BOAT | A boat got stuck in a hurricane. |
| PEACH—POPE | The pope ate a peach. |
| KNIFE—JELLY | A knife spread the jelly. |

| | |
|---|---|
| KNIGHT—BOTTLE | A knight drank from a bottle. |
| LAP—HOOK | A hook got stuck in her lap. |
| LATCH—PIANO | The piano had a latch on it. |
| LIBRARY—BUTTERFLY | A butterfly flew into the library. |
| LIME—CRYSTAL | The lime was squeezed on the crystal. |
| LIMOUSINE—CLOCK | A clock was inside the limousine. |
| LIZARD—MEDAL | The lizard wore a medal of honor. |
| MONUMENT—KNUCKLE | The knuckle was scraped on the monument. |
| MUD—MISSILE | A missile landed in the mud. |
| NAIL—JEEP | The jeep got a flat tire from a nail. |
| NEEDLE—FOX | A needle was stuck in the fox's paw. |
| NUTMEG—CHOCOLATE | Nutmeg was sprinkled on the chocolate. |
| OLIVE—NET | A net was used to grab olives from a tree. |
| ONION—CHISEL | The onion was chopped with a chisel. |
| PALACE—BRIDGE | A bridge led to the palace. |
| PASSAGE—PIT | There was a pit in the passage way. |
| PASTE—OTTER | An otter played with paste. |
| PEA—FUR | Green peas were spilled on the fur coat. |
| ORNAMENT—CORNER | The ornament sat in the corner. |
| PLUM—PLUG | A plug pierced the skin of the plum. |
| PRAIRIE—GLOBE | A globe sat in the prairie. |
| PRINCESS—APPLE | The princess ate an apple. |
| QUARTER—JANITOR | The janitor found a quarter. |
| CIRCUS—COKE | He drank a coke at the circus. |
| RADIO—OVEN | The radio was in the oven. |
| RASH—LIGHTNING | The lightning caused a rash. |
| RIBBON—CANE | The cane was decorated with ribbons. |
| RIFLE—CROW | The rifle was aimed at the crow. |

# Chapter 3

# Neural Basis of Reduced Specificity in Semantic Retrieval in Older Relative to Young Adults

## Abstract

Compared with the pronounced age-related deficits observed in episodic retrieval, semantic retrieval processes appear relatively intact in older adults. Deficits arise, however, when automatic, data-driven processes are insufficient to support semantic retrieval. Left inferior prefrontal cortex (LIPC) is recruited in young adults during controlled semantic retrieval, though its role is controversial. The goals of the present fMRI study were (a) to determine whether LIPC supports controlled semantic retrieval or, alternatively, whether its role is to actively suppress competitors arising during the retrieval process; and (b) to determine whether patterns of LIPC engagement during semantic retrieval differ in young and older adults. We scanned young and older adults while they performed a semantic repetition priming task. In the Within-Task condition, participants performed the same semantic retrieval task on words seen at study and at test; in the Across-Task condition, participants performed two different semantic retrieval tasks at exposures one and two. The selection hypothesis, which posits that LIPC selects from competing representations in working memory, would predict a neural cost in the Across-Task priming condition, because LIPC would be engaged to actively suppress the previously facilitated semantic information. The controlled retrieval hypothesis, which posits that LIPC provides top-down control to excite semantic representations in posterior regions, would predict reduced neural facilitation for Across-Task priming by regions that support access to task-specific, goal-directed semantic representations. Consistent with the controlled retrieval hypothesis, young adults exhibited task-specific repetition-related responses in anterior LIPC. In the same region, older adults exhibited equivalent priming for the Within- and Across-Task conditions, consistent with the hypothesis that they failed to prevent irrelevant

information from entering working memory during Across-Task trials. No evidence of a neural cost in LIPC was observed in either group to support the selection hypothesis.

## Introduction

Conscious, declarative memory comprises episodic memory for specific events and semantic memory for general world knowledge (Tulving, 1972). In contrast to the age-related deficits seen in episodic memory, semantic memory appears to be relatively preserved in older adults (e.g., Burke & Peters, 1986; Horn & Cattell, 1967; Lima, Hale, & Myerson, 1991). For example, one of the most commonly used measures of semantic function, vocabulary, shows stability or even improvement in older adults, at least through their sixth decade (e.g., Horn & Cattell, 1967). Semantic priming also remains intact in older adults (e.g., Bowles & Poon, 1985; Burke, White, & Diaz, 1987; Burke & Yee, 1984; Howard, Shaw, & Heisey, 1986; see Light, 1992, for a review). Semantic priming reflects the facilitated processing of an item after processing a semantically related item. For example, one is more likely to produce and more rapid to identify the word "cat" after having heard the word "dog" than after hearing the word "apple." The preservation of semantic priming in older adults suggests that activation continues to spread unimpeded through neural networks that store general knowledge, implying that these semantic networks are relatively resistant to the effects of aging.

Some semantic memory tasks, however, do reveal age differences. For example, the age-related encoding differences described in Chapter 1 demonstrated that older adults were less efficient at generating semantically meaningful associations to link unrelated words than were young adults but were able to embrace and encode such descriptors when they were provided to them. In addition, older adults tend to generate fewer exemplars from a given semantic category than do young adults in semantic fluency tasks (e.g., Kozora & Cullum, 1995; Tomer & Levin, 1993; Troster, Salmon, McCullough and Butters, 1989; Troyer, Moscovitch, and Winocur, 1997; Whelihan & Lesher, 1985; Wiederholt et al., 1993). A recent study also showed that older adults are slower and less accurate to perform a word matching task when cognitive control is required to focus on a specific semantic dimension of the stimulus, particularly when participants must reject lures that are close semantic associates of the probe word (Badre & Wagner, 2002a).

The pattern of sparing and loss in semantic memory suggests that older adults may not experience problems with the network that stores semantic information but rather with top-down control processes needed to access information from that network when automatic, bottom-up processes are not sufficient to do so. Such control processes may include constraining memory search to meet task goals and selecting from information returned by that search process (Buckner, 2003). To test this theory, Balota and colleagues directly compared age differences in priming under conditions of automatic and controlled processing (Balota, Black, & Cheney, 1992). In the automatic processing condition, in which priming was supported by strong, pre-experimental semantic relationships between prime and probe, older adults showed normal priming. Nevertheless, when priming was dependent upon controlled processes (i.e., at longer SOAs and when the prime consisted of a category name that had not been associated with the probe prior to the experiment), older adults showed reduced facilitation.

Impaired semantic fluency performance in patients with frontal lobe dysfunction indicates that control processes are necessary in fluency tasks, as well (Baldo & Shimamura, 1998; Moscovitch, 1995; Rosen & Engle, 1997). Further, several studies suggest that semantic fluency deficits in older adults are due to the task's controlled processing requirements, including generating probe cues to support search and deciding when to switch between cues used to probe semantic memory (e.g., Mayr & Kliegl, 2000; Troyer et al., 1997).

Investigators also have suggested that older adults process semantic representations too broadly, failing to adequately filter irrelevant from relevant semantic information (Hasher & Zacks, 1988). For example, intervening distractor words slow the reading of target words to a greater degree in older than young adults, particularly when the distractors are semantically related to the target words (Connelly, Hasher, & Zacks, 1991). In the auditory domain, to-be-ignored background voices disrupt recall in older more than young adults, when the speech is semantically meaningful, demonstrating that the interference is cognitive rather than auditory (Tun, O'Kane, & Wingfield, 2002). Further, older adults fail to suppress high-probability sentence completions they have generated after the generated word has been disconfirmed as a valid completion (Hartman & Hasher, 1991). Likewise, they fail to update disconfirmed high-probability interpretations of garden-path sentences. Thus, Hamm and Hasher (1992) found that older adults were more likely to spontaneously access both low- and high-probability interpretations of a garden-path sentence, whereas young adults tended to access only the high-probability interpretation.

Such deficits may reflect an impairment specific to inhibition, i.e., the ability to (a) prevent task-irrelevant information from entering working memory, and (b) delete previously relevant information that is no longer task-relevant (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). Alternatively, age-related impairments in semantic retrieval may reflect a broader loss of cognitive control, resulting from the failure to maintain and update information about task context, such as internal goals and external stimulus features (Braver & Barch, 2002). In this scheme, the failure of top-down control signals in prefrontal cortex to bias representations in posterior association cortices (Miller & Cohen, 2001) could result in (a) a failure to *inhibit* task-irrelevant representations, or (b) a failure to *excite* task-relevant representations when data-driven processes are not sufficient to activate them. Unlike the disinhibition hypothesis (Hasher & Zacks, 1988), the cognitive control theory can account for the failure to observe facilitation in older adults when priming depends on controlled processes (Balota et al., 1992).

Whether due to a more general loss of cognitive control or a specific inhibitory deficit at a cognitive level, the neural basis of age-associated failures in controlled semantic retrieval is not yet well specified. It can be expected, however, that frontal lobe dysfunction plays a role in the deficit, because prefrontal cortex has (a) been implicated in controlled semantic retrieval in young adults (for review, see Badre & Wagner, 2002b); and (b) is disproportionately vulnerable to aging (Esiri, 1994; Raz et al., 1997, 2004; Salat et al., 1999, 2004; West, 1996; for review, see Raz, 2000). A recent cross-sectional volumetric study of 200 healthy adults, for example, found that the anterior prefrontal cortex (PFC), including most of Brodmann's area 45, shrunk an average of 5.36% per decade (Raz et al., 2004). For older adults, this loss of volume was second in severity only to the hippocampus, which decreased in volume 6.38% per decade after age 50. In a region that included Brodmann's area 47, the most anterior portion of LIPC, shrunk 3.35% per decade.

Lateral PFC regions running along the left inferior frontal gyrus (Brodmann's areas 45, 47, and 44/6) have been implicated in numerous studies of controlled semantic retrieval. In one commonly used task, participants are shown a concrete noun and must generate a semantically related verb (e.g., Petersen et al., 1988, 1989; Martin et al., 1995; Raichle et al., 1994). The verb-generation task requires control because it constrains the participant to generate a verb even when the most common associate is not a verb. These LIPC regions are also active during performance of semantic classification tasks (e.g., deciding whether a word is abstract or concrete) in older (Logan et al., 2002) as well as young (e.g., Kapur et al., 1994; Demb et al., 1995; Gabrieli et al., 1996; Wagner et al., 1998, 2000) adults. Repetition of these tasks has been associated with faster behavioral responses and reduced neural activation in these regions (e.g., Demb et al., 1995; Gabrieli et al., 1996; Wagner et al., 1997), even when the task changes across exposures (Dobbins et al., 2004; Wagner et al., 2000; but see Thompson-Schill, 1999).

Studies of patients with LIPC lesions also underscore the contention that this region is necessary to support semantic retrieval when controlled processing is required. As mentioned above, patients with left frontal lobe lesions perform poorly in letter and category fluency tasks, which rely on self-initiated search and retrieval strategies (Baldo & Shimamura, 1998). LIPC patients were impaired in a verb generation task, but only when there were many competitors among the set of possible responses (Thompson-Schill et al., 1998). In another study, patients with left frontal lobe lesions showed normal semantic priming with unambiguous words, but showed no facilitation for ambiguous words despite the presence of disambiguating contextual information (Metzler, 2001).

While it seems clear that LIPC regions subserve control processes that can support semantic retrieval, the precise nature of these processes is controversial. Under one theory, LIPC is engaged whenever automatic, data-driven processes are insufficient to elicit activation of a semantic network in posterior areas (Badre & Wagner, 2002b; Wagner, 2000, 2001). In such cases, LIPC is called upon to send a top-down control signal to bias relevant semantic networks in posterior association cortex. An alternative theory is that LIPC does not support semantic retrieval, per se, but rather is engaged whenever control is needed to select from competing representations in working memory (Thompson-Schill, 1998, 1999a).

In an attempt to characterize frontally mediated control processes that support semantic retrieval, some researchers have used a semantic repetition priming paradigm in which the task changes between the first and second exposure of a stimulus (Thompson-Schill et al., 1999a; Wagner et al., 2000). This paradigm assumes that the information accessed to perform the first task will be made more available to retrieval and will thus compete with the information needed to perform the second task upon stimulus repetition.

Previous behavioral research has demonstrated that priming is eliminated or reduced when a semantic judgment made at second exposure is different than that at first exposure (Franks et al., 2000; Thompson-Schill & Gabrieli, 1999b; Thompson-Schill & Kan, 2001; Vriezen, Moscovitch, & Bellos, 1995). Across-task priming has been studied in only a few neuroimaging studies, however. Using a verb generation task and fMRI, Thompson-Schill and colleagues (1999a) observed significant behavioral facilitation (i.e., faster RTs relative to baseline) in across-task and within-task conditions. A corresponding pattern of generalized neural priming was observed in ventral temporal regions in both conditions. In LIPC, the within-task condition elicited neural priming as well, replicating the findings of many past studies (e.g., Demb et al., 1995, Raichlë et al., 1994; van Turennout, Bielamowicz, & Martin, 2003; Wagner et al., 2000). Across-task priming, however, resulted in *greater* activation in LIPC relative to novel words, paradoxically reflecting a cost for previous exposure. This pattern of activity was consistent with the authors' hypothesis that the role of LIPC is to select from competing items in working memory (i.e., the performance of one semantic task at initial exposure facilitated later re-instantiation of that information, which then needed to be actively suppressed when a competing piece of information needed to be selected; Thompson-Schill et al., 1998; 1999a).

Some studies, however, have failed to observe a neural cost when the retrieval task is switched between initial and repeated exposures. Demb and colleagues (1995) observed neither facilitation nor a cost in LIPC in the across-task priming condition. Wagner and colleagues (2000) observed task-specific priming, a repetition-related reduction only in the within-task condition, in anterior LIPC (BA 45/47). They found no increased activation in LIPC in the across-task condition; instead, neural priming was observed in both within-task and across-task conditions in posterior LIPC (BA 44/6). The authors hypothesized that the pattern of task-specific priming in anterior LIPC indicated that that region subserved semantic analysis, while the generalized priming in posterior LIPC supported the contention that it participates in phonological analysis (Fiez, 1997; Price et al., 1997; Poldrack et al., 1999). The common feature across both exposures in the across-task condition was the presentation of the probe word itself. It is possible, however, that Demb et al. (1995) and Wagner et al. (2000) failed to observe above-baseline selection-related activity in posterior LIPC because the two tasks used were not similar enough to elicit competition. In particular, in both of these studies, one task was a non-semantic task, while the other was a semantic task.

The present study used fMRI to compare the neural effects of within-task and across-task repetition priming in young and older adults using only semantic classification. The experiment had two primary objectives: (a) to adjudicate between the two proposed hypotheses about the role of LIPC in semantic retrieval, and (b) to determine the extent to which PFC processes supporting these cognitive control processes differ in healthy young and older adults.

We predicted that older adults would show normal within-task repetition priming in LIPC regions, as has been observed previously (Lustig & Buckner, 2004). The critical question was whether older adults would exhibit alterations relative to young adults in BOLD-dependent activity during the across-task condition. Evidence of an impairment in controlled retrieval would include neural facilitation that did not differentiate between the within- and across-task conditions in anterior LIPC regions where task-specific repetition priming has been observed in young adults (Wagner et al., 2000). Evidence of an age-associated impairment in selection would include brain activation patterns that demonstrated a failure by older adults to show a neural cost for across-task priming in areas where young adults exhibited this type of selection-related activity.

The current investigation also had the potential to distinguish between two accounts of repetition priming. Repetition-related reductions in response time and neural activity have typically been attributed to the increased availability of semantic representations through the tuning — and thus, increased efficiency — of neural networks supporting these representations (Wiggs and Martin, 1998). A recent study, however, suggested that what is facilitated in semantic repetition priming is not access to recently activated representations but rather access to recently learned stimulus-response (S-R) mappings (Dobbins et al., 2004). In that study, opposing behavioral responses were elicited at the initial and repeated exposure by switching the focus of the repeated semantic task (judgment of bigness at time one vs. judgment of smallness at time two). Because the same size information was presumably used to make both the bigness and smallness judgments, the resulting reduction in neural priming in posterior LIPC was interpreted as an indication that repetition priming results may in some cases reflect facilitation of specific stimulus-response mappings, rather than increased availability of semantic representations. In the current experiment, the correct answer to half of the across-task trials was the same at study and test, and half were different across the two exposures. This design allowed us to investigate the relative contributions of response and representational facilitation in LIPC and other brain regions in young and older adults. Importantly, this analysis also allowed us to determine whether any interference-related activity in older adults reflected failures in response inhibition due to interference from a previously conflicting S-R mapping, rather than semantic inhibition due to interference from conflicting stimulus representations.

## Methods

Participants. We enrolled 21 young (age 18-35, M=21.7, nine female) and 21 older (age 60-84, M=70.8, 10 female) right-handed adults according to procedures approved by the MIT Committee on the Use of Humans as Experimental Subjects. Recruitment procedures and eligibility requirements were identical to those described in Chapter 2, Experiment 3. Older participants had an average of 18.0 years of education, compared with 16.1 for young adults, many of whom were still undergraduate students. In addition to the session in the scanner, older participants subsequently completed a series of standardized cognitive tests that included tasks shown to reflect frontal and temporal lobe function (Table 1; Glisky et al., 1995, 2001). All older participants included in the analysis had Mini-Mental Status Examination scores of at least 27, with the exception of one male participant who received a score of 26 and one female participant who received a score of 25. Because both participants performed above the bottom quartile of older adults in accuracy on the semantic classification tasks, they were included in the subsequent analyses.

Table 1. Performance on Standardized Cognitive Tests by Older Participants and Estimates of Published Normative Data for Adults Aged 65 to 75 Years[a].

| | **Older Adults** M(SD) | **Norm** M(SD) |
|---|---|---|
| Total Number of Words in Letter Fluency (FAS) | 48.0(15.1) | 39.2 (11.9) |
| Mental Arithmetic, WAIS-R | 16.3 (3.0) | 12 (4.0) |
| Mental Control, WMS-R | 5.7 (0.5) | 5.0 (1.5) |
| Backward Digit Span, WMS-R | 6.1 (1.5) | 7.6 (2.0) |
| Visual Paired Associates II (Delayed Recall), WMS-R | 5.5 (0.7) | 4.0 (2.5) |
| Logical Memory I (Immediate Recall), WMS-R | 28.5 (7.3) | 24.0 (7.5) |
| California Verbal Learning Test, Long-Delay Cued Recall (Delis, Kramer, Kaplan & Ober, 1987) | 11.9 (2.4) | 10.3 (3.7) |

[a] From Glisky, Polster, & Routhieaux, 2001.

Behavioral Methods. We created a stimulus list of 256 concrete common nouns that could be rated reliably across participants in response to each of three questions: (1) SMALL?; (2) STRAIGHT?; or (3) ORGANIC?. Pilot testing ensured that each word elicited the same response to each question from a majority of pilot participants (~90%). In addition, the words were selected such that one-eighth were rated as small, straight, and organic; one-eighth were small, straight, and not organic; one-eighth were small, not straight, and not organic; and so on. Thus, a correct response to one semantic judgment about a particular item was not predictive of a correct response to either of the other possible semantic judgments.

Using these 256 common nouns, 21 unique study-test list sets were created, such that each list was seen by one young and one older participant. In each set, three quarters, or 192 of the nouns were to be presented at study; the remaining 64 were set aside for unprimed test trials. Of the 192 words used in the study list, one third were assigned to the Within-Task condition and the remaining two thirds were assigned to the Across-Task condition. Within each condition, the normative answer to the size, shape, or composition judgment presented in each trial was "yes" for half of the words and "no" for the remainder, based on pilot testing. At test, all 256 words were presented for a size judgment only. In the Within-Task condition, the semantic judgment task was the same at test as at study; thus, the correct response at study was always congruent with the correct response at test. In the Across-Task Condition, the semantic judgment task differed at study and test. In addition, the normative response to half of the Across-Task words was congruent with the normative response to the test question (e.g., "ORGANIC? olive" at study followed by "SMALL? olive" at test), while for the remainder of Across-Task trials, the normative responses at study and test were incongruent ("ORGANIC? needle" at study followed by "SMALL? needle" at test). Each list was counterbalanced to ensure that word length and frequency (Kucera & Francis, 1967) did not differ across conditions.

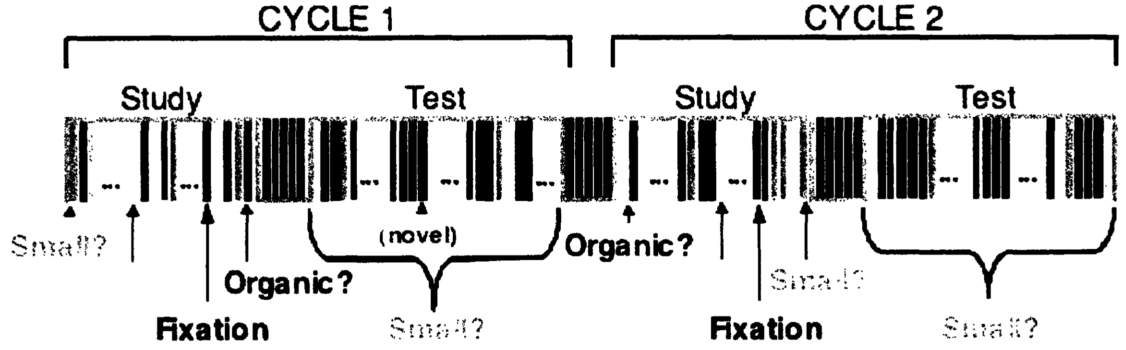


**Figure 1:** Schematic of the mixed block/event-related design showing the two study-test cycles that occurred in each of the two scan runs.

Before entering the scanner, participants performed practice trials until it was clear they understood the three semantic judgment tasks they would be performing. Once in the scanner, stimuli were presented in white font on a black background using Matlab (Mathworks, Natick, MA). Stimuli were presented over two runs using a mixed block/event-related design (Figure 1). Each run comprised two cycles of study and test blocks, with 30-sec fixation blocks interleaved between the study and test blocks. Within each task block, words were presented visually in a pseudo-randomized order, jittered by fixation null events that varied in duration from 2.5 sec to 10 sec in 2.5 sec increments. The order of conditions and fixation null events was determined using an optimization algorithm (Dale, 1999). In each study block, participants viewed 48 common nouns, and made a yes/no judgment of size ("Is it smaller than a 13-inch box?"), shape ("Are its edges more straight than curvy?"), or composition ("Is it made of organic material?") for each word (i.e., 16 trials/task). In each test block, the 48 studied words were re-presented along with 16 novel words. For all words in the test blocks, participants made a size judgment. Thus, for repeated words, the semantic judgment made at repetition was either identical to (*Within-Task*: size→size) or different from (*Across-Task*: shape→size, or composition→size) the judgment made at first exposure, with repetition of the target word being identical across the Within-Task and Across-Task conditions (Figure 2).

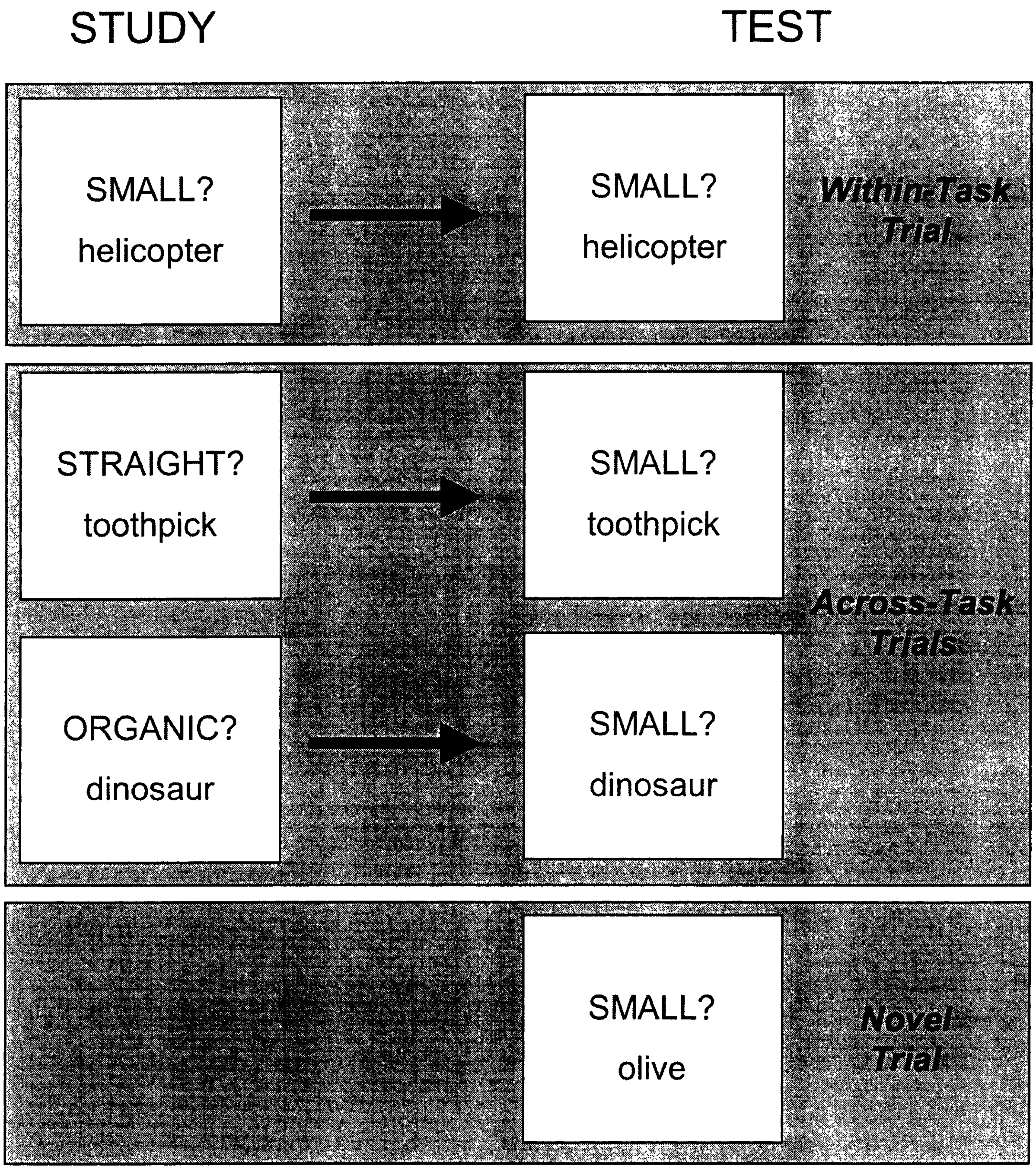


**Figure 2:** Schematic of study and test trials.

Each trial began with the presentation of a cue indicating the type of semantic judgment to be made (e.g. "SMALL?") above a fixation cross. After 500 msec, the fixation cross was replaced by the stimulus word for 400 msec, which itself was replaced after 1000 msec by a fixation cross again. All type was then removed from the screen for 600 msec. There was no inter-trial interval. Participants made a yes-no response by pressing one of two keys with their left index or middle finger.

MRI acquisition procedure. Functional MRI data were acquired using a gradient-echo echo-planar sequence (repetition time = 2500 msec, echo time = 30 msec, 21 axial slices aligned parallel to the AC-PC plane, 3.125 X 3.125 X 5 mm, 1-mm interslice skip, 432 volumes per run) in a 1.5T Siemens Sonata scanner. High-resolution T1-weighted (MP-RAGE) structural images were collected for anatomical visualization. Cushions were placed around each participant's head to minimize head movement. Visual stimuli were presented on a projection screen reflected on a mirror attached to the head coil; responses were recorded from finger presses on a magnet-compatible button box.

MRI analysis procedures. We analyzed the data with SPM99 (Wellcome Department of Cognitive Neurology, London), using standard preprocessing procedures. Structural and functional images were normalized to EPI and T1-weighted anatomical templates based on the MNI305 stereotaxic space. Images were resampled into 3-mm cubic voxels and spatially smoothed with an 8-mm full-width half maximum isotropic Gaussian kernel.

The statistical analyses were performed using the general linear model. Trials from each condition were modeled using a canonical hemodynamic response and its first-order temporal derivative, using only trials in which participant responses at both study and test were correct (i.e., matching the normative responses for those words). The remaining trials, in which participants made an error on either or both exposures, were modeled separately. Effects were estimated using a subject-specific fixed-effects model, with session-specific effects and head motion treated as confounds. Linear contrasts were used to obtain subject-specific estimates for each effect. The resulting estimates were entered into a second-level analysis treating participants as a random effect, using a one-sample t test against a contrast value of zero at each voxel. The resulting regions of activations for main effects were considered reliable if they comprised at least five contiguous voxels that exceeded an uncorrected threshold of $p<.001$. Age X Condition interactions were considered reliable if five contiguous voxels exceeded an uncorrected threshold of $p<.005$, following Cabeza et al. (1997).

Region-of-interest (ROI) analyses were undertaken to further characterize the degree to which neural responses differed across conditions and age groups in functionally defined, and a priori predicted, prefrontal (PFC) regions. For these analyses, spherical ROIs were identified by selecting all significant voxels within an 8-mm radius of the maxima defined by the contrast of interest. Signal within each ROI was then calculated for each subject by selectively averaging the data with respect to peristimulus time for trials in each condition. The time point representing the peak signal change was determined by averaging the signal change relative to fixation baseline across all conditions and all participants. Integrated signal change (i.e. the sum of signal change relative to fixation at the peak time point and at the two time points surrounding the peak) was entered into a mixed-effects analysis of variance (ANOVA) that treated priming condition as a repeated measure and age group as a between-participants variable, with participants as a random effect.

## Results

Behavioral results. Behavioral effects were considered reliable at an α-level of 0.05. RTs and response accuracy were analyzed using a mixed-effects ANOVA with Priming Condition (Within-task, Across-Task/Congruent-Response, Across-

Task/Incongruent-Response for study trials, with the addition of Novel for test trials) as a within-participants variable and age group as a between-participants variable.

*Accuracy*. Response probabilities were analyzed for study and test trials. Only 2.5 sec was allowed for each response. Thus, for a portion of trials no response was recorded. Older adults made significantly fewer responses to study trials in the allotted time (90.4%) than did young adults (97.0%), F(1,40)=7.06, p<.05, but the two groups did not differ in the number of test trials recorded (96.4% across the two groups), F(1,40)=1.80, *ns*. The number of study responses also differed as a function of condition: Significantly fewer responses were recorded for the shape and composition judgment questions used for Across-Task study trials than to the size judgment questions used for Within-Task study trials, F(1,40)=3.50, p<05. The Age X Condition interaction was significant, F(2,80)=10.11, p<.001. Post hoc contrasts revealed that the main effect of Priming Condition was driven entirely by the older adults as the discrepancy in accuracy between Within- and Across-Task study trials was observed only among older participants, for congruent-response trials t(20)=4.70, p<.001, and for incongruent-response trials t(20)=4.38, p<.001.

Of the trials in which responses were recorded, older adults were marginally less accurate (88.2%) than were young adults (91.0%), F(1,40)=3.60, p=.07. The effect of Priming Condition was significant, F(3,120)=10.00; p<.001, with higher accuracy for the Within-Task study trials (93.6%) than for the Across-Task trials, whether in the congruent (88.4%), t(41)=5.01, p<.001, or incongruent (86.9%) response condition, t(41)=6.45, p<.001. There was a trend for an interaction between Age Group and Priming Condition (p=.06), but t tests revealed that the pattern of performance was qualitatively similar in young and older adults.

In addition, we examined the probability that participants would respond correctly as a proportion of all trials (i.e., including ones where responses were not recorded; Table 2). The hit rate was greater for young than older adults, F(1,40)=7.92, p<.01. The effect of Priming Condition was once again significant, F(2,80)=40.53, p<.001, with lower hit rates for both Across-Task trial types than Within-Task trials. Although this pattern was similar in young and older adults, a significant Priming Type X Age Group interaction, F(2,80)=9.34, p<.001, indicated that the gap in accuracy between Within-Task and Across-Task trials was greater in older than young adults.

Table 2. Correct Responses as a Proportion of All Test Trials.

| | | Within-Task | | Across-Task/ Congruent Response | | Across-Task/ Incongruent Response | | Novel | |
|---|---|---|---|---|---|---|---|---|---|
| | | M | SE | M | SE | M | SE | M | SE |
| Young | Study | 0.94 | 0.02 | 0.89 | 0.01 | 0.89 | 0.02 | na | na |
| | Test | 0.95 | 0.01 | 0.97 | 0.02 | 0.92 | 0.01 | 0.94 | 0.01 |
| Older | Study | 0.92 | 0.02 | 0.81 | 0.03 | 0.80 | 0.03 | na | na |
| | Test | 0.95 | 0.02 | 0.95 | 0.02 | 0.91 | 0.02 | 0.92 | 0.02 |

In contrast to study trials, on test trials, in which only size judgments were made, the number of responses recorded did not differ as a function of Age Group, F(1,40)=1.70, ns, or Priming Condition, F(3,120)<1, and the two variables did not interact, F(3,120)=1.00. Accuracy of trials in which participants responded did not differ as a function of Age Group, F(1,40)<1, ns. There was a main effect of Priming Type, however, as participants were less accurate in responding to Across-Task/Incongruent-Response trials than all other trials types, and Novel trials were less accurate than Across-Task/Congruent-Response trials. Age Group and Priming Type did not interact, F(3,120)<1, ns.

In terms of accuracy as a function of all trials (i.e., number of hits relative to the total number of trials), the effect of Priming Condition was significant, F(3, 120)=10.00, p<.001. Participants were less accurate in responding to Novel trials than any of the repetition conditions: Within-Task, t(41)=2.35, p<.05; Across-Task/Congruent-Response, t(41)=2.42, p<.05; Across-Task/Incongruent-Response, t(41)=4.94, p<.001. In addition, participants were more accurate on Within-Task trials than Across-Task/Congruent-Response, t(41)=3.11, p<.005, and Across-Task/Incongruent-Response trials, t(41)=5.136, p<.001. We also observed an effect of response congruency, as participants were more accurate when correct responses at test were congruent with those at study, F(41)=5.62, p<.001. Young and older adults did not differ, F(1,41)=1.01, p>.30, and there was no interaction between Priming Type and Age Group, F(3,120)<1.

Response latencies. The analysis of median response latencies included only trials on which participant responses were accurate (i.e., matched normative responses) at both study and test (Figure 3).

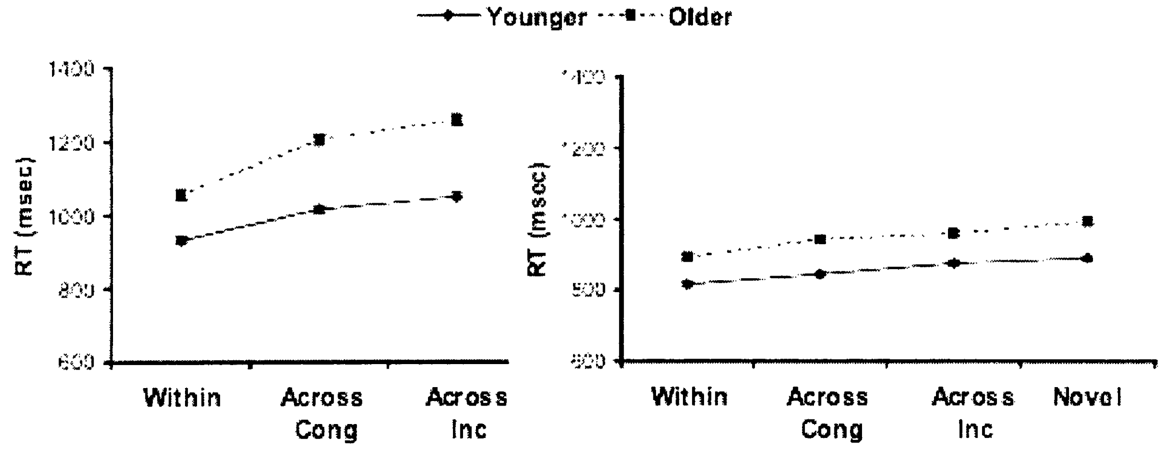


Figure 3: At left, RTs for study trials for With-Task, Across-Task/Congruent Response, and Across-Task/Incongruent Response conditions. At right, test trials RTs for the same conditions and Novel, unprimed trials.

The analysis of study trials revealed a main effect of Age Group, F(1,40)=15.63 p<.001, as older participants were slower to respond than were young adults. In addition, the effect of Priming Condition was significant, F(2,80)=79.12, p<.001. For both age groups, responses were faster for Within-Task trials than Across-Task/Congruent-Response trials, which in turn elicited faster responses than for Across-Task/Incongruent-Response trials. Thus, participants were faster to respond to Across-Task/Congruent-Response trials than to Across-Task/Incongruent-Response trials, even though they had not yet made the incongruent test response. This unexpected result is addressed in the Discussion below. We found an interaction between Age Group X Priming Type, F(2,80)=5.34, p<.01, reflecting a more pronounced priming effect in both Within- and Across-Task conditions in older relative to young adults. This difference in response times between the two congruency conditions was no greater for the older than young adults F(1,40)<1, however, suggesting that the type of semantic task performed (i.e., size vs. shape vs. organic judgment) rather than the stimulus-response mapping was driving the age-related effect.

The critical measure of priming was the latency pattern across test trial types (Figure 1B). Unlike the study trials, at test participants performed the same task across all conditions, with the only difference being their history with each of the stimulus words. Thus, RT differences could not be attributed to differences in the task per se, but rather to differences in the effects of prior exposure.

The effect of Priming Condition on RT for test trials was significant, F(3, 120)=49.61, p<.001. All three repetition conditions showed priming relative to Novel trials: Same Task, t(41)=11.12, p<.001; Across-Task/Congruent-Response, t(41)=6.31, p<.001; Across-Task/Incongruent-Response, t(41)=3.29, p<.003. In addition, responses to Within-Task trials were faster than to Across-Task/Congruent-Response, t(41)=5.59, p<.001, and Across-Task/Incongruent-Response trials, t(41)=8.51, p<.001. We also found an effect of response congruency, as participants were quicker to respond when correct responses at test were congruent with responses at study, F(41)=3.10, p<.005. Overall, older adults were slower to respond than were young adults, F(1, 40)=9.68, p<.004. Age Group and Priming Condition did not interact, F(3,120)=1.30, p>.20, however, showing that the pattern of priming did not differ significantly across the two age groups.

## fMRI Results

Effect of Semantic Competition. To investigate the effect of semantic interference, fMRI data were first analyzed by collapsing across the two Across-Task response conditions, congruent and incongruent. Analyses were conducted on test trials in three conditions: Novel, Within-Task, and Across-Task trials. The aim was to identify whether there were regions in LIPC that showed one of two patterns: (a) *generalized priming,* in which activation is greater for Novel trials than either of the two repetition conditions, and activation levels in the two repetition conditions do not differ from each other; (b) *task-specific priming*, in which repetition-related reductions occurred only during Within-Task trials, and activation for these trials was reduced relative to Across-Task trials, demonstrating the sensitivity of neural responses to differences in the dimension of semantic information accessed.

To identify regions that showed task-specific repetition priming, we conducted a voxel-wise contrast of Novel > Within-Task trials across all participants. Regions showing repetition-related response reductions for Within-Task trials included anterior and posterior regions of LIPC and the fusiform gyrus. To investigate potential age differences within PFC regions of interest, we extracted time courses of activation for each condition.

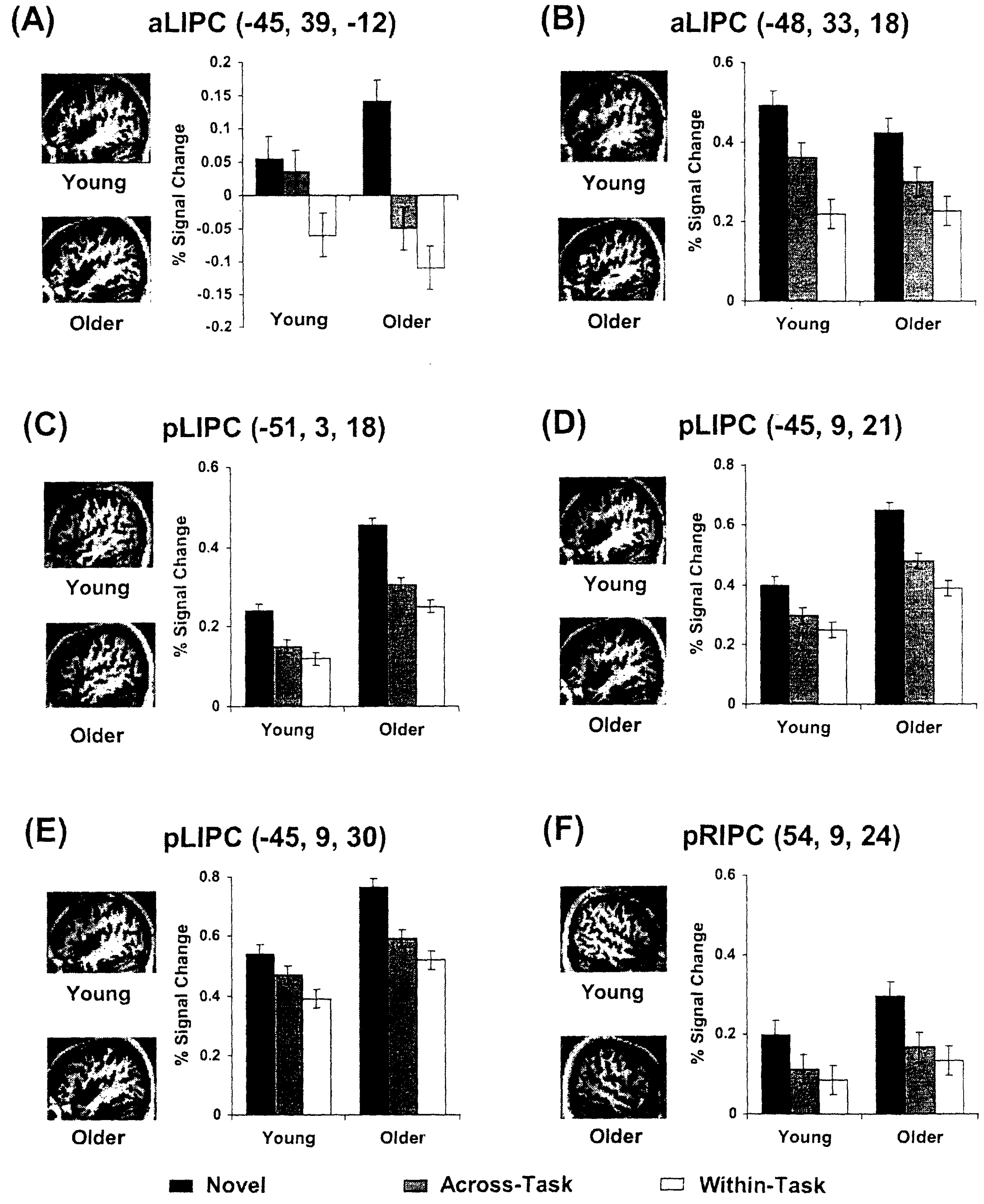


**Figure 4:** At left of each, brain slices from a representative Young and older participant. At right, integrated percent signal change for each priming condition in anterior LIPC (A and B), posterior LIPC (C through E), and posterior right inferior prefrontal cortex (F). All clusters were defined by the contrast of Novel > Within-Task trials, with the exception of (E), which was defined by the Novel > Across-Task contrast.

We observed within-task priming in two clusters in anterior LIPC (aLIPC) and three in posterior LIPC (pLIPC). One of the aLIPC clusters was centered in the most anterior portion of LIPC (BA 47, MNI coordinates –45, 39, -12, Figure 4A). An ANOVA of integrated signal change revealed a main effect of Priming Condition, F(2,80)=7.94, p<.002. We found no main effect of Age Group, F(1,40)<1. Although the interaction between Age Group and Priming Condition, F(2,80)=2.09, p=.13, did not reach significance, planned contrasts revealed that the priming effects were specific to older adults. No repetition-related response reductions were observed in any condition among young adults. Older adults, however, showed significant response reductions in the Within-Task condition, t(20)=3.16, p=.005 and in the Across-Task condition, t(20)=2.20, p<.05. Moreover, an overlapping region of activation (coordinates of -45, 33, -12) was identified by a voxel-based analysis showing regions where repetition-related response reductions for Across-Task trials were greater in older than young adults, as indicated by an Age X Condition (Novel vs. Across-Task) interaction. Analyses of time courses revealed generalized priming in older adults in this region: BOLD responses were reduced relative to Novel trials in the Within-Task t(20)=2.32, p<.05, and Across-Task t(20)=4.20, p<.001, conditions, and response levels did not differ across the two primed conditions t(20)=1.01, p>.30. In contrast, among young adults, BOLD responses to Within-Task trials were reduced relative to Across-Task trials, t(20)=2.12, p<.05, and the magnitude of activation in Within-Task trials was lower than in Novel trials, although this difference was not significant, t(20)=1.69, p=.11.

The second aLIPC cluster identified by the Novel – Within-Task contrast was located in Brodmann's area 47/45 (-48, 33, 18; Figure 4B). As in the aforementioned aLIPC cluster, activation differed as a function of Priming Condition, F(2,80)=11.23, p<.001, but there was no main effect of Age, F(,40)<1. and no Age X Condition interaction, F(2,80)<1. Although the pattern of priming was similar in young and older adults, planned contrasts again revealed that the repetition-related reductions generalized across tasks to a greater extent in older than young adults. Young participants exhibited task-specific priming: repetition-related reductions were observed only in the Within-Task condition, t(20)=3.01, p=.007. Activity also was reduced in the Within-Task condition relative to the Across-Task condition, t(20)=3.02, p<.01. In contrast, among older adults, significant priming occurred in both the Within-Task, t(20)=2.67, p=.015, and Across-Task repetition conditions, t(20)=2.11, p<.05, and these two conditions did not differ from each other, t(20)=1.09, p=.29.

In addition to the aLIPC clusters, the contrast of Novel > Within-Task trials revealed three partially overlapping clusters of activation in pLIPC (~BA 44/6). In contrast to the pattern seen in aLIPC , neural priming generalized across both task conditions in both age groups in two of the clusters (coordinates of -51, 3, 18, Figure 4C, and –45, 9, 21, Figure 4D). In the third cluster (coordinates of -45, 9, 30, Figure 4E), generalized priming was observed in older adults, and in young adults, though priming was not significant in the Within-Task condition relative to the Novel baseline, t(20)=1.70, p=.10, the level of activation did not differ between Within- and Across-Task conditions, unlike in the aLIPC clusters.

A voxel-wise contrast of New – Across-Task trials intended to identify regions that showed across-task priming in young and older adults revealed two clusters in pLIPC (coordinates of -51, 6, 15 and –45, 12, 21), both of which overlapped clusters identified in the New > Within-Task contrast. This result was not surprising, given the observation of generalized priming in those clusters. These clusters were nevertheless analyzed to confirm the pattern of results seen in the partially overlapping clusters discussed above. Results showed the repetition-related signal reductions generalized across Within-task and Across-Task trials equally in young and older adults in each cluster. Further, planned contrasts confirmed that significant neural priming occurred in both repetition conditions in both young and older adults in both clusters. The two repetition conditions did not differ from each other in either cluster.

Because older adults have exhibited greater bilaterality in prefrontal activity in a number of domains including episodic retrieval (see Chapter 2, this manuscript) and working memory (Reuter-Lorenz et al., 2000), we included right inferior prefrontal cortex (RIPC) among our regions of interest. Only one cluster of activity was observed in RIPC. The Novel > Across-Task contrast identified a cluster in posterior RIPC (coordinates of 54, 9, 24, Figure 4F), which showed a similar pattern of activity in young and older adults. We found no Age X Condition interaction, $F(2,80)<1$. Young adults exhibited priming in both Within-Task, $t(20)=2.12$, $p<.05$, and Across-Task trials, $t(20)=2.24$, $p<.05$, and the two repetition conditions did not differ from each other, $t(20)<1$. In older adults, significant neural priming occurred in the Across-Task condition, $t(20)=3.00$, $p<.01$, and a trend for priming in the Within-Task condition, $t(20)=2.03$, $p=.06$. As with the young adults, the two repetition conditions did not differ from each other, $t(20)<1$.

We next conducted a voxel-wise contrast of Across-Task – Novel trials to determine whether there were regions of prefrontal cortex that exhibited a neural cost associated with prior processing of a stimulus in a competing semantic dimension. No areas of activation were observed in prefrontal cortex, even at a threshold of $p<.005$. To verify that neither young nor older adults exhibited a neural cost in LIPC from across-task competition, we also conducted the contrast separately for each age group. No regions of LIPC showed greater activation for Across-Task trials than Novel trials for either of the two age groups, at p<.001 or p<.005. In other PFC regions, activity was observed at p<.005 in young adults in frontopolar cortex (coordinates of –27, 48, 0; ~BA10) and in older adults in right dorsolateral PFC (coordinates of 35, 30, 42, ~BA9).

Effect of response competition and facilitation. To directly test whether the greater neural facilitation seen for Within-Task relative to Across-Task trials in LIPC may have been driven by increased availability of learned stimulus-response mappings, a contrast was created by subtracting congruent from incongruent response trials in the Across-Task condition. No regions showed differential activation at a threshold of p<.001. At a more lenient threshold of p<.005, however, we found a cluster of activity in pLIPC (–45, 12, 6; Figure 5). Extracting data from time courses revealed a priming effect for congruent but not incongruent trials in young adults, t(20)=2.40, p<.05, though the two types of Across-Task trials did not differ significantly from each other, t(20)=1.64, p>.10. In older adults, priming was observed in both Within-Task, t(20)=2.11, p<.05, and Across-Task/Congruent-Response trials, t(20)=2.29, and congruent responses elicited significantly less activation than did incongruent responses, t(20)=2.55. The pattern observed in this cluster, however, was not found in any of the above-mentioned clusters in LIPC. In each of the aLIPC and pLIPC regions mentioned above, BOLD responses did not differ as a function of response congruency in young or older adults.

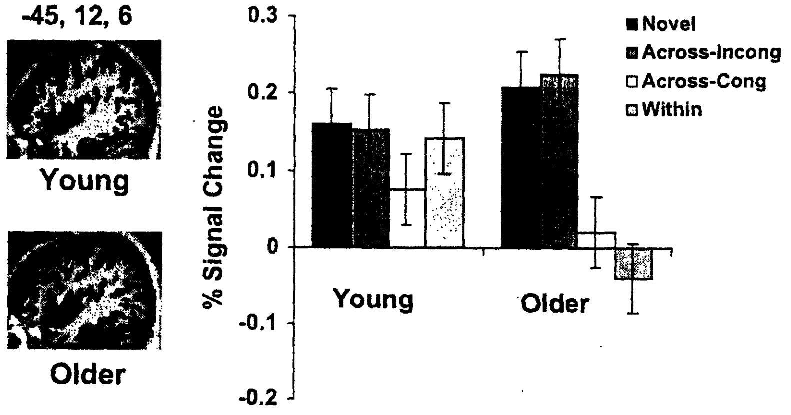


**Figure 5:** Integrated percentage signal change for a pLIPC cluster defined by the contrast of Across-Task/Incongruent Response > Across-Task/Congruent Response.

## Discussion

The present study had two primary goals. One goal was to test two theories about the role of LIPC during semantic retrieval. The second goal was to investigate whether the older adults would show different patterns of activity in LIPC during controlled semantic retrieval.

### The Role of LIPC in Semantic Retrieval

According to one theory of LIPC function, this region does not directly support semantic retrieval but rather is engaged during semantic retrieval tasks only when cognitive control is needed to select from competing representations in working memory (Thompson-Schill et al., 1999a). An alternative theory is that LIPC supports controlled retrieval in a material-specific manner, engaging posterior subregions to retrieve and maintain phonological representations and anterior subregions to access and maintain more abstract, semantic representations (Badre & Wagner, 2002b; Wagner et al., 2000, 2001). The two theories predict different patterns of LIPC activity in across-task semantic repetition priming, the task used in the present study. The former theory would predict a neural cost for prior processing of previously relevant information, as the familiar but now-irrelevant information forms a prepotent competitor for novel semantic information demanded by the new task. The latter theory predicts facilitation in regions supporting phonological maintenance and task-specificity, but no neural cost, in regions supporting the access of semantic features of stimuli.

The current study found no evidence of a neural cost associated with across-task priming in LIPC regions, and thus did not provide support for the selection hypothesis. We observed repetition-related decreases in young adults in both anterior and posterior regions of LIPC. In the young adults, priming in aLIPC regions was task specific, occurring only when the features accessed at test were identical to those accessed at study. Neural priming was also observed in pLIPC, but the degree of repetition-reductions was not influenced by the particular dimension of semantic information accessed as neural priming was equivalent in the Within- and Across-Task conditions. These results are consistent with the theory that LIPC supports controlled semantic retrieval.

It is unclear why the present study failed to replicate a previous observation of a neural cost in pLIPC during across-task priming (Thompson-Schill et al., 1999a). One possibility relates to differences in the behavioral paradigms used in the two studies. Thompson-Schill and colleagues (1999a) used a word generation task rather than a semantic decision task. The productive demands of a generation task may foster greater interference than does a yes/no semantic classification task. This possibility would be consistent with behavioral evidence that production tasks are more impaired by divided attention at encoding than are classification tasks, suggesting that the former are more dependent on frontal lobe function (Gabrieli et al., 1999). Alternatively, it also is plausible that the intrusion of competitors at the priming test phase would increase the amount of phonological information being accessed, and that this effect could be more pronounced in a word generation than a classification task. This in turn would be expected to increase activation in pLIPC as a result of its sensitivity to variations in verbal maintenance load (Rypma et al., 1999).

A second possibility relates to differences in experimental design across the two studies. In Thompson-Schill et al. (1999a), the semantic classification tasks were counterbalanced such that each task was performed equally often by participants. A limitation of the present study's design was that one of the three semantic tasks used in the study was performed far more frequently than the other two. A size judgment was required on a third of study trials and on all of the test trials.[5] The pattern of response latencies during the study trials suggests that participants were affected by the preponderance of size-judgment trials. RTs for shape and organic judgments during the study trials were shorter when the correct response was congruent with what it would have been if a size judgment had been required. Thus, it appears that participants either consciously or unconsciously accessed information about the size of a given stimulus even before a size judgment was required. This may have been a strategic response to the speeded nature of the semantic classification task, or it may have been an unconscious response. In either case, if participants were already accessing size information during study trials, it may have reduced the overall level of competition produced at test. A task design that fostered greater competition may have elicited the type of neural cost that was absent in the present study. While it is impossible from this null result to rule out the possibility that one role of LIPC is to select from competing representations in working memory, the current results lend further support to the theory that aLIPC supports the controlled retrieval of specific semantic information from long-term memory stores. Further, the insensitivity of pLIPC to variations in semantic content builds on prior observations that implicate this region in the online maintenance of phonological codes (Fiez, 1997; Price et al., 1997; Poldrack et al., 1999).

---

[5] The intent of using the same semantic judgment tasks across all test trials was to ensure that differences in performance were not due to differences in the difficulty of the task itself. However, this goal could also have been achieved by counterbalancing semantic judgment tasks across the Across- vs. Within-Task conditions.

## Age Differences in the Neural Correlates of Semantic Retrieval

The second aim of the study was to determine whether the cognitive control processes mediated by LIPC during semantic retrieval were associated with similar patterns of BOLD responses in young and older adults. We found no age differences in behavioral priming. In young and older adults, repetition-related reductions in RTs occurred in both repetition conditions, with greater priming in the Within-Task than Across-Task condition. The two age groups did not show a significant difference in patterns of priming across the two repetition conditions, as evidenced by the lack of an age X condition interaction. However, planned contrasts revealed that the pattern of priming was not identical in the two groups. Young adults exhibited generalized priming in pLIPC and task-specific priming in aLIPC; older adults exhibited generalized priming in both LIPC regions. The finding of reduced specificity in older adults in regions supporting specific, controlled semantic retrieval in young adults is consistent with the hypothesis that older adults fail to gate irrelevant information from entering working memory (Hasher & Zacks, 1988). Moreover, the results converge with prior finding that increased Stroop interference in older adults was associated with increased BOLD response in aLIPC (BA 47; Langenecker et al., 2004; Milham et al., 2002).

In the present study, the unique pattern of LIPC activity emerged in older adults even though they exhibited a pattern of behavioral priming identical to that seen in the young adults. From a methodological point, matching behavior between two comparison groups is advantageous because it ensures that activation differences are due to age and not performance (See Footnote 2, Chapter 2 for further discussion of this approach in aging neuroimaging studies). The question, then, is whether the differing patterns carry functional significance. One response is that if these differences in neural activity occur even in a very simple semantic retrieval task (in which performance accuracy among older adults exceeded 90%), then these age effects in LIPC may have a greater impact on behavior as tasks become more demanding. Indeed, Milham et al. (2002) found aLIPC activity was a significant predictor of Stroop performance in older adults during incongruent (i.e., conflict) trials but not congruent trials.

### Stimulus-Response Mappings

Behaviorally, greater priming was observed for Across-Task trials in which responses at test were identical to responses at study than those in which responses differed across the two priming exposures. These behavioral results are consistent with recent data that suggest a portion of semantic repetition-priming effects can be attributed to learned stimulus-response mappings (Dobbins et al., 2004), rather than facilitated retrieval of recently accessed semantic representations. The S-R effect, however, does not account for all of the behavioral priming observed in either the current study or Dobbins et al. (2004). In both instances, participants exhibited behavioral priming even when S-R mappings did not match across the two stimulus exposures. Additionally, in the current study, priming was observed when *neither* the S-R mapping nor the specific dimension of semantic information retrieved was the same across the two exposures (i.e., in the Across-Task/Incongruent Response condition). For example, making a composition judgment at study (e.g., "is an olive organic?") facilitated later access to size information about that same object (e.g., "is an olive small?"). This conclusion must be interpreted with caution, however, because the congruency-related speeding seen during the study trials (i.e., at initial exposure) suggests that in the current study, size information about individual words was accessed even before it was probed.

At a neural level, repetition-related response reductions were observed among older adults in one cluster in pLIPC for trials with identical responses across both exposures, consistent with the interpretation that they were using stimulus-response mappings. The pattern of results in young adults is more difficult to interpret: If they were relying on stimulus-response mappings, the pattern of activation would suggest they were doing so only for Across-Task trials, not Within-Task trials. We observed no congruency effects in any of the other LIPC clusters that showed priming effects.

In conclusion, the present study found support for the hypothesis that anterior LIPC supports controlled semantic retrieval. The results failed to validate the theory that posterior LIPC mediates selection of items from working memory. Rather, the results were consistent with the hypothesis that pLIPC supports the maintenance of phonological representations in working memory. Older adults exhibited a pattern activity in pLIPC that was similar to that seen in young adults, but exhibited a more generalized pattern of neural priming in aLIPC, consistent with the theory that older adults fail to filter irrelevant semantic representations from working memory (Hasher & Zacks, 1988). These age differences in the pattern of neural activity appear to reflect age differences in semantic inhibition rather than response inhibition.

## References

Badre, D., & Wagner, A.D. (2002a). Prefrontal and medial temporal contributions to controlled semantic retrieval in cognitive aging. Proceedings of the Ninth Annual Meeting of the Cognitive Neuroscience Society.

Badre, D., & Wagner, A.D. (2002b). Semantic retrieval, mnemonic control, and prefrontal cortex. Behavioral and Cognitive Neuroscience Reviews, 1, 206-218.

Baldo, J. V., & Shimamura, A. P. (1998). Letter and category fluency in patients with frontal lobe lesions. Neuropsychology, 12: 259-267.

Balota, D. A., Black, S. R., & Cheney, M. (1992). Automatic and intentional priming in young and older adults: Reevaluation of the two-process model. Journal of Experimental Psychology: Human Perception and Performance, 18, 485-502.

Bowles, N. L., & Poon, L. W, (1985). Aging and retrieval of words from semantic memory. Journal of Gerontology, 40, 71-77.

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. Neuroscience and Behavioral Review, 26, 809-817.

Buckner, R.L. (2003). Functional-anatomic correlates of control processes in memory. Journal of Neuroscience, 23, 3999-4004.

Burke, D. M., & Peters, L. (1986). Word associations in old age: Evidence for consistency in semantic encoding during adulthood. Psychology and Aging, 1, 283-292.

Burke, D. M., & Yee, P. L. (1984). Semantic priming during sentence processing by young and older adults. Developmental Psychology, 20, 903-910.

Connelly, S.L., Hasher, L., & Zacks, R.T. (1991). Age and reading: The impact of distraction. Psychology and Aging, 6, 533-541.

Dale, A.M. (1999). Optimal experimental design for event-related fMRI. Human Brain Mapping, 8, 109-114.

Delis, D.C., Kramer, J., Kaplan, E., & Ober, B.A. (1987). The California Verbal Learning Test. San Antonio, TX: Psychological Corp.

Demb, J. B., Desmond, J. E., Wagner, A. D., Vaidya, C. J., Glover, G. H., & Gabrieli, J. D. E. (1995). Semantic encoding and retrieval in the left inferior prefrontal cortex: A functional MRI study of task difficulty and process specificity. Journal of Neuroscience, 15, 5870-5878.

Dobbins, I. G., Schnyer, D. M., Verfaellie, M., & Schacter, D. L. (2004). Cortical activity reductions during repetition priming can result from rapid response learning. Nature, 428, 316-319.

Esire, M. M. (1994). Dementia and normal aging: Neuropathology. In F.A. Huppert, C. Brayne, & D.W. O'Connor (Eds.), Dementia and normal aging (pp. 385-436), Cambridge, England: Cambridge University Press.

Fiez, J. A. (1997). Phonology, semantics, and the role of the left inferior prefrontal cortex. Human Brain Mapping, 5, 79-83.

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

Franks, J. J., Bilbrey, C. W., Khoo, G. L., & McNamara, T. P. (2000). Transfer-appropriate processing (TAP) and repetition priming. Memory & Cognition, 28, 1140-1151.

Gabrieli, J. D. E., Vaidya, C. J., Stone, M., Francis, W. S., Thompson-Schill, S. L., Fleischman, D. A., Tinklenber, J. R., Yesavage, J. A., Wilson, R. S. (1999). Convergent behavioral and neuropsychological evidence for a distinction between identification and production forms of repetition priming. Journal of Experimental Psychology: General, 128, 479-498.

Gabrieli, J. D. E., Desmond, J. E., Demb, J. B., Wagner, A. D. et al. (1996). Functional magnetic resonance imaging of semantic memory processes in the frontal lobes. Psychological Science, 7, 278-283.Hamm, V.P., & Hasher, L. (1992). Age and the availability of interference: Memory for previously relevant information. Psychology and Aging, 7, 56-64.

Glisky, E. L., Polster, M. R., & Routhieaux, B. C. (1995). Double dissociation between item and source memory. Neuropsychology, 9, 229-235.

Glisky, E. L., Rubin, S. R., & Davidson, P. S. R. (2001). Source memory in older adults: An encoding or retrieval problem? Journal of Experimental Psychology: Learning, Memory, and Cognition, 27, 1131-1146.

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

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

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. In D. Gopher & A. Koriat (Eds.), Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application (pp. 653-675). Cambridge, MA: MIT Press.

Horn H. L., & Cattell R. B. (1967). Age differences in fluid and crystallized intelligence. Acta Psychologica, 26, 107-129.

Howard D. V., Shaw R. J., & Heisey J. G. (1986). Aging and the time course of semantic activation. Journal of Gerontology, 41, 195-203.

Kapur, S., Rose, R., Liddle, P. F., Zipurksy, R. B., Brown, G.,M., Stuss, D., Houle, S., & Tulving, E. (1994). The role of left prefrontal cortex in verbal processing: Semantic processing or willed action. Neuroreport, 5, 2193-2196.

Kozora, E., & Cullum, C.M. (1995). Generative naming in normal aging: Total output and qualitative changes using phonemic and semantic constraints. The Clinical Neuropsychologist, 9, 313-325.

Kucera, H., & Francis, N. (1967). Computational Analysis of present-day American English. Providence: Brown University Press.

Langenecker, S. A., Nielson, K. A., & Rao, S. M. (2003). FMRI of healthy older adults during Stroop interference. NeuroImage, 21, 192-200.

Light, L. (1992). The organization of memory in old age. In FIM Craik & TA Salthouse (Eds.), The handbook of aging and cognition (pp. 111-166). Hillsdale NJ: Erlbaum.

Lima S., Hale S., & Myerson J. (1991). How general is general slowing? Evidence from the lexical domain. Psychology and Aging, 6, 416-425.

Logan, J. M., Sanders, A. L., Snyder, S. Z., Morris, J. C., & Buckner, R. L. (2002). Under-recruitment and nonselective recruitment: Dissociable neural mechanisms associated with aging. Neuron, 33, 827-840.

Lustig, C., & Buckner, R. L. (2004). Preserved neural correlates of priming in old age and dementia. Neuron, 42, 865-875.

Martin, A., Haxby, J.V., Lalonde, F.M., Wiggs, C.L., & Ungerleider, L.G. (1995). Discrete cortical regions associated with knowledge of color and knowledge of action. Science, 270, 102-105.

Mayr, U.,& Kliegl, U. (2000). Complex semantic processing in old age: Does it stay or does it go? Psychology and Aging, 15, 29-43.

Metzler, C. (2001). Effects of left frontal lesions on the selection of contex-appropriate meanings. Neuropsychology, 15, 315-328.

Milham, M. P., Erickson, K. I., Banich, M. T., Kramer, A.F., Webb, A., Wszalek, T., Cohen, N. J. (2002). Brain and Cognition, 49, 277-296.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. Annual Review of Neuroscience, 24, 167-202.

Moscovitch, M. (1995). Models of consciousness and memory. In M.S. Gazzaniga (Ed.), The cognitive neurosciences (pp. 1341-1356). Cambridge, MA: MIT Press.

Petersen, S. E., Fox, P. T., Posner, M. E., Mintun, M., Raichle, M. E. (1988). Positron emission tomographic studies of the cortical anatomy of single-word processing. Nature, 331, 585-589.

Petersen, S.E., Fox, P.T., Posner, M.I., Mintun, M., Raichle, M.E. (1989). Positron emission tomographic studies of the processing of single words. Journal of Cognitive Neuroscience, 1, 153-170.

Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. E. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. NeuroImage, 10, 15-35.

Price, C. J., Moore, C. J., Humphreys, G. W., & Wise, R. S. J. (1997). Segregating semantic from phonological processes during reading. Journal of Cognitive Neuroscience, 9, 727-733.

Raichle, M. E., Fiez, J. A., Ficeen, T. O., MacLeod, A. M., Pardo, J. V., & Fox, P. T. et al. (1994). Practice-related changes in human brain functional anatomy during nonmotor learning. Cerebral Cortex, 4, 8-26.

Raz, N., Gunning, F.M., Head, D., Dupuis, J. H., McQuain, J. M., Bridggs, S. D., Thornton, A. E., Loken, W. J., & Acker, J. D. (1997). Selective aging of human cerebral cortex observed in vivo: Differential vulnerability of the prefrontal gray matter. Cerebral Cortex, 7, 268-282.

Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F. I. M. Craik and T. A. Salthouse (Eds.), The handbook of aging and cognition, 2nd Ed. Mahwah, NJ: Lawrence Erlbaum Associates.

Raz, N., Gunning-Dixon, F., Head, D., Rodrigue, K. M., Williamson, A., & Acker, J. D. (2004). Aging, sexual dimorphism, and hemispheric asymmetry of the cerebral cortex: replicability of regional differences in volume. Neurobiology of Aging, 25, 377-396.

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

Rosen, V. M., Engle, R. W. (1997). The role of working memory capacity in retrieval. Journal of Experimental Psychology: General, 126, 211-227.

Rypma, B., Prabhakaran, V., Desmond, J. E., Glover, G.H., & Gabrieli, J. D. E. (1999). Load-dependent roles of frontal brain regions in the maintenance of working memory. NeuroImage, 9, 216-226.

Salat, D. H., Kaye, J. A., & Janowsky, J. S. (1999). Prefrontal gray and white matter volumes in healthy aging. Archives of Neurology, 56, 338-344.

Salat, D.H., Buckner, R.L., Snyder, A.Z., Greve, D.N., Desikan, R.S., Busa, E., Morris, J.C., Dale, A.M., Fischl, B. (2004). Thinning of the cerebral cortex in aging. Cerebral Cortex, 14, 721-730.

Thompson-Schill, S. L., D'Esposito, M., & Kan, I. P. (1999). Effects of repetition and competition on activity in left prefrontal cortex during word generation. Neuron, 23, 513-522.

Thompson-Schill, S. L., & Gabrieli, J. D. E. (1999). Priming of visual and functional knowledge on a semantic classification task. Journal of Experimental Psychology: Learning, Memory, and Cognition, 25, 41-51.

Thompson-Schill, S. L., & Kan, I. P. (2001). Perceptual and conceptual sources of priming on a word generation task. Memory and Cognition, 29, 698-706.

Thompson-Schill, S. L., Swick, D., Farah, M. J., D'Esposito, M., Kan, I. P., & Knight, R. T. (1988). Verb generation in patients with focal frontal lesions: A neuropsychological test of neuroimaging findings. Proceedings of the National Academy of Science of the United States of America, 95, 15855-15860.

Tomer, R., & Levin, B.E. (1993). Differential effects of aging on two verbal fluency tasks. Perceptual and Motor Skills, 76, 465-466.

Tröster, A. I., Salmon, D. P., McCullough D., Butters N. (1989). A comparison of the category fluency deficits associated with Alzheimer's and Huntington's disease. Brain and Language, 37, 500-513.

Troyer, A. K., Moscovitch, M., & Winocur, G. (1997). Clustering and switching as two components of verbal fluency: Evidence from young and older healthy adults. Neuropsychology, 11, 138-156.

Tulving, E (1972). Episodic and semantic memory. In E. Tulving & W. Donaldson (Eds.), Organization of memory (pp. 381-403). New York: Academic Press.

Tun, P. A., O'Kane, G., & Wingfield, A. (2002). Distracting by competing speech in young and older adult listeners. Psychology and Aging, 17, 453-467.

Van Turennout, M., Bielamowica, L., & Martin, A. (2003). Modulation of neural activity during object naming: Effects of time and practice. Cerebral Cortex, 13, 381-391.

Vriezen, E. R., Moscovitch, M., & Bellos, S. A. (1995). Priming effects in semantic classification tasks. Journal of Experimental Psychology: Learning, Memory, and Cognition, 21, 933-946.

Wagner, A. D., Desmond, J. E., Demb, J. B., Glover, G. H., Gabrieli, J. D. E. (1997). Semantic repetition priming for verbal and pictorial knowledge: functional MRI study of left inferior prefrontal cortex. Journal of Cognitive Neuroscience, 9, 714-726.

Wagner, A. D., Koutstaal, W., Maril, A., Schacter, D. L., & Buckner, R. L. (2000). Task-specific repetition priming in left inferior prefrontal cortex. Cerebral Cortex, 10, 1176-1184.

Wagner, A. D., Paré-Blagoev, E. J., Clark, J., & Poldrack, R.A. (2001). Recovering meaning: Left prefrontal cortex guides controlled semantic retrieval. Neuron, 31, 329-338.

Wagner, A. D., Schacter, D. L., Rotte, M., Koutstaal, W., Maril, A., Dale, A. M., Rose, B. R., & Buckner, R. L. (1998). Building memories: Remembering and forgetting of verbal experiences as predicted by brain activity. Science, 281, 1188-1191.

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

Wiggs, C. L., & Martin, A. (1998). Properties and mechanisms of perceptual priming, Current Opinions in Neurobiology, 8, 227-233.

Whelihan, W. M., & Lesher, E. L. (1985). Neuropsychological changes in frontal functions with aging. Developmental Neuropsychology, 1, 371-380.

Wiederholt, W. C., Cahn, D., Butters, N. M., Salmon, D. P., Kritz-Silverstein, D., & Barrett-Connor, E. (1993). Effects of age, gender and education on selected neuropsychological tests in an elderly community cohort. *Journal of the American Geriatrics Society, 41*, 639-647.

# Conclusions

## Chapter 1: Recollection Impairments in Older Adults: A Memory Binding or Memory Search Deficit?

In Chapter 1, the limits of age-related recollection deficits were explored in a series of behavioral studies. Experiment 1A demonstrated that older adults were not able to recognize pairs of words as well as young adults even when extensive means were taken to help them acquire the associative information at encoding. Both young and older adults performed better when they were given visual imagery training to help them link the word pairs and when incidental encoding instructions were used. However, even this level of support was not sufficient to close the gap in performance between older and young adults. Moreover, the fact that older adults took twice as long on average to form a link between the semantically unrelated words in a pair indicated that this process was much more effortful for them.

In Experiment 1B, participants received even more assistance at encoding. Once again incidental encoding instructions were used, but in this experiment participants were provided with sentences that would help them link the semantically unrelated words. This manipulation did eliminate the age gap in performance. Young and older adults performed equally well in associative recognition, a task in which large age differences have previously been observed even when far fewer stimuli were used (Naveh-Benjamin, 2000).

Although associative recognition can be accomplished through self-initiated recall (i.e., a recall-to-reject strategy, Rotello et al., 2000), it can also be accomplished by a default strategy based on a lack of recollection (Yonelinas, 1997). Self-initiated production is required for success in every trial on paired-associate recall. In Experiment 2, performance on associative recognition was compared with paired associate recall in young and older adults to determine whether the requirement of self-initiated processing would reveal age differences not observed in associative recognition. Results showed that paired-associate recall was more difficult than associative recognition, as both groups performed worse in recall than recognition. Results in associative recognition replicated the findings of Experiment 1B; in both cases, older adults performed as well as young adults. Unexpectedly, older adults also performed as well as young adults in paired-associate recall, despite repeated findings that age-related retrieval deficits increase as test difficulty increases (Ceci & Tabor, 1981; Craik, Byrd, & Swanson, 1987; Craik & McDowd, 1987; Schonfield & Robertson, 1966; reviewed in Craik & Jennings, 1992).

In their everyday lives, older adults do not generally have the benefit of external support to help them acquire new associations. However, the results show that older adults retain the cognitive resources to bind disparate semantic information when input conditions are optimal. Further, it supports prior findings that the binding problems associated with recollection deficits in older adults are primarily due to encoding failures (e.g., Glisky et al., 2001).

## Chapter 2: Age Differences in Patterns of Recollection Success and Recollection Attempt in BOLD Responses During Episodic Retrieval

The encoding methods developed in the series of behavioral experiments reported in Chapter 1 provided an opportunity to use functional MRI investigate whether the neural processes that support successful recollection differ in young and older adults. With the use of these encoding procedures, associative recognition accuracy was matched in young and older adults, guaranteeing that differences in observed patterns of neural activity, as indicated by BOLD response, were due to age differences and not differences in the level of performance.

Results of this fMRI study revealed that older adults showed a different pattern of responses in areas that were associated with recollection success in young adults. In young adults, greater activation was observed for successful recollection relative to recognition without recollection in two regions: left inferior temporal/fusiform cortex and posterior left inferior prefrontal cortex (LIPC). Older adults activated these regions equally for all conditions in which recollection was attempted, regardless of the level of recollection success or the true memory status (old vs. new pairs) of the word pairs.

The results support prior claims that increased left-lateralized activations observed in older adults during episodic retrieval reflect more widespread engagement of regions to support retrieval attempt (Cabeza et al., 2002; Daselaar et al., 2003). Further, the results constrain the conditions under which such age differences can be expected to be observed.

## Chapter 3: Neural Basis of Reduced Specificity in Semantic Retrieval in Older Relative to Young Adults

While extensive measures such as those used in Experiment 1-3 are needed to close age gaps in episodic memory performance, older adults often perform semantic retrieval tasks as well as young adults, with no such assistance. The exception appears to be cases where cognitive control, supported by prefrontal cortex, is needed to constrain or facilitate the search of long-term memory stores. In Experiment 4, we induced a need for cognitive control in semantic retrieval by using a semantic repetition priming task to facilitate access to off-target semantic information. This manipulation allowed us to test two competing hypotheses about the role of LIPC in semantic retrieval in young adults, and to determine if neural activity supporting these control operations differed in young and older adults.

Behavioral results revealed the same pattern of performance in older and young adults. Priming was observed in the Within-Task repetition priming condition, when identical semantic retrieval tasks were performed at study and test exposures, and in the Across-Task repetition priming condition, when different semantic retrieval tasks were performed across the two exposures. The level of priming, however, was greater in the Within-Task condition than the Across-Task condition.

Patterns of neural activity in LIPC sub-regions, as indirectly measured by BOLD response, were similar but not identical across the two age groups. While no significant Age X Condition interaction was observed, the pattern of activity in anterior LIPC was not identical in the two age groups. Among young adults, this region was sensitive to variations in the semantic information accessed across the two exposures, showing repetition-related reductions in BOLD response in the Within-Task but not the Across-Task condition. Moreover, the level of activation differed across the two primed conditions. Older adults, in contrast, exhibited statistically equivalent neural priming across the two conditions, consistent with prior findings that they fail to filter irrelevant semantic information from entering working memory. In contrast, in posterior LIPC, both young and older adults showed generalized priming. There was no evidence of a neural cost in LIPC activity due to competition from task-irrelevant information in either young or older adults.

The results lend support to the hypotheses that (a) LIPC supports controlled semantic retrieval with anterior regions supporting access to conceptual representations and posterior regions supporting access to phonological representations; and (b) older adults fail to inhibit irrelevant information from entering working memory, as indicated by greater generalized priming in LIPC regions that support task-specific priming in young adults.

## Summary

Studies of aging and memory frequently call attention to older adults' cognitive failures. Taken as a whole, this dissertation offers several perspectives on older adults' cognitive successes. The behavioral studies of associative recognition and paired-associate cued recall demonstrate that older adults retain the capacity to bind and retrieve associative information as well as younger adults when they receive similar, enriched input. The findings also point to ways that we may help older adults better cope with the mnemonic demands in their everyday lives. In particular, outside mediators, such as visualization aids, may help older adults acquire associative information as efficiently as younger adults do without such outside assistance. The findings of the fMRI study of associative recognition suggest that despite the structural brain changes that accompany aging, older adults nevertheless can exploit brain regions that contribute to recollection success in young adults, perhaps in ways that allow them to compensate for reductions in neural processing capacity.

The results of the fMRI study of semantic retrieval were mixed. No age differences were observed in behavior in a semantic repetition priming task, even when conditions demanded cognitive control. However, given the past evidence of age deficits in inhibitory tasks, age differences likely would be revealed in a more demanding cognitive task than the one used in the present study. Older adults did exhibit reduced retrieval specificity in prefrontal regions that support controlled, task-specific semantic retrieval in younger adults. The present findings may shed light on at least one brain region that may be linked to inhibitory deficits – anterior LIPC.

## References

Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: Compensatory brain activity in high-performing older adults. NeuroImage, 17, 1394-1402.

Ceci, S. J., & Tabor, L. (1981). Flexibility and memory: Are the elderly really less flexible? Experimental Aging Research, 7, 147-158.

Craik, F. I. M., Morris, L. W., Morris, R. G., & Loewen, E. R. (1990). Relations between source amnesia and frontal lobe functioning in older adults. Psychology and Aging, 5, 148-151.

Craik, F. I. M., Byrd, M., & Swanson, J. M .(1987). Patterns of memory loss in three elderly samples. Psychology and Aging, 2, 79-86.

Daselaar, S. M., Veltman, D. J., Rombouts, S. A. R. B., Raaijmakers, J. G. W, & Jonker, C. (2003). Neuroanatomical correlates of episodic encoding and retrieval in young and elderly subjects. Brain, 126, 43-56.

Glisky, E. L., Rubin, S. R., Davidson, P. S. R. (2001). Source memory in older adults: An encoding or retrieval problem? Journal of Experimental Psychology: Learning, Memory, and Cognition, 27, 1131-1146.

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: tests of an associative deficit hypothesis. Journal of Experimental Psychology: Learning, Memory, and Cognition, 26, 1170-1187.

Schonfield, A. E. D., & Robertson, B. A. (1966). Memory storage and aging. Canadian Journal of Aging, 20, 228-236.

Rotello, C. M., Macmillan, N.A., & Van Tassel, G. (2000). Recall-to-reject in recognition: Evidence from ROC curves. Journal of Memory and Language, 43, 67-88.

Schacter, D. L., Savage, C. R., Alpert, N. M., Rauch, S. L., & Albert, M. S. (1996). The role of hippocampus and frontal cortex in age-related memory changes: A PET study. Neuroreport, 7, 1165-1169.