Distribution Agreement

In presenting this thesis or dissertation as a partial fulfillment of the requirements for an advanced degree from Emory University, I hereby grant to Emory University and its agents the non-exclusive license to archive, make accessible, and display my thesis or dissertation in whole or in part in all forms of media, now or hereafter known, including display on the world wide web. I understand that I may select some access restrictions as part of the online submission of this thesis or dissertation. I retain all ownership rights to the copyright of the thesis or dissertation. I also retain the right to use in future works (such as articles or books) all or part of this thesis or dissertation.

Signature: _____ Date_____

Cory Shields Inman

Dynamic neural connectivity of autobiographical memory retrieval processes

By

Cory Shields Inman

Doctor of Philosophy

Psychology

_____
Stephan Hamann, Ph.D.
Advisor

_____
Patricia Bauer, Ph.D.
Committee Member

_____
G. Andrew James, Ph.D.
Committee Member

_____
Daniel D. Dilks, Ph.D.
Committee Member

_____
Joseph Manns, Ph.D.
Committee Member

_____
James Rilling, Ph.D.
Committee Member

Accepted:

_____
Lisa A. Tedesco, Ph.D.
Dean of the James T. Laney School of Graduate Studies

_____
Date

Dynamic neural connectivity of autobiographical memory retrieval processes

By

Cory Shields Inman
B.A, Georgia State University, 2006
M.A., Emory University, 2011

Advisor: Stephan Hamann, Ph.D.

An abstract of
A dissertation submitted to the Faculty of the
James T. Laney School of Graduate Studies of Emory University
In partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in Psychology
2014

Abstract

Dynamic neural connectivity of autobiographical memory retrieval processes
By Cory Shields Inman

The brain is comprised of dynamic networks of functional regions that interact with one another to execute various processing demands. Autobiographical memory (AM) involves the orchestration of multiple cognitive processes that evolve over time, including memory access and subsequent elaboration. Previous neuroimaging studies have contrasted memory access and elaboration processes in terms of regional brain activation and connectivity within coordinated multi-region networks rather than between specific regions like the hippocampus and prefrontal cortex (PFC). The purpose of the present studies was to determine the changes in interregional connectivity strength across AM retrieval processes to understand network level mechanisms of AM retrieval and test theoretical accounts of dynamic AM retrieval processes. In two AM retrieval experiments, we predicted that dynamic (time-varying) connections would reflect early memory-access related connections between hippocampal and PFC regions and a separate set of later, elaboration-related connections between lateral frontal working memory regions and parietal/occipital visual imagery regions. In both studies, healthy adults generated AMs from neutral cue words in a pre-scan session and were later cued to retrieve the AMs while being scanned with fMRI. We used a moving-window graph theory analysis to examine dynamic changes in the strength of connectivity among regions involved in AM retrieval. In addition, we examined the extent to which these core AM retrieval regions became more or less central to integrating distributed information throughout a whole brain network. In particular, in both studies, dynamic network analyses showed that early, access-related processing involved a primarily anterior, fronto-temporal network associated with strategic search and initial reactivation of specific episodic memory traces. In addition, in line with predictions, brain network connectivity during later retrieval processes primarily included strong connections between occipital-parietal regions and fronto-parietal regions associated with mental imagery, reliving, and working memory processes. Taken together, these studies particularly help refine and extend dynamic neural processing models of AM retrieval, like the self-memory system theory, by providing evidence of the specific connections throughout the brain that change in their synchrony with one another as processing progresses from access of specific events in the past to elaborative reliving of the past event.

Dynamic neural connectivity of autobiographical memory retrieval processes

By

Cory Shields Inman
B.A, Georgia State University, 2006
M.A., Emory University, 2011

Advisor: Stephan Hamann, Ph.D.

A dissertation submitted to the Faculty of the
James T. Laney School of Graduate Studies of Emory University
In partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in Psychology
2014

Acknowledgements

I am tremendously thankful to the close network of friends, colleagues, and mentors I have gained throughout my graduate school experience. In particular, I would like to thank my advisor, Stephan Hamann, for the time, patience, and mentorship he has given me throughout graduate school. I am grateful for the many opportunities he has given me to become a well-rounded and independent scientist. I would also like to thank my colleague and mentor, Andy James, for his mentorship and always knowing when to provide encouragement. I am also appreciative of the support of my committee members, Patricia Bauer, Danny Dilks, Joe Manns, and Jim Rilling, in supporting me through my development as a scientist. I am thankful to Patricia Bauer for helping to shape me into a more accurate, thoughtful, and considerate scientist. I am also grateful for the encouragement and guidance Danny Dilks and Joe Manns have provided me throughout my graduate career. In addition, I am thankful to Paula Mitchell, Emily Stills, and the rest of the Psychology department staff for helping me navigate through graduate school. Finally, I would like to thank Helen Mayberg and her lab for giving me the opportunities that have helped set the foundation for my future career as a scientist.

I am thankful to my parents, Jennifer and David Inman, and my close extended family for their unconditional love and encouragement that I could accomplish anything I set out to achieve in life. I would like to also thank my brother, Christopher Inman, for always going above and beyond to encourage me as I completed this work. Last, but certainly not least I would like to thank my loving and supportive wife, Anna Inman, who has been there to motivate me at every moment of uncertainty.

Finally, I would like to thank my lab family over the years, including my lab twin Carolina Campanella and siblings Katye Vytal, Jenni Stevens, and Anaïs Stenson, who, though setting the example of great graduate students and scientists, have inspired me to be a better colleague, mentor, scientist, and friend.

Table of Contents

List of Tables....ii

List of Figures iii

General Introduction 1

Autobiographical memory retrieval: Cognitive Processes 5

Autobiographical memory retrieval: Neural Processes 10

Autobiographical Memory Retrieval: Functional Integration and Connectivity...18

The present study 26

Study 1: Dynamic functional connectivity changes between access and elaboration of autobiographical memories 39

Introduction 39

Method 54

Results 73

Discussion 81

Study 2: Large-scale functional network organization changes across autobiographical memory retrieval processes 96

Introduction 96

Method 113

Results 130

Discussion 151

General Discussion 170

References 184

List of Tables

Study 1

Table 1. *Region of Interest (ROI) hemisphere, label, and MNI coordinates*.....63

Table 2. *Connections with stronger connectivity early versus late and late versus early*.....78

Study 2

Table 1. *Region of Interest (ROI) hemisphere, label, and MNI coordinate*.....118

Table 2. *Connections with stronger connectivity early versus late 1 period*.....136

Table 3. *Connections with stronger connectivity during the late 1 versus early period*.....139

Table 4. *Connections with stronger connectivity late 2 versus early period*.....142

Table 5. *Connections with stronger connectivity late 3 versus early period*.....145

Table 6. *Top 10% most change in degree centrality for whole brain network nodes by time period*.....149

List of Figures

Study 1

Figure 1. Illustration of an AM retrieval trial.....60

Figure 2. Illustrations of core network ROIs.....64

Figure 3. Illustration of core network ROIs from a) dorsal sagittal and b) ventral axial perspective.....68

Figure 4. Stable network during AM retrieval.....75

Figure 5. Stronger connections early versus late in AM retrieval.....77

Figure 6. Stronger connections late versus early in AM retrieval.....79

Study 2

Figure 1. Illustration of an AM retrieval trial.....115

Figure 2. Illustrations of core network ROIs.....119

Figure 3. Illustration of core network ROIs from a) dorsal sagittal and b) ventral axial perspective.....124

Figure 4. Stable network during AM retrieval.....132

Figure 5. Stronger connections early versus late 1 in AM retrieval.....135

Figure 6. Stronger connections late 1 versus early in AM retrieval.....138

Figure 7. Stronger connections late 2 versus early in AM retrieval.....141

Figure 8. Stronger connections late 3 versus early in AM retrieval.....144

General Introduction

Retrieval of autobiographical memories (i.e., episodic memories related to the self) is a complex process that requires several cognitive operations to occur in concert over time. Autobiographical memories (AMs) are typically much more varied in their temporal and spatial context, emotional characteristics, visual imagery, relation to self, and narrative structure than laboratory controlled and encoded episodic memories (Cabeza & St Jacques, 2007; Daselaar et al., 2008; Rubin, 2005). AM retrieval involves a complex set of processes such as access of memories related to an internal or external cue and elaboration and maintenance of the details of the accessed AM memory (Conway & Pleydell-Pearce, 2000; Tulving, 1983). On the neural systems level, regions throughout the brain interactively orchestrate these cognitive retrieval processes.

The time course of AM memory retrieval is typically relatively extended in duration, frequently unfolding over seconds to minutes. Across this protracted time course, important changes occur with regard to the memory processes that are most active, for example, a shift from regions involved in the process of accessing and constructing a memory to those involved in elaborating and maintaining a memory in working memory (Daselaar et al., 2008). Although many neuroimaging studies that have examined AM retrieval as if it were a stationary process, more recently, attention has focused on the nature of the dynamic changes in brain processes that occur during AM retrieval. For example, Daselaar et al. (2008) reported some brain regions are active during memory access (hippocampus, right prefrontal cortex, and other regions) while another set is more active during memory elaboration (parietal regions, occipital cortex).

Although it is widely recognized that memory retrieval requires the functional

interaction of regions throughout the brain rather than regions acting in isolation, current theories of AM retrieval largely focus on evidence of regional brain activation and frequently do not consider the role of neural network interactions. Evidence from studies of declarative memory retrieval clearly shows that the brain relies on the functional interaction of regions throughout the brain to retrieve rich, coherent, and cue-relevant memories (Greenberg et al., 2005; St. Jacques, Kragel, & Rubin, 2011). According to current memory retrieval models, the reactivation of distributed, stored memory traces through strategic memory search is particularly likely to require the functional interaction of regions throughout the brain (Daselaar et al., 2008; Svoboda, McKinnon, & Levine, 2006). Recently, studies of AM retrieval have begun to examine the extent to which these sets of active regions act as a synchronized network that changes as the hypothesized retrieval process shifts from access or construction of a memory to reliving or elaboration of that memory (McCormick, St-Laurent, Ty, Valiante, & McAndrews, 2013; St. Jacques et al., 2011).

A specific set of brain regions are consistently involved in AM retrieval (Svoboda et al., 2006). One study has shown that the neural regions underlying AM retrieval processes of access and elaboration dynamically change in predominance over the retrieval episode (Daselaar et al., 2008). There is growing evidence that the regions underlying these AM retrieval processes are functionally coordinated with one another (i.e., functional connectivity) within and across these process periods (McCormick et al., 2013; St. Jacques et al., 2011). Although these initial studies of the AM retrieval network provide evidence that connectivity between regions involved in AM retrieval changes over time, such studies have only examined a subset of the important types of dynamic

changes in neural connectivity that occur during AM retrieval. In particular, previous studies have not examined which specific connections between brain regions change and how they change over the AM retrieval period (i.e., stronger or weaker; more or less central to functional activity). In other words, the available data examining connectivity during AM retrieval processes describes the interactions between large-scale networks (e.g., a medial temporal lobe, cinguloopercular, and fronto-parietal networks) involved in AM retrieval (St. Jacques et al., 2011) rather than the interactions between specific regions within these large-scale networks or components (e.g., amygdala, hippocampus, medial PFC, lateral PFC, precuneus, etc.). McCormick et al. (2013) examined the hippocampus' dynamic role during AM retrieval, but did not examine at the dynamic functional connectivity between other core AM retrieval regions or how the hippocampus' role relative to the rest of the brain changes over time.

The goal of the current study was to address these current gaps in the literature by using novel, multivariate analysis techniques that test for functional changes in the specific connections over time between a large network of core AM retrieval regions. In particular, along with a sliding-window cross-correlation functional connectivity approach, the current studies utilize a mathematical approach known as graph theory to characterize complex brain networks with a small number of neurobiologically meaningful and easily computable measures (Bullmore & Sporns, 2009; Hutchison et al., 2013; Rubinov & Sporns, 2010).

Characterizing neural network dynamics associated with a cognitive function facilitates understanding of higher-order cognitive functions based on the typical functions of regions in the network (Spreng & Grady, 2009). In other words, inference of

coordinated activity within networks associated with a particular cognitive function can clarify the necessity and importance of particular regions for the examined cognitive function (Mcintosh, 1999). Theories of neural connectivity suggest that the same activity change in an isolated brain region may be observed across several cognitive operations, but the functions of those regions within in a neural system underlying the cognitive operation might be quite different. Some theories of functional connectivity propose that the relation of the activated region to other areas determines the cognitive mechanisms underlying any cognitive behavior (Buchel, Coull, & Friston, 1999; Mcintosh, 1999). Description of the network dynamics in AM retrieval is critical to delineating the neural mechanisms associated with theoretical models of memory retrieval. A currently influential theoretical model of AM, the self-memory system model (SMS; Conway & Pleydell-Pearce, 2000), suggests that AM retrieval involves complex, strategic search, monitoring, and control processes that are guided by current goals and self-knowledge. Clarifying the specific interactions between distributed sets of brain regions that support self-reference, memory processes, search, monitoring, and goal-related processes will help to refine current models of autobiographical memory retrieval specifically, as well as models of declarative memory retrieval more generally.

The following section first provides an overview of the main cognitive processes involved in AM retrieval and evidence supporting the view that these processes unfold dynamically over time. Next, the functional roles of brain regions implicated in these dynamic cognitive processes are reviewed in light of recent evidence suggesting that these regions interact in the context of dynamically connected networks that change across the time course of AM retrieval. Different approaches to understanding the

network dynamics of AM retrieval will be discussed, with an emphasis on identifying connectivity methods that are best suited to understanding dynamic AM networks. The final section provides a brief overview of the main goals and methods for the two empirical studies that were conducted to examine the neural dynamics of AM retrieval processes.

Autobiographical memory retrieval: Cognitive Processes

Autobiographical memory retrieval is generally thought to involve a sequence of specific retrieval processes that unfold from access to elaboration of a cued memory (Cabeza & Moscovitch, 2013; Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Rubin, 1982; Rugg & Vilberg, 2012; Tulving, 1983). This sequence of processes shares several features with episodic retrieval in that a spatiotemporally specific episode from the past is accessed and elaborated upon to meet specific retrieval goals (Tulving, 1983). One current influential theory on the retrieval of AMs (Conway, 2009; Conway & Pleydell-Pearce, 2000) stipulates that AM retrieval begins with an initial process of memory access (i.e., construction) in which a specific memory is selected from one's personal past. Initial retrieval processes are referred to as memory access or construction-related because it is thought to involve, strategic controlled search, memory monitoring, and rebinding of the episodic details to the cued context of the memory. In the memory access period, upon receiving a cue, the participant first experiences a automatic memory retrieval process engaged in when a specific cue interacts with information stored in memory, referred to as ecphory (Cabeza & Moscovitch, 2013; Moscovitch & Melo, 1997; Moscovitch, 1995; Tulving, 1983). After more general and personal knowledge is

accessed, various episodic elements of the memory are bound into a cohesive memory that can then be re-experienced (Conway, 2009).

To illustrate, imagine involuntarily or voluntarily being cued to remember receiving or buying your first car. In this period of retrieval, one specific memory is selected for retrieval (e.g., getting your first car) based on the retrieval cues provided. During the selection of a specific target memory for retrieval, other similar memories may need to be inhibited (e.g., memories of purchasing other cars). Tulving (1983) and others (Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008) have proposed that evidence of this mnemonic inhibition is that a set of neural activations dominates over other neural activations. Theoretical accounts would consider the memory as having been retrieved once a specific memory is identified and accessed. These accounts also emphasize that memory retrieval requires further retrieval and elaboration of its rich detail and full context.

Once a memory has been accessed and elaborated, its content must be maintained in working memory until the given retrieval goals are completed (Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008). The retrieval goals and need for sparse or rich elaboration are determined by the particular situation. For instance, a situation in which you tell a friend about your new car relative to your first car might require minimal elaboration, whereas recounting a past experience, like a car accident, for eyewitness testimony might require more thorough elaboration. In many cases the memory may need to be elaborated upon by filling in details of the memory to accomplish the retrieval goal (e.g., object specific details like the kind, color, and model of the car; contextual details like where, when, how the car was received). In many

retrieval cases, as a memory is elaborated upon sensory details of the original experience would be mentally re-experienced. The extent to which an AM is relived or re-experienced is modulated by the self-relevance, meaning, and emotional content of the retrieved memory (Muscatell, Addis, & Kensinger, 2010). Elaboration processes are thought to continue until the retrieval goals are met, the memory has been fully elucidated, or a new memory is cued and accessed.

One recent theory that proposes this dynamic model of autobiographical memory retrieval is known as the self-memory system (SMS). SMS theory suggests that autobiographical memory retrieval involves our autobiographical knowledge base, which consists of knowledge about life-time periods, general events, and specific events, dynamically interacting with one's "working self" (Conway & Pleydell-Pearce, 2000). The working self is defined as a core part of the working memory system (Baddeley, 2003; Conway & Pleydell-Pearce, 2000) consisting of control processes that coordinate and modulate other computationally distinct systems. Conway and Pleydell-Pearce propose that the working self and the autobiographical knowledge base are instantiated by certain sub-networks of the brain that dynamically change in their predominance of activity and coordination throughout the retrieval of an autobiographical memory. Specifically, SMS theory posits that immediately after a cue provokes specific information in memory to be retrieved, activation in frontal and temporal networks should occur due to their involvement in the instantiation of the working self (i.e., ecphory; Moscovitch & Melo, 1997; Moscovitch, 1995). This access of memory process is similar to another proposed memory process known as retrieval mode, which has been defined as a mental set that guides retrieval of episodic information (Velanova et al.,

2003). Controlled memory access processes are followed by integration of the accessed memory with details that allow for one to mentally re-experience the memory, which is hypothesized to be related to increased activation in posterior parietal and occipital networks. Behavioral and neuroimaging examinations of this model have provided evidence in support of this dynamic model of AM retrieval (Conway et al., 1999; Conway, Pleydell-Pearce, & Whitecross, 2001; Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011), but none of the studies to date have comprehensively demonstrated that regions involved in AM retrieval organize into specific neural networks that dynamically change as AM retrieval unfolds from access to elaboration processes.

The temporal dynamics of transitions between the access and elaboration processes underlying AM retrieval are essential to mapping correlated changes underlying neural processing. The time course of access or mnemonic search processes can occur relatively quickly, but significantly depends on the goals of the retrieval episode and the strength of the memory. Most laboratory studies of AMs use the Galton/Crovitz cue-word technique to elicit AMs (Crovitz & Schiffman, 1974; Galton, 1879; for review see Rubin, 1982). In this paradigm, participants are asked to provide a specific memory for a past event to each of a series of generic cue words (e.g., “car”). Access of unrehearsed AMs to these generic cue words typically happens between 7 and 12 seconds from the presentation of the cue, but this may vary depending on the difficulty of retrieving a specific memory for that cue (Addis, Knapp, Roberts, & Schacter, 2011; Addis, McIntosh, Moscovitch, Crawley, & McAndrews, 2004; Addis, Pan, Vu, Laiser, & Schacter, 2009; Barsalou, 1988; Rubin & Schulkind, 1997). For instance, Rubin and

Schulkind (1997) found that college-aged students began writing an average of 10 seconds after presentation of the cue, whereas 35 and 70 year old participants took an average of 16 to 20 seconds to begin writing (Rubin & Schulkind, 1997). Addis et al. (2011) find that memories cued by generic, unrehearsed cues takes 8 s ± 2 s. Rehearsed AMs to generic cues tend to be accessed much more quickly (i.e., 3 s; Daselaar et al., 2008). The time taken to elaborate varies as a function of the instructions, goal, or attention that can be allocated to the retrieval task. A few studies have utilized these estimates and participant responses to delineate the time course of memory access and elaboration, but there has not been a systematic examination of the typical time to access and richly elaborate upon an unrehearsed AM to generic cues outside the context of fMRI study design constraints (Addis & Schacter, 2008; Daselaar et al., 2008).

In an fMRI study examining the predominant regions involved in access and elaboration processes (Daselaar et al., 2008), researchers found that certain frontal and temporal regions dominated initial processing resources (access), whereas other parietal and occipital regions dominated later processing resources (elaboration). Daselaar et al. refer to the two AM retrieval processes as access and elaboration to avoid other terms that entail stronger theoretical claims (i.e., construction). Access and elaboration are thought to be the main component processes of AM retrieval and are typically examined separately (Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; Muscatell et al., 2010; Tulving, 1983). Daselaar et al. note that it is possible that both processes are engaged in parallel during early and late processing, but there are shifts in the predominance of access-related processing in the earliest periods relative to retrieving the cue and elaboration-related processing in later periods after the memory has been

accessed. Examination of the neural connectivity dynamics of AM retrieval processes across time might be able to clarify which cognitive and neural resources are engaged during early, late, or both processing periods (McCormick et al., 2013; St. Jacques et al., 2011).

In general, it is difficult to sharply distinguish between the point during retrieval where access has completed and elaboration processes have begun. Indeed, because AM retrieval may involve sequential waves of access of related mnemonic information, it is more accurate and useful to define these processing periods in terms of the relative dominance of access-related vs. elaboration-related processing, and it is this definition that is adopted in the current study. In most previous studies, this transition point between access and elaboration processes has been operationalized with a subject-initiated button press (indicating that a memory has been successfully accessed) during a silent retrieval session (Daselaar et al., 2008; Greenberg et al., 2005; McCormick et al., 2013; St. Jacques et al., 2011). Although this approach provides an approximation of the timing of transition between cognitive processes, it further constrains examination of activity related to these two processes rather than allowing for a more dynamic illustration of the processes unfolding over time windows with even widths. This sliding time window approach allows for an unconstrained exploration of the change in predominant cognitive states over the duration of memory retrieval (Anderson & Fincham, 2013; Hutchison et al., 2013).

Autobiographical Memory Retrieval: Neural Processes

A core network of regions involved in autobiographical memory retrieval has been found to be relatively consistent across neuroimaging studies, although individual

neuroimaging studies have reported additional brain regions beyond this core network. In an early meta-analysis of autobiographical memory brain activations, Maguire (2001) found that distributed networks of neural regions involved in processing declarative memory include the MTL (i.e., hippocampus, parahippocampal gyrus), retrosplenial cortex, posterior parietal regions (i.e., inferior parietal and precuneus), as well as lateral and medial PFC. Subsequent studies and meta-analyses have provided evidence in support of this core network (Addis et al., 2004; Burianova, McIntosh, & Grady, 2010; Daselaar et al., 2008; Greenberg et al., 2005), for a recent meta-analysis see Svoboda et al., 2006). In a recent meta-analysis, Svoboda et al. (2006) found that the core AM network also included the cerebellum and the temporoparietal junction (TPJ). Several secondary regions are consistently activated in studies of AM. Across studies secondary region activation tends to depend on the nature of the memory retrieval task (Svoboda et al., 2006). Studies which manipulate the emotionality of stimuli or cues have found that the amygdala and sensory processing regions like the secondary visual cortex are active in retrieval of personally significant and contextually rich AMs (Addis et al., 2004; Cabeza et al., 2004; Fink, 2003; Rubin, 2005). Researchers have gained insight into the hypothesized functions of these regions in the core network for AM retrieval through extrapolation of their typical functions across a variety of cognitive tasks in both neuropsychological and neuroimaging studies.

Nearly all of the meta-analyses and empirical studies to date implicate regions in the MTL as the primary hub for memory retrieval processing (Addis et al., 2011; Conway, Pleydell-Pearce, Whitecross, & Sharpe, 2002; Daselaar et al., 2008; Greenberg et al., 2005; Maguire, 2001; Svoboda et al., 2006). The exact functions of the

hippocampus and parahippocampal gyrus in memory retrieval are still vigorously debated and examined. Current evidence suggests that the passage of time and qualitative aspects of the retrieved memory like personal significance, amount of detail recalled, and vividness modulated the involvement of the MTL in declarative memory (Svoboda et al., 2006). Early fMRI studies of AM did not find activation of the MTL due to the use of control tasks that were shown to mask the activation of regions that perform similar processing across the experimental and control task (Andreasen et al., 1995; Andreasen et al., 1999; Fink et al., 1996; Gemar, Kapur, Segal, Brown, & Houle, 1996; Markowitsch et al., 2000; Markowitsch, Vandekerckhove, Lanfermann, & Russ, 2003). For instance, the use of rest and other memory conditions tend to alter or mask activation of the MTL within a target memory condition because these tasks also activate the MTL (Stark & Squire, 2001). Interestingly, several studies using non-memory reference conditions find clear patterns of MTL activation (Svoboda et al., 2006). Interestingly, several studies using non-memory reference conditions find clear patterns of MTL activation (as detailed in Svoboda et al., 2006). Given only studies of hemodynamic activation, the function of the MTL within and across various declarative memory networks is currently ambiguous. Daselaar et al. (2008) found that the hippocampus was predominantly activated earlier in AM memory retrieval during the access of memory context and details. This hippocampal activation decreased as access and search processes were giving way to the later elaborative processes. The MTL's central role in memory retrieval make it a prime candidate for exploration of the dynamic functional connections that are made throughout retrieval of complex autobiographical memories.

After the MTL, the prefrontal cortex (PFC) is most often discussed as being core to autobiographical memory networks. Both medial and lateral aspects of the PFC are implicated in autobiographical memory retrieval. The medial aspect of the PFC is implicated in processing and recollecting the self-relevance of a particular memory and is thought to be particular to AM retrieval (D'Argembeau et al., 2007; Gusnard, Akbudak, Shulman, & Raichle, 2001; Markowitsch et al., 2003; Oddo et al., 2010; Simons & Spiers, 2003). The lateral aspect of the PFC is thought to be involved in a strategic memory search process known as retrieval mode, especially in the right hemisphere (Wagner, 1998). Retrieval mode is the mental set that guides the retrieval of specific, episodic information (Velanova et al., 2003). Neuropsychological evidence (Barceló, Suwazono, & Knight, 2000; Knight, Richard Staines, Swick, & Chao, 1999) converges with fMRI data to suggest that ventrolateral PFC implements top-down control signals to bias processing in posterior cortical regions like the parietal and late visual cortex (Ranganath and Knight, 2005; Petrides, 2002; Ranganath & Paller, 1999, 2000). Daselaar et al. (2008) found that the medial and right PFC are involved early in AM retrieval during the memory access period. Daselaar et al. found that the left lateral PFC is involved later in processing during the memory elaboration period and is thought to be involved in cognitive control (Wagner, Maril, Bjork, & Schacter, 2001) , attentional selection of visual information (Hopfinger, Buonocore, & Mangun, 2000), and working memory maintenance operations (Wager & Smith, 2003). These subdivisions of the PFC seem to contribute different functional computations to the core memory retrieval network. The connectivity of the frontal, parietal cortices, and the MTL, both medially and laterally, has been demonstrated across a number of tasks, especially declarative

memory retrieval, as well as during rest (Vincent et al., 2006; Vincent, Kahn, Snyder, Raichle, & Buckner, 2008). A characterization of dynamic changes in the functional connectivity of the medial and lateral PFC fully is needed to better understand the PFC's essential role in strategic search and working memory processes.

The posterior cingulate cortex (PCC; or retrosplenial cortex) is also often described as part of the core autobiographical memory network. Although the RSC and PCC seem to have distinct cytoarchitecture, the specific functions of the RSC and PCC have not been fully dissociated from one another across studies and meta-analyses. Thus, this treatment will discuss their functions as at least similar and potentially the same (Svoboda et al., 2006). Damage to these regions can cause deficits in memory due to a disconnection syndrome, known as diencephalic amnesia (Aggleton & Pearce, 2001; Gainotti, Almonti, Di Betta, & Silveri, 1998). The RSC is also anatomically well connected to the hippocampus and the thalamus (Daselaar et al., 2008). These regions have been hypothesized to act as an essential node between thalamic inputs/outputs and the hippocampus (Kobayashi & Amaral, 2003) and have been found to particularly active during retrieval of vividly recollected episodic memories (Botzung, Rubin, Miles, Cabeza, & LaBar, 2010; Cabeza & St Jacques, 2007; Kobayashi & Amaral, 2003; Svoboda & Levine, 2009; Svoboda et al., 2006). Daselaar et al. (2008) found that the RSC and PCC show greater activity during memory access relative to memory elaboration suggesting that these regions might help aid in memory search and retrieval of sensory details.

Other regions of the core autobiographical memory network include those engaged in retrieval of sensory information (e.g., visual cortex), including mental

imagery of the sensory information (e.g., precuneus and inferior parietal cortex), and goal-directed control processes. As mentioned earlier, the left lateral PFC is involved in control, selection, and maintenance of mnemonic information in later aspects of remembering associated with elaboration (Daselaar et al., 2008). As elaboration persists activations underlying elaboration and the extent to which the memory is re-experienced may be engaged and reengaged until the retrieval goal is achieved. Daselaar et a. found that regions engaged in various facets of visuospatial processing (i.e., visual cortex, parietal cortices, and TPJ) are more active later than early in AM retrieval during the predominately elaborative period of memory retrieval. This additional sensory processing seems to vary as a function of the extent to which a memory is reported as relived or re-experienced (Cabeza & St Jacques, 2007; Daselaar et al., 2008; St. Jacques et al., 2011).

Relative to other types of episodic memories, AMs are more likely to be relived and contain emotional content due to the inherently personal nature of autobiographical memories (Fivush, 2011). In fact, this personal, emotional nature is a presumed source of the long-term preservation for autobiographical memories (Bauer, 2007; Bauer, Stevens, Jackson, & Souci, 2012; Brewer, 1996; Conway et al., 2002). Many studies have demonstrated that emotional stimuli enhance recollection and alters patterns of brain activation (Addis, Leclerc, Muscatell, & Kensinger, 2010; Cahill et al., 1996; Canli, Zhao, Brewer, & Cahill, 2000; Hamann, Cahill, & Squire, 1997; Hamann, Ely, Grafton, & Kilts, 1999; LaBar & Cabeza, 2006). To date, several neuroimaging studies have specifically examined AM retrieval of emotionally arousing events (for a review Kensinger & Corkin, 2004). Many of the emotional AM studies show activation of the amygdala and other regions of the limbic system relative to retrieval of more neutral AMs

(Denkova, Chakrabarty, Dolcos, & Dolcos, 2011; Markowitsch & Staniloiu, 2011; St Jacques, Dolcos, & Cabeza, 2010). Findings of limbic system modulation in AM retrieval is consistent with many studies showing that emotional processing during encoding or retrieval of arousing memories engages the amygdala (Hamann, 2001). In regards to re-experiencing the retrieved memory, emotional AMs tend to elicit more activation in visual processing regions than non-emotional memories, suggesting that perhaps emotional AMs are more vividly experienced. The connectivity of amygdala and visual processing regions has been described as a feed-forward system of influence from the amygdala to the visual processing regions (Anderson & Phelps, 2001). During recollection of highly emotional memories the amygdala tends to be more activated during the access of the memory, while visual cortex activity tends to peak during the elaboration of the memory (Daselaar et al., 2008). The inter-connectivity and activation of emotion processing, memory, and visual processing regions is consistent with the personal and salient nature of most AMs.

Although there is robust consistency in the regions typically active in the retrieval of autobiographical and semantic memories, there is much less consistency in the brain hemispheres to which these activations are found (Conway et al., 2002; Daselaar et al., 2008; Maguire, 2001; Svoboda et al., 2006). Meta-analyses of AM retrieval report that the typical AM retrieval network is left lateralized (Conway et al., 2002; Maguire, 2001; Svoboda et al., 2006). Svoboda et al. (2006) suggested that this left lateralization of the AM network was due to the tendency for memory cues to be presented verbally (i.e., auditory or text). Maguire et al. (2001) also included review of several studies of hippocampal amnesic patients in their meta-analysis and review. Based on synthesis of

both the neuroimaging data and neuropsychological data they suggest that the right MTL might be more involved in spatial navigation, whereas the left MTL might have a more general role in reconstructing the context and episodic details of AMs (Maguire, 2001). Similarly, Conway et al. (2002) suggested that this left bias might be due to the initial search processes of general autobiographic knowledge (i.e., semantic knowledge) to locate and contextualize the subsequent AM access. Interestingly, in the only study to examine the spatiotemporal dynamics of AM retrieval processing, Daselaar et al. (2008) found that lateral frontal regions in the core network were predominantly right lateralized during early AM retrieval (i.e., access and search processes) and later lateral frontal regions were predominantly left lateralized (i.e., elaboration and maintenance processes). Daselaar et al. (2008) note that the right lateralization of the PFC activation during the early processing period is consistent with previous studies that propose a 'retrieval mode' during episodic memory search and access. Lateralization may also be modulated by other aspects of the AM retrieval task like the extent to which the memory is to have a narrative structure (i.e., more verbal information) versus only mentally 'relived' (i.e. more visual imagery) might modulate the activity to the left hemisphere due to more verbal processing (Petrides, 2002). Questions of hemispheric lateralization will require more focused tests than are examined in the present studies in which variables associated with lateralization of activation in AM are specifically manipulated.

The consistency of activation within this core network of regions and AM retrieval's relatively gradual change in cognitive processing, makes AM retrieval a well suited candidate for further investigation into the dynamic functional integration of each region's connectivity with other core network regions and regions throughout the brain.

Initial studies of neural connectivity during AM retrieval have used various techniques for examining the functional connectivity of regions activated during AM retrieval. These techniques include seed-based connectivity studies (region-to-region connectivity (Greenberg et al., 2005), multivariate seed-based approaches like partial least squares (PLS) analysis (McCormick et al., 2013), and independent components analysis (ICA; St. Jacques et al., 2011). In combination with evidence from neural activation studies of AM retrieval, all of these approaches have provided important evidence that specific regions or large-scale components composed of many brain regions with similar time course signals, change in their functional connectivity strength with one another over the duration of AM retrieval. Other multivariate, multi-region and whole brain analyses of AM retrieval data, such as sliding window cross-correlation analysis and graph theory, are needed to provide a full examination of the dynamic changes in cognitive processing that occur throughout the brain during AM retrieval.

Autobiographical Memory Retrieval: Functional Integration and Connectivity

Many cognitive neuroscientists work from the viewpoint that complex interactions between distributed objects of information processing (i.e., functional brain regions) give rise to cognitive processes (Wig, Schlaggar, & Petersen, 2011). In particular, memory is not a property of brain regions operating in isolation, but instead reflects processing throughout dynamic brain networks (Maguire, 2001). Taking advantage of recent technological, mathematical, and computational advances, researchers have started to disentangle the unequivocal complexity of functional and structural networks throughout the whole brain. Many analysis techniques for inferring the connections regions have with one another (i.e., functional connectivity) have been

developed over the past two decades of neuroimaging research (i.e., seed-based connectivity; ICA; PLS; graph theory; Bullmore & Sporns, 2009; Calhoun, Adali, Pearlson, & Pekar, 2001; Hutchison et al., 2013; Mcintosh, 1999; McKeown, 2000; Rubinov & Sporns, 2010). Other connectivity methods for inferring the influences regions have upon one another, which infer both strength and direction of connectivity (i.e., effective connectivity), have also been used to examine functional integration during AM retrieval. Evidence gained from these advances in theory and methodology have shown that brain networks, like many other man-made and biological systems, reveal an underlying non-random, functional architecture that characterizes and mediate the brain's cognitive functions.

Within the past decade, studies of functional connectivity have primarily focused on characterizing both specific (e.g., the default mode; Buckner, Andrews-Hanna, & Schacter, 2008; Fox et al., 2005) and large-scale functional connectivity in the absence of experimental demands (i.e., resting state functional connectivity fMRI). Functional connectivity is defined by the temporal relations of distinct brain areas. To date, studies of functional connectivity during experimental tasks have mainly focused on static representations of region-to-region connectivity (e.g., seed-based functional connectivity or psycho-physiological interactions) within a small set of regions found to be active during particular task conditions. These small, static representations of connectivity between task activated regions during a specific point in the task processing provides insights into the coordination between these regions during that moment in the task, but they neglect the apparent, dynamic, complex nature of cognitive processing that occur across multiple time scales and throughout the brain as we move through the world. In

other words, interactions between specific functional units in the brain's complex systems dynamically adapt to a continually changing environment over multiple temporal scales (Bassett et al., 2011). In order to generate accurate models of brain function during cognition it is essential that cognitive neuroscientists utilize the aforementioned recent methodological and computational advances to characterize these dynamic changes in large-scale functional networks during various cognitive tasks (i.e., problem solving, emotion regulation, memory encoding and retrieval, etc.).

Autobiographical memory retrieval is a particularly good candidate to begin to test theories of dynamic cognitive and neural processing with fMRI because established theories of AM retrieval suggests that it is composed of multiple cognitive processes that evolve over a relatively extended period of time (seconds rather than milliseconds) depending on the task demands. Approaches to examining dynamic functional connectivity have received growing attention recently as sliding-window neuroimaging analysis approaches have become more computationally feasible (Bassett et al., 2011; for thorough review see Hutchison et al., 2013). Although initial studies of functional connectivity during AM retrieval did not account for the dynamic nature of retrieval, they do provide important evidence that has guided theory and evidence to the point that calls for a better understanding of the dynamic neural organization that underlies AM retrieval processes.

Maguire, Mummery, and Büchel (2000) were the first to examine neural connectivity and regional influences during AM retrieval. Previous to their meta-analysis, Maguire et al. examined whether influences between brain regions within the memory retrieval network changed as a function of the type of memory being recollected using

SEM. In the scanner, participants were auditorily cued with brief passages taken from narratives of memories they had written in an earlier questionnaire session. These brief passages were categorized by experimenters to cue a particular type of real-world memory from one of four categories: autobiographical events, public events, autobiographical facts, and general knowledge. Importantly, these four memory types vary on temporal specificity and personal relevance. They tested a declarative memory retrieval network model that included many of the consistently activated regions described for autobiographical and semantic retrieval. Connections in their network were based on known human and primate anatomy (Amaral and Insausti, 1990; Arnold et al., 1994; Van Hoesen, 1982, 1997). Path coefficients were estimated by examining the coupling between the time courses of activity in the relevant brain regions to infer the strength of a given connection between regions. They predicted that strength of influence between regions within the MTL (parahippocampal gyrus and hippocampus) and between the MTL and temporal lobe regions would change as a function of the type of memory being retrieved. They found increased connectivity between parahippocampal gyrus and both the hippocampus and temporal pole during AM retrieval relative to the other types of memory retrieval. In contrast, they found increased connectivity between the lateral temporal cortex and temporal pole during retrieval of public events and facts (i.e., semantic memory).

Later studies focused on regions that were activated during AM retrieval and their functional connectivity to one another (Greenberg et al., 2005). Greenberg et al. examined the role of the MTL and prefrontal cortex using fMRI during AM retrieval for cue words that had been established prior to the scanning session with the participant.

They used a semantic category generation task as a control condition to contrast with activation during AM retrieval. Their results indicated several of the core network regions to be activated during AM retrieval relative to semantic category generation, including the amygdala, left hippocampus, and right ventrolateral PFC. After establishing which regions were active during AM retrieval they further examined the activated regions with a seed-based functional connectivity analysis. Seed-based functional connectivity analyses are performed by extracting the fMRI BOLD signal time course for a 'seed' region of interest (ROI) and running a correlation analysis with signal in the rest of the voxels in the brain to determine which other voxels throughout the brain follow a similar time course. This type of analysis is considered the most basic type of functional connectivity analysis and is useful when testing basic a priori hypotheses of functional connectivity during a task. One limitation of this type of analysis is that it only looks at the correlation of a single time course to other regions on the brain rather than the correlations (i.e., functional connectivity) between a network of regions defined a priori. Using this seed-based analysis, Greenberg et al. found that the amygdala, left hippocampus, and right VLPFC were functionally connected in the AM retrieval condition, but not in the semantic category generation task. Findings from this study led to later studies of the spatiotemporal dynamics of these regions and other regions that had been shown to be involved in AM retrieval (Daselaar et al., 2008).

Although the first studies establishing models of functional and effective connectivity during AM memory retrieval were very informative, data accumulated since their publication and developments in connectivity analyses lend the opportunity to establish more refined models of functional and effective connectivity during AM

retrieval (St. Jacques et al., 2011). First, many earlier retrieval tasks didn't guarantee that the participants were retrieving the memories rather than just listening to a description of a memory or retrieving a recently "rehearsed" version of the memory. Retrieval tasks using generic unrehearsed cues require the participant to reconstruct a spontaneous memory. However, due to issues related to speech related movement artifact during fMRI, researchers can only be somewhat certain that the participant was recalling a memory at all during the retrieval period, so in many cases researchers opt to have participants rehearse the memories prior to scanning to ensure that a memory can be generated for all cues. Furthermore, initial studies were less interested in the dynamic changes in processing during AM retrieval. As described above, several studies and theories of memory retrieval suggest that memories follow a typical flow of processing from memory access to elaboration upon the accessed material. Basing their hypotheses off of a few studies that have begun to establish the changes in neural activation across AM retrieval processes (Conway et al., 2001; Daselaar et al., 2008), two recent studies have examined the dynamic changes in connectivity between these activated regions over the different cognitive processing periods (McCormick et al., 2013; St. Jacques et al., 2011).

As a follow-up to other work that had showed activation of relatively distinct regions involved in the access and elaboration of AMs (Daselaar et al., 2008), St. Jacques et al. (2011) performed an initial examination of the dynamic neural networks that underlie access and elaborative processes during AM retrieval. Participants performed a similar fMRI task to previous AM retrieval studies. Cues were auditorily presented with no rehearsal prior to the scanning session. Using fMRI and independent components

analysis (ICA), they first established that four networks (i.e., components) of regions that tended to vary together. These components consisted of a medial PFC network, MTL network, frontoparietal network, and cinguloopercular network. ICA is useful in distinguishing the coactivation of spatially distinct networks contributing to a particular task (Calhoun et al., 2001; McKeown, 2000). Each component was ascribed to a particular functional role in AM retrieval based on established functions of regions within this network. For example, the mPFC component was described as being involved in self-referential processes, whereas the frontoparietal network was associated with strategic search during access processes. St. Jacques also performed a dynamic causal modeling (DCM) analysis with these four multi-region components as nodes in the network model to infer whether there was a causal influence between each component across the memory retrieval task. They found that the mPFC component drove activation within the system and that other aspects of the participant's subjective retrieval experience, like memory accessibility and recollective qualities, modulated the influence various components had upon on another. In particular, memory accessibility modulated the influence of the frontoparietal and MTL components on the mPFC component, indicative of greater fluency between these components when the memory is easier to retrieve. They also found that the participant's recollective experience (i.e., extent of reliving the memory) modulated the influence of the mPFC on the MTL during elaboration, suggesting that greater connectivity between these systems supports more vivid recollective experience for the memory. This study's findings added to the existing literature by showing that different large-scale, multi-region networks are differentially involved in access and elaboration autobiographical memories. Even though this

evidence is certainly informs the extent to which different large-scale systems interact with one another during AM retrieval, this study does not fully address how specific connections of regions within and between components involved in AM retrieval change as the cognitive processing transitions from initial access-dominated processing to later elaboration-dominated processing. More recent studies have begun to address this gap in the literature with similar dynamic connectivity approaches (McCormick et al., 2013).

Deriving their hypotheses from the previous theory and empirical evidence outlined above, McCormick et al. (2013) asked participants to retrieve an AM from an unrehearsed cue word. In particular, they hypothesized that connections between hippocampal and neocortical activity would shift from the anterior hippocampus being more connected to primarily frontal neocortical regions during memory access and the posterior hippocampus being more connected to occipital and parietal regions during AM elaboration. Using fMRI and spatiotemporal partial least squares analysis (st-PLS) McCormick et al. characterized how frontal, temporal, parietal, and occipital regions that were activated in access or elaboration time windows of their AM retrieval task interacted with the anterior and posterior hippocampus during the hypothesized access and elaboration periods of AM retrieval.

Spatiotemporal PLS is a multivariate, correlation technique used to analyze the association between brain activity and experimental conditions without having to convolve the shape and time course of the hemodynamic response function (Addis et al., 2004; Krishnan, Williams, McIntosh, & Abdi, 2011; McIntosh, Chau, & Protzner, 2004; McIntosh, 1999; McIntosh & Lobaugh, 2004). PLS is useful for identifying common, multi-region brain networks for particular periods of time during a task that fit with a

theoretical model of the underlying cognitive processing timing. McCormick et al. used a seed based version of this technique to test their hypothesis, finding that the left anterior hippocampus was well connected to frontal areas during memory access (i.e. construction). During elaboration, the posterior left and right hippocampus interacted with parietal and occipital areas. Although McCormick et al's study provides important evidence that the anterior and posterior hippocampus play distinct roles in coordinating dynamic changes in neocortical networks during both access and elaboration, their focus on the hippocampus leaves the remaining question of how other core AM retrieval regions, including the hippocampus, interact with one another during transient AM retrieval periods. Multivariate techniques such as sliding-window cross-correlation analysis and graph theory offer the opportunity to characterize the specific region to region changes across the entire core AM retrieval network as cognitive processes transition from early access-related processing to later elaboration-related processing.

The present study

The overall aim of the current research was to test theories of transient changes in cognitive processing during AM retrieval with dynamic measures of large-scale, complex brain network connectivity in two fMRI studies of AM retrieval. The present research specifically aimed to 1) determine the dynamic functional connectivity of specific connections between core AM retrieval regions as retrieval processes unfold from early, access-related processing to late, elaboration-related processing and 2) determine the dynamic changes in large-scale functional network characteristics of core AM retrieval brain regions in the context of the whole brain using topological, graph theory metrics. The AM retrieval tasks utilized to meet these aims include two similar and relatively

standard, rehearsed cue word AM retrieval tasks with long retrieval requirements (several seconds) performed during fMRI scanning in young adults. Dynamic functional connectivity analysis of this AM retrieval data include sliding window, cross-correlation analyses and graph theoretic metrics of core brain regions involved in AM retrieval. These approaches were selected to assess the changing configuration of AM retrieval networks during the hypothesized early, access-related and later, elaboration-related processing periods in each of the two AM retrieval datasets.

Cross-correlation analysis is a basic approach to examining pairwise variations in inter-regional BOLD signal synchrony for an established network of nodes. In the present study's case this network of nodes included core brain regions previously established as involved in AM retrieval. Examining statistically significant changes in correlation strength for individual ROI pairs across distinct time windows during a task (i.e., stronger in time window 1 versus time window 2 and visa versa) is one approach to examining the dynamic changes in functional connectivity over time throughout a pre-determined network or the whole brain. This allows for characterizations of specific changes in region-to-region connectivity and larger patterns of changes in connectivity that depended on the underlying cognitive mechanism (e.g., shift from stronger connectivity between frontotemporal regions to occipito-parietal regions over time). In the present studies, this type of analysis was performed for 18 core AM retrieval network regions selected from the only study to examine dynamic changes in neural activation during access and elaboration processes of AM retrieval and a well-established meta-analysis of regions activated by AM retrieval processes (Daselaar et al., 2008; Svoboda et al., 2006).

Given the complexity of such a multivariate system, mathematical approaches to determine simple organizational features of the system are needed.

Graph theory is a branch of mathematics in which mathematical structures (graphs) are used to model pairwise relations (i.e., edges or connections) between objects (i.e., nodes or in the case of fMRI ROIs; Bullmore & Sporns, 2009; Power et al., 2011; Rubinov & Sporns, 2010; Wig et al., 2011). In brain science, graphs are networks composed of a pre-determined set of functional regions involved in a task or a functional parcellation of regions throughout the whole brain. In particular, graphs are abstract representations of the components in a network that are useful in visualizing important topological properties of a network's organization and structure (Bullmore & Sporns, 2009; Wig et al., 2011). Although graphs are useful for visualizing properties of a network's structure, the matrix of a network's connections, known as an adjacency matrix, is the primary computational unit for analysis of graph properties or metrics. Graph metrics are used to help determine simple organizational features of the complex network architecture and include many objective measures of node-based and network-based properties.

The primary graph properties related to functional brain connectivity are strength and centrality (Rubinov & Sporns, 2010). In graph theory terms, node strength is one of the most basic metrics of a node's connectivity to the network and is defined as the either the sum or average correlation coefficient between a given region and all of the regions that are connected to it. Whereas the correlation coefficient strength in the cross-correlation analyses reflects the correlation between only two regions, node strength is a more general measure of a region's connectivity with the rest of the network. The

centrality metric in a brain network is used to identify brain regions that frequently interact with many other brain regions. In other words, regions with high centrality are considered hubs of information processing in a network. Regions with high centrality have been shown to facilitate functional integration of information from throughout the network and are key to a network's vulnerability and resilience to damage (Power et al., 2011; Rubinov & Sporns, 2010; Sporns, Chivalo, Kaiser, & Hilgetag, 2004). Common centrality measures are based on the idea that brain regions with more short paths within a network act as important information flow controls (Sporns, Chivalo, Kaiser, & Hilgetag, 2004). For example, in a social network the person with the most connections (i.e., high centrality) with others will likely have a larger influence on the communication within that network than a person with only a few connections (i.e., low centrality). The most common metric for measuring centrality is node degree centrality. Degree centrality is a fundamental graph theory measure for individual nodes in a network that is measured by the number of other nodes connected to a particular node. In order to be considered connected, the relation between regions must meet some sort of pre-defined criteria like having a correlation greater than a specific threshold. In analyses of brain network dynamics during a task these graph metrics of a region's centrality allow for a characterizations of the region's facilitatory role in the integration of distributed information during a particular period in the AM retrieval processes. In the present studies, these graph metrics were utilized as dynamic measures of the extent of a region's synchronization to the rest of the core AM retrieval network (i.e., node strength) and role in integrative processing (i.e., degree centrality) in a whole brain network.

The current research consisted of two related experiments in which adult participants engaged in AM retrieval of word cues that were selected prior to fMRI scanning to elicit a specific autobiographical memory. Study 1 aimed to examine the dynamic changes in functional connectivity across early and late periods of AM retrieval between regions that have been consistently implicated in AM retrieval processes. In contrast to previous studies of AM retrieval that apply an event-related general linear model according to a participants report of accessing the memory, a model-free approach was utilized in the analysis of this data to better capture the changes in AM network connectivity across the entire retrieval condition. The experimental design for study 1 consists of AM retrieval after the presentation of a personal and neutral cue word for a shorter duration relative to some previous studies of AM retrieval (e.g. 16 seconds vs. 24+ seconds). In this iteration of the AM retrieval procedure, additional prompts were given after the cue word to aid and remind participants to continue to elaborate on a given memory for the duration of each AM retrieval trial. Study 2 was designed to address some of the potential design limitations of study 1.

Study 2 aimed to examine the dynamic changes in functional connectivity across the AM retrieval processes as well, but was designed to examine AM retrieval processes for a longer duration (i.e., 30 seconds), with a shorter presentation of the memory cue, and without supplementary elaboration prompts. These changes in experimental design were made to allow for a more naturalistic AM retrieval condition in which the memory cue had to be maintained in working memory, additional cues to aid elaboration had to be internally generated, and each memory had sufficient time to be fully elaborated upon. Given these characteristics for study 2, we were able to observe the elaboration process

beyond the initial elaboration period observed in study 1, to test whether changes in connectivity patterns between the initial late period and early period persist throughout the rest of AM retrieval. Through the shared and distinct characteristics of both studies, the overall aim of this thesis was to test current theories of AM retrieval dynamics (i.e., self-memory system) by characterizing the changes in the connectivity strength of individual regions involved in AM retrieval and topological relationship of each core AM retrieval region to every other AM retrieval region and the whole brain.

The analysis approach to examining dynamic functional connectivity was the same across both studies, consisting of sliding-window, cross-correlation analysis and graph metric analyses of core AM retrieval regions. Pairwise cross-correlation analyses were performed across time windows throughout AM retrieval for all connections in the 18 region, core AM retrieval network previously established as involved in AM retrieval (Cabeza & St Jacques, 2007; Conway et al., 1999, 2002; Daselaar et al., 2008; Maguire, 2001; Svoboda et al., 2006). Dynamic graph metric analyses were performed for a whole brain homologue of each of the 18 core AM retrieval regions in a 200-region whole brain network. In particular, the functional synchrony (e.g., node strength) and centrality (e.g., degree) of each of the 18 core AM retrieval network regions was examined in relation to a whole brain network. The same functional connectivity parcellation of the whole brain into 200 ROIs was used to determine the topological properties of parcellated ROIs that were homologous to the 18 core AM retrieval ROIs (Craddock, James, Holtzheimer, Hu, & Mayberg, 2012). This methodological framework was utilized for both studies in order to test the theories of transient changes in cognitive processing during AM retrieval with dynamic measures of large-scale, complex brain network connectivity.

Based on the evidence from studies of cognitive processing, neural activation, and brain connectivity during AM retrieval, both studies have similar hypotheses for the predominant brain networks during early, access-related and later, elaboration-related processing during AM retrieval. First, we expect the nearly all of the core AM retrieval regions to be at least moderately connected to one another (i.e., $r > 0.3$) and that most of the network will be stable throughout AM retrieval base on the evidence that these regions tend to activate with one another (Cabeza et al., 2004; Cabeza & St Jacques, 2007; Conway et al., 1999; Muscatell et al., 2010; Svoboda et al., 2006). To confirm that each study had sufficient power (i.e. number of time points in each time window) to estimate biological relevant network organization, we would expect that the strongest stable or non-dynamic connections should be observed between regions local (i.e., within the same lobe) and contralateral to one another due to similar processing roles of regions that are closer and homologous to one another. In other words, we would expect that the stable network would have a structured, non-random topological organization that fits with the numerous studies of large-scale connectivity in task and resting-state studies of the brain.

Many previous studies have found that the mPFC activity is modulated by the extent of self-referential processing required by the memory being retrieved (Bonnici et al., 2012; D'Argembeau et al., 2007). Given that autobiographical memory is particularly defined as memories related to the self we would expect that self-referential processes may be engaged to various regions throughout AM retrieval, but not necessarily be predominantly connected to certain parts of the network in either the early or late time periods. Evidence supporting this hypothesis suggest that the medial PFC was engaged

throughout retrieval and thus we expected that connectivity to the mPFC would remain stable throughout AM retrieval (St. Jacques et al., 2011). St. Jacques et al. also found that their MTL component, consisting of the hippocampus, parahippocampal gyrus, and posterior cingulate, was engaged throughout AM retrieval. Differing from the predictions of stability in mPFC connections, evidence from McCormick et al. (2013) would suggest that St. Jacques et al's MTL component did not sufficiently differentiate between subregions of the medial temporal lobe (e.g. anterior and posterior hippocampus) that play different roles the earlier and later periods of AM retrieval.

In light of the findings of the research reviewed above (Conway et al., 2001; Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011), we generally expect anterior connections (i.e., frontal and temporal) to be stronger and more central to integrating distributed information during early, access-related process than later processing periods. During later, elaboration-related processing we generally expect a more distributed pattern of connectivity that predominantly consists of posterior connections (i.e., parietal-occipital and frontoparietal). The hypothesized component processes within each of the dynamic processing periods (i.e., early-access and late-elaboration) and the specific connections that would be predicted to underlie each component process are described below to further define specific predictions for each processing period.

According to the hypothesized component processes during the early, access-related processing period of autobiographical memory retrieval we expected to see dynamic changes in connectivity between specific regions in the frontal lobe, medial temporal lobe, and parietal lobe. In particular, previous evidence suggests that the

ventrolateral PFC is specifically involved in memory search or retrieval mode processing (Daselaar et al., 2008; Rugg & Vilberg, 2012; Velanova et al., 2003; Wagner, 1998). Furthermore, neuropsychological evidence (Barceló et al., 2000; Knight et al., 1999) converges with fMRI data to suggest that ventrolateral PFC implements top-down control signals to bias processing in posterior cortical regions like the parietal and late visual cortex (Ranganath and Knight, 2005; Petrides, 2002; Ranganath & Paller, 1999, 2000). Thus, we expected the VLPFC to play a central role during access-related processing with stronger connections to the anterior hippocampus and posterior parietal regions. Evidence in support of this prediction would show that the VLPFC had stronger connections to MTL and parietal regions and was more central (e.g. higher degree) in the early-access period relative to the late-elaboration period. Strong laterality predictions are not made given that neither of the present studies specifically manipulated variables known to modulate the VLPFC's laterality and the lack of consensus in the previous literature on the laterality of the VLPFC's involvement in strategic search-related processing.

In addition to lateral frontal strategic search processes, several reviews have suggested that another component process during the early-access period is initial reconstruction of specific memory context and details related to the cue (Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Tulving, 2002). A rich literature of hippocampal lesion studies (Addis, Moscovitch, & McAndrews, 2007; Maguire, Vargha-Khadem, & Mishkin, 2001; Squire, 2004; Tulving, 2002; Wixted & Squire, 2011) and neuroimaging studies of AM retrieval suggest that the hippocampus is involved in the construction and rebinding of memory details (Daselaar et al., 2008; Greenberg et al.,

2005; McCormick et al., 2013; St. Jacques et al., 2011). Greenberg et al. (2005) did not examine changes in connectivity across AM retrieval, but found that the left anterior hippocampus exhibited strong functional connectivity to the right VLPFC during AM retrieval. McCormick et al. (2013) further specifies this construction and rebinding function to involve stronger connections between the left anterior hippocampus and the lateral and medial PFC during the early-access period. Findings from the present study that would support this previous evidence would show that the hippocampus, more specifically the anterior hippocampus, is more strongly connected to medial and lateral PFC regions earlier relative to later in retrieval. We also would expect the anterior hippocampus to play a more central role (i.e., higher degree) in the AM retrieval network during this early-access period relative to the later periods. In addition to the hippocampus, Daselaar et al. implicated the medial retrosplenial cortex or posterior cingulate cortex in memory reconstruction processes early in AM retrieval. Based on this evidence we would expect that connections between the hippocampus and the PCC would be stronger early relative to late in retrieval. In summary, early, access-related processing was predicted to be primarily characterized by a predominantly anterior network of connections that have been previously shown to underlie strategic memory search processes (i.e., retrieval mode) and initial reconstruction of the cue context with specific event details. Evidence supporting models of dynamic AM retrieval suggests that the strength of engagement, connectivity, and centrality of this primarily anterior, access-related network would diminish as a more posterior network of regions become engaged to process aspects of re-experiencing the specific AM found during memory access.

Once a specific memory has been accessed for each AM cue, connections between regions in the parietal and occipital lobes were predicted to become stronger and more central to the AM retrieval network as the specific memory is elaborated upon. Elaboration or reconstruction of the remembered experience is hypothesized to consist of several component processes including visual imagery and sensory processing of memory details, continuation of processes to rebind memory details and context, and maintenance of event details that have been retrieved in working memory (Addis et al., 2004; Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011). Regions throughout all lobes of the brain have been implicated in each of these component processes based on the fMRI tasks of various cognitive behaviors that tend to activate each region (Svoboda et al., 2006). In particular, regions in the occipital and parietal cortex have been implicated in visual imagery processing when a participant is imagining an experience or retrieving a memory (Addis et al., 2011; Daselaar et al., 2008; Ganis, Thompson, & Kosslyn, 2004). Thus, we expected to see stronger connectivity between the occipital cortex (i.e., BA19, extrastriate cortex) and both medial and lateral parietal cortex during the late-elaboration period relative to the early-access period of AM retrieval. We expected these patterns of posterior connectivity to persist through the duration of the retrieval period after the early period of retrieval (this was only possible to assess in study 2, due to an increased retrieval period duration).

The process of rebinding of memory context and details are thought to persist from the early-access period through to the late-elaboration period as new details are found and incorporated into the memory representation (McCormick et al., 2013).

Evidence from McCormick et al. (2013) suggests that the posterior hippocampus is more strongly connected to medial and lateral parietal areas during late-elaboration processes than early-access processes. Poppenk et al. (2013) propose that the role of the posterior hippocampus in memory retrieval is to retrieve the precise spatiotemporal context and episodic details of the remembered event. Based on the posterior hippocampus' proposed role in memory retrieval processes, we expected that the posterior hippocampus, bilaterally, would be more strongly connected to core AM retrieval regions in the parietal cortex during late-elaboration related processing relative to early-access related processing. We also predicted the posterior hippocampus would play a more central role in the later periods of processes.

Finally, connections between the dorsolateral frontal cortices and superior parietal cortices have been implicated in the process of maintaining information in working memory and representational control processes (Baddeley, 2003; Vincent et al., 2008; Wager & Smith, 2003). As the specified memory is elaborated upon the previously recalled details would likely need to be maintained in working memory, thus we predicted that frontoparietal connections would become stronger than during early-access processes. As reviewed above, a wealth of previous research has identified a posterior network of regions that are typically engaged during the component processes hypothesized to underlie elaborative memory retrieval processes. Support for our hypotheses would demonstrate that regions in this more posterior network change in the extent of their synchronization with one another from earlier to later in retrieval as more elaboration-related processes begin to predominate autobiographical memory retrieval processes.

In summary, the goal of the present study was to investigate predictions regarding different patterns of connectivity that were hypothesized to underlie the dynamic cognitive processes engaged during autobiographical memory retrieval. In particular, we hypothesized, based on previous literature, that connections of regions throughout the core AM retrieval network would reliably and dynamically change as autobiographical memories from one's personal past are retrieved and elaborated upon, reflecting a transition from access-related to elaboration-related processes. Overall, we predicted anterior connections (i.e., frontal and temporal) to be stronger and more central to integrating distributed information during early, access-related processing than later processing periods. During later, elaboration-related processing we predicted a more distributed pattern of connectivity that predominantly consists of posterior connections (i.e., parietal-occipital and frontoparietal).

Study 1: Dynamic functional connectivity changes between access and elaboration of autobiographical memories

Encoding and retrieval of autobiographical memories is a fundamental cognitive ability that is essential to the formation and maintenance of one's self-concept through time. Theories of the cognitive processes that underlie autobiographical memory retrieval have developed along side the theoretical developments in similar forms of declarative memory, like episodic memory (i.e., memory for where, what, and when an event occurred in the past) and semantic memory (i.e., explicit knowledge of the world; Tulving & Thomson, 1973; Tulving, 1983). In particular, autobiographical memories (AMs) are much more varied in their temporal and spatial context, emotional characteristics, visual imagery, relation to self, and narrative structure than laboratory controlled and encoded episodic memories (Cabeza & St Jacques, 2007; Daselaar et al., 2008; Rubin, 2005). Autobiographical memories are considered by some to be episodic memories specifically related to the self (Cabeza & St Jacques, 2007; Tulving, 2002). Other researchers draw a further distinction for autobiographical memory as a subset of episodic memory in which the rememberer must have the conscious experience of the self mentally time traveling to a personal past (autonoetic awareness; Fivush, 2011). Recent theories of autobiographical memory retrieval propose that AMs are dynamic mental constructions generated from a personal knowledge base (Conway & Pleydell-Pearce, 2000). Retrieval of autobiographical memories entails a complex coordination of cognitive processes that unfold over time to generate these mental reconstructions, such as strategic mnemonic search, rebinding of episodic details to context, memory monitoring, maintenance, and elaboration. Although the neural regions activated during

this complex and dynamic behavior have begun to be established, the neural mechanisms formed through the coordinated activity of these brain regions is much less established. The goal of the present study is to address this gap in evidence for dynamic theories of AM retrieval by examining the changes in functional connectivity and topological properties of a core AM retrieval network as retrieval unfolds from access-related to elaboration-related processing.

One recent theory of autobiographical memory that builds on many previous theories of episodic and autobiographical memory retrieval is known as the self-memory system (SMS). SMS theory proposes that autobiographical memory retrieval involves our autobiographical knowledge base which consists of knowledge about life-time periods, general events, and specific events interacting with the "working self" (Conway & Pleydell-Pearce, 2000). The working self is defined as a core part of the working memory system (Baddeley, 2003; Conway & Pleydell-Pearce, 2000) consisting of control processes that coordinate and modulate other computationally distinct systems. Conway and Pleydell-Pearce (2000) propose that the working self and the autobiographical knowledge base are instantiated by certain sub-networks of the brain that dynamically change in their predominance of activity and coordination throughout the retrieval of an autobiographical memory. Specifically, SMS theory posits that immediately after a cue provokes specific information in memory to be retrieved, activation in frontal and temporal networks should occur due to their involvement in the instantiation of the working self (i.e., ecphory; Moscovitch & Melo, 1997; Moscovitch, 1995). This access of memory process is similar to another proposed memory process known as retrieval mode, which has been defined as a mental set that guides retrieval of episodic information

(Velanova et al., 2003). Controlled memory access processes are followed by integration of the accessed memory with details that allow for one to mentally re-experience the memory, which is related to increased activation in posterior parietal and occipital networks. Some research has provided supportive evidence of various brain activations that fit with this dynamic hypothesis (Conway et al., 1999; Conway, Pleydell-Pearce, & Whitecross, 2001; Daselaar et al., 2008; St. Jacques et al., 2011), but the SMS theory presently lacks needed evidence of the dynamic interactions or connectivity between specific core brain regions involved in AM retrieval. In particular, a characterization of how specific neural networks change as a function of the complex cognitive processes underlying autobiographical memory retrieval is needed to help disentangle the dynamic nature of the proposed autobiographical memory retrieval processes.

Autobiographical memory is the result of many component processes that occur over time to enable the re-experiencing of a phenomenologically rich and textured past (Svoboda et al., 2006). Many neuroimaging studies have been performed examining the neural correlates of AM retrieval. Summarizing across these neuroimaging studies, several literature reviews and meta-analyses have reviewed the regions typically activated in fMRI studies of autobiographical memory retrieval (Cabeza & St Jacques, 2007; Conway et al., 2002; Maguire, 2001; Svoboda et al., 2006). In an early meta-analysis of autobiographical memory, Maguire (2001) found that distributed networks of neural regions involved in retrieving autobiographical memories include the MTL (i.e., hippocampus, parahippocampal gyrus), retrosplenial cortex, posterior parietal regions (i.e., inferior parietal and precuneus), as well as lateral and medial PFC. Subsequent studies and meta-analyses have provided evidence in support of this core network (Addis

et al., 2004; Burianova, McIntosh, & Grady, 2010; Daselaar et al., 2008; Greenberg et al., 2005), for the most recent meta-analysis see Svoboda et al., 2006). Svoboda et al. (2006) found that the core AM network also included the cerebellum and the temporoparietal junction (TPJ). Several secondary regions are consistently activated in studies of AM including regions involved in mentally re-experiencing the memory (i.e., occipital cortex in visual imagery processing) and processing the emotional qualities of the memory. Across studies secondary region activation tends to depend on the nature of the memory retrieval task (Svoboda et al., 2006). For instance, the amygdala has been implicated in studies that manipulate the emotional content of an autobiographical memory. All of these core network regions have been assigned to particular processing roles in the retrieval of AMs based on the typical cognitive processes that tend to activate these regions.

Reviewing many of the neuroimaging studies of AM retrieval, Svoboda et al. (2006) found the core AM retrieval network included several regions in the frontal lobe, including the dorsolateral and ventrolateral prefrontal cortex (DLPFC and VLPFC) and the medial PFC (mPFC). The medial aspect of the PFC is implicated in processing and recollecting the self-relevance of a particular memory and is thought to be particularly active during AM retrieval relative to more episodic or semantic memory retrieval (D'Argembeau et al., 2007; Gusnard et al., 2001; Markowitsch et al., 2003; Oddo et al., 2010; Simons & Spiers, 2003). Bilaterally, the DLPFC has been implicated in working memory related processes and the VLPFC has been implicated in strategic, strategic memory search (i.e., "retrieval mode"; Rugg & Vilberg, 2012; Rugg & Wilding, 2000; Vincent et al., 2008). As mentioned earlier, the lateral PFC is involved in control,

selection, and maintenance of mnemonic information in later aspects of remembering associated with elaboration (Daselaar et al., 2008). In addition, nearly all of the meta-analyses and empirical studies to date implicate regions in the MTL as the primary hub for memory retrieval processing. Current evidence suggests that the passage of time and qualitative aspects of the retrieved memory like personal significance, amount of detail recalled, and vividness modulated the involvement of the MTL in declarative memory (Svoboda et al., 2006). The hippocampus is primarily implicated in the AM retrieval processes of rebinding episodic details with the contextual details specified by the retrieval cue (Cabeza & Moscovitch, 2013; Eichenbaum, Sauvage, Fortin, Komorowski, & Lipton, 2012; Poppenk, Evensmoen, Moscovitch, & Nadel, 2013; Squire, 2004). Activity of other MTL regions like the amygdala tend to be modulated by the emotional content and arousal produced by an autobiographical memory. The retrosplenial cortex (RSC) or posterior cingulate cortex (PCC) is also often described as part of the core autobiographical memory network. These regions have been shown to act as an essential structural node between thalamic inputs/outputs and the hippocampus and might be involved in memory search processes and retrieval of sensory details (Kobayashi & Amaral, 2003). For instance, damage to the RSC or PCC causes deficits in memory due to a disconnection syndrome, known as diencephalic amnesia (Aggleton & Pearce, 2001; Gainotti et al., 1998). Other regions of the core autobiographical memory network include those engaged in retrieval of sensory information (e.g. visual cortex), including mental imagery of this sensory information (e.g. precuneus and inferior parietal cortex), and goal-directed control processes (e.g. dorsal frontoparietal regions; Svoboda et al., 2006). These functions may be engaged and reengaged until the retrieval goal is

achieved. Regions engaged in various facets of visuospatial processing (i.e., visual cortex, parietal cortices, and TPJ) are engaged later in processing during the predominately elaborative period of memory retrieval. This additional sensory processing seems to vary as a function of the extent to which a memory is reported as relived or re-experienced (Cabeza & St Jacques, 2007; Daselaar et al., 2008; St. Jacques et al., 2011).

An important consideration of this set of core regions activated during AM retrieval is that all but a few of the studies to date have examined AM retrieval as a stationary, non-dynamic process that does not change over time. Some reviews have tried to decipher temporal, dynamic properties of AM retrieval by contrasting findings from studies that had long retrieval periods (20-120 seconds) with those that had shorter retrieval periods (10-20 seconds; Svoboda et al., 2006). However, even though fMRI has less temporal resolution that electrophysiological methods like EEG, this meta-analytic approach overlooks the important temporal information that is captured moment-to-moment in fMRI and cannot accurately address the actual temporally dynamic states that underlie AM retrieval. One early study that aimed to address this issue by using slow cortical potentials was performed by Conway et al. (2001). This study showed that the process of AM retrieval seemed to evolve over time from left frontal and anterior temporal regions to more posterior, parietal and occipital regions. A follow-up PET imaging study showed that AM retrieval activated a large swath of the left frontal cortex, in addition to parietal and occipital regions. Conway et al's slow cortical potential study was the first to examine AM retrieval as a dynamic process that evolved from one cognitive process to the next over the retrieval period. Whereas the EEG data could determine the dynamic temporal properties of the changing cognitive processing, it was

unable to identify specific regions activated across these evolving AM retrieval processes. Although their PET study of these processes begins to address this issue, it necessarily had to treat the AM retrieval period as a stationary set of processes due to PET imaging's lack of temporal resolution that could map dynamic cognitive processes. Although all but a few studies examined AM retrieval as a stationary process, these studies provided key findings regarding the set of regions that were core to AM retrieval processes. Interestingly, in a later study that examined the dynamic nature of AM retrieval processing with fMRI, Daselaar et al. (2008) found that lateral frontal activations were predominantly right lateralized during early AM retrieval (i.e., access and search processes) and later lateral frontal activations were predominantly left lateralized (i.e., elaboration and maintenance processes). They note that the right lateralization of the PFC activation during the early processing period is consistent with previous studies that propose a 'retrieval mode' during memory search and access (Daselaar et al., 2008). Lateralization may also be modulated by other aspects of the AM retrieval task like the extent to which the memory is to have a narrative structure versus just mentally 'relived' might modulate the activity to the left hemisphere due to more verbal processing.

Many cognitive neuroscientists work from the viewpoint that complex interactions between distributed objects of information processing (i.e., functional brain regions) give rise to cognitive processes (Wig et al., 2011). In particular, memory is not the property of brain regions operating in isolation, but rather memory is the property of dynamic brain networks that underlie the cognitive processing needed to retrieve memories from our recent and distant past (Maguire, 2001). The consistency of activation

within this core network of regions makes AM retrieval a well suited candidate for further investigation into the functional integration of each region's connectivity with other core network regions and regions throughout the brain. Although these regions are consistently activated across many studies, there are notable differences between the evidence that activation and functional connectivity studies provide to mechanistic explanations of cognitive processing. Studies of neural activation help identify the processing roles of particular regions by taking advantage of well-constructed control conditions that are subtracted from the activation map in the experimental condition (i.e., AM retrieval versus semantic retrieval or visual imagery). On the other hand, functional connectivity differs from studies of activation in that connectivity studies account for the temporal correlation of the signal in two or more regions over time. Temporal synchronization of the activation in two regions is typically interpreted as a measure of the extent to which the regions are sharing information or communicating with one another in service of a specific cognitive process.

Initial studies of neural connectivity during AM retrieval have used various techniques for examining the functional connectivity of regions activated during AM retrieval. These techniques include seed-based connectivity studies (region-to-region connectivity; Greenberg et al., 2005), multivariate seed-based approaches like partial least squares (PLS) analysis (McCormick et al., 2013), and independent components analysis (ICA; St. Jacques et al., 2011). Using a seed-based analysis to examine the connectivity between regions that were activated during their AM retrieval task, Greenberg et al. found that the amygdala, left hippocampus, and right VLPFC were more strongly coupled with one another in an AM retrieval task than in a semantic category

generation task. One of the first multivariate and dynamic examinations of connectivity during AM retrieval came from St. Jacques et al. (2011). Using a technique for identifying spatially distinct networks contributing to a particular task known as ICA (Calhoun et al., 2001; McKeown, 2000), St. Jacques et al. found four spatially distinct yet correlated sets of regions, known as components, that tended to vary together and dynamically shift in predominance during earlier and later retrieval periods. These components consisted of a medial PFC network, MTL network, frontoparietal network, and cinguloopercular network. Each component was ascribed to a particular functional role in AM retrieval based on established functions of regions within this network from previous studies, like the mPFC in self-referential processing and the frontoparietal network in strategic search and working memory processes. Combining aspects of the approaches described above, McCormick et al. (2013) was particularly interested in examining the roles of the anterior and posterior hippocampus in the dynamic processing of AM retrieval. They chose a method that is useful for identifying connected, multi-region brain networks for particular periods of a task known as partial least squares analysis (PLS; McIntosh, Chau, & Protzner, 2004; McIntosh, 1999; McIntosh & Lobaugh, 2004). McCormick et al. used a seed based version of this technique to test their hypothesis of anterior hippocampal connectivity to frontal regions early in retrieval and posterior hippocampal connectivity to parietal regions later in retrieval. They found support for their hypothesis in that the left anterior hippocampus was well connected to frontal areas during early, access-related processing. During later elaboration the posterior hippocampus, bilaterally, interacted with parietal and occipital areas. This finding provides evidence that the anterior and posterior hippocampi play distinct roles in

coordinating dynamic changes in neocortical networks during both access and elaboration. All of these approaches have provided important evidence that specific regions or large-scale components composed of many brain regions with similar time course signals, change in their functional connectivity strength with one another over the duration of AM retrieval. Other multivariate, multi-region and whole brain analyses of AM retrieval data, like sliding window cross-correlation analysis and graph theory, are needed to provide a full characterization of the dynamic changes in cognitive processing that occur between specific regions the brain during AM retrieval.

The aim of the current study was to test the theories of transient changes in cognitive processing during AM retrieval with dynamic measures of large-scale, complex brain network connectivity. Specifically, the current study examines the dynamic changes in functional connectivity across early and late periods of AM retrieval between regions that have been consistently implicated in AM retrieval processes. In contrast to previous studies of AM retrieval that apply an event-related general linear model according to a participants report of accessing the memory, a model-free approach was utilized in the analysis of this data to better capture the changes in AM network connectivity across the entire retrieval condition. The experimental design for the current study consists of AM retrieval after the presentation of a personal and neutral cue word for a shorter duration relative to some previous studies of AM retrieval (e.g. 16 seconds vs. 24+ seconds). In this iteration of the AM retrieval procedure, additional prompts were given after the cue word to aid and remind participants to continue to elaborate on a given memory for the duration of each AM retrieval trial. Thus, this study's design was optimized to ensure that all of the presented cue words had an associated memory for each participant and the

memories were given sufficient prompts to encourage elaboration of each AM throughout the retrieval trial. The present study tests current theories of AM retrieval dynamics (i.e., self-memory system) by characterizing the changes in the connectivity strength of individual regions involved in AM retrieval and topological relationship of each core AM retrieval region to every other AM retrieval region and the whole brain.

Based on the evidence from studies of cognitive processing, neural activation, and brain connectivity during AM retrieval, the current study characterizes functionally connected brain networks during early, access-related and later, elaboration-related AM retrieval processing. First, we expect the nearly all of the core AM retrieval regions to be at least moderately connected to one another (i.e., $r > 0.3$) and that most of the network will be stable throughout AM retrieval base on the evidence that these regions tend to activate with one another (Cabeza et al., 2004; Cabeza & St Jacques, 2007; Conway et al., 1999; Muscatell et al., 2010; Svoboda et al., 2006). To confirm that each study had sufficient power (i.e. number of time points in each time window) to estimate biological relevant network organization, we would expect that the stable network would have a structured, non-random topological organization that fits with the numerous studies of functional large-scale connectivity in task and resting-state studies of the brain.

Many previous studies have found that the mPFC activity is modulated by the extent of self-referential processing required by the memory being retrieved (Bonnici et al., 2012; D'Argembeau et al., 2007). Given that autobiographical memory is particularly defined as memories related to the self, we would expect that self-referential processes may be engaged throughout AM retrieval. Evidence supporting this hypothesis suggest that the medial PFC was engaged throughout retrieval and thus we expected that

connectivity to the mPFC would remain stable throughout AM retrieval (St. Jacques et al., 2011). St. Jacques et al. also found that their MTL component, consisting of the hippocampus, parahippocampal gyrus, and posterior cingulate, was engaged throughout AM retrieval. Differing from the predictions of stability in mPFC connections, evidence from McCormick et al. (2013) would suggest that St. Jacques et al's MTL component did not sufficiently account for specific aspects of the medial temporal lobe (e.g. anterior and posterior hippocampus) that play different roles the earlier and later periods of AM retrieval.

Considering the findings of the research reviewed above (Conway et al., 2001; Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011), we generally expect anterior connections (i.e., frontal and temporal) to be stronger and more central to integrating distributed information during early, access-related process than later processing periods. During later, elaboration-related processing we generally expect a more distributed pattern of connectivity that predominantly consists of posterior connections (i.e., parietal-occipital and frontoparietal). To further describe specific predictions for each processing period, the hypothesized component processes within the each of the dynamic processing period (i.e., early-access and late-elaboration) and the specific connections that would be predicted to underlie each component process are described below.

According to the hypothesized component processes during the early, access-related processing period of autobiographical memory retrieval we expected to see dynamic changes in connectivity of frontal lobe to MTL and frontal lobe to parietal lobe connections. Previous evidence suggests that the ventrolateral PFC is specifically

involved in memory search or retrieval mode processing (Daselaar et al., 2008; Rugg & Vilberg, 2012; Velanova et al., 2003; Wagner, 1998). Thus, we expected the VLPFC to play a central role during access-related processing. Evidence in support of this prediction would show that the VLPFC had stronger connections and was more central (e.g. higher degree) in the early-access period relative to the late-elaboration period. Strong laterality predictions are not made given that neither of the present studies specifically manipulated variables known to modulate the VLPFC's laterality and the lack of consensus in the previous literature on the laterality of the VLPFC's involvement in strategic search-related processing.

In addition to lateral frontal strategic search processes, several reviews have suggested that another component process during the early-access period is initial reconstruction of specific memory context and details (Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Tulving, 2002). A rich literature of hippocampal lesion studies (Addis, Moscovitch, & McAndrews, 2007; Maguire, Vargha-Khadem, & Mishkin, 2001; Squire, 2004; Tulving, 2002; Wixted & Squire, 2011) and neuroimaging studies of AM retrieval suggest that the hippocampus is involved in the construction and rebinding of memory details (Daselaar et al., 2008; Greenberg et al., 2005; McCormick et al., 2013; St. Jacques et al., 2011). Although Greenberg et al. (2005) did not examine changes in connectivity across AM retrieval, they found that the left anterior hippocampus exhibited strong functional connectivity to the right VLPFC during AM retrieval. McCormick et al. (2013) further specifies this construction and rebinding function to involve stronger connections between the anterior hippocampus and the PFC during the early-access period. Findings from the present study that would support this

previous evidence would show that the hippocampus, more specifically the anterior hippocampus, is more strongly connected to medial and lateral PFC regions earlier relative to later in retrieval. We also would expect the anterior hippocampus to play a more central role (i.e., higher degree) in the AM retrieval network during this early-access period relative to the later periods. In addition to the hippocampus, Daselaar et al. implicated the medial retrosplenial cortex or posterior cingulate cortex in memory reconstruction processes early in AM retrieval. Based on this evidence we would expect that connections between the hippocampus and the PCC would be stronger early relative to late in retrieval. In summary, early, access-related processing was predicted to be primarily characterized by a predominantly anterior network of connections that have been previously shown to underlie strategic memory search processes (i.e., retrieval mode) and initial reconstruction of the cue context with specific event details. Previous literature suggests that the strength of engagement, connectivity, and centrality of this primarily anterior, access-related network would diminish as a more posterior network of regions become engaged to process aspects of re-experiencing the specific AM found during memory access.

Once a specific memory had been identified for each AM cue, connections between regions in the parietal and occipital lobes were predicted to become stronger and more central to the AM retrieval network as the specific memory is elaborated upon. Elaboration or reconstruction of the remembered experience is hypothesized to consist of several component processes including visual imagery and sensory processing of memory details, continuation of processes to rebind memory details and context, and maintenance of event details that have been retrieved in working memory (Addis et al., 2004; Cabeza

& St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011). Regions throughout all lobes of the brain have been implicated in each of these component processes based on the cognitive fMRI tasks that tend to activate each region (Svoboda et al., 2006). In particular, regions in the occipital and parietal cortex have been implicated in visual imagery processing when a participant is imagining an experience or retrieving a memory (Addis et al., 2011; Daselaar et al., 2008; Ganis, Thompson, & Kosslyn, 2004). Thus, we expected to see stronger connectivity between the occipital cortex (i.e., BA19, extrastriate cortex) and both medial and lateral parietal cortex during the late-elaboration period relative to the early-access period of AM retrieval. We expected these patterns of posterior connectivity to persist through the duration of the retrieval period after the early period of retrieval.

The process of rebinding of memory context and details are thought to persist from the early-access period through to the late-elaboration period as new details are found and incorporated into the memory representation (McCormick et al., 2013). Evidence from McCormick et al. (2013) suggests that the posterior hippocampus is more strongly connected to medial and lateral parietal areas during late-elaboration processes than early-access processes. Poppenk et al. (2013) propose that the role of the posterior hippocampus in memory retrieval is to retrieve the precise spatiotemporal context and episodic details of the remembered event. Based on the posterior hippocampus' proposed role in memory retrieval processes, we expected that the posterior hippocampus, bilaterally, would be more strongly connected to core AM retrieval regions in the parietal cortex during late-elaboration related processing relative to early-access related

processing. We also predicted the posterior hippocampus would play a more central role in the later periods of processes.

In addition, connections between the dorsolateral frontal cortices and superior parietal cortices have been implicated in the process of maintaining information in working memory and representational control processes (Baddeley, 2003; Vincent et al., 2008; Wager & Smith, 2003). As the specified memory is elaborated upon the previously recalled details would likely need to be maintained in working memory, thus we predicted that frontoparietal connections would become stronger than during early-access processes. As reviewed above, a wealth of previous research has identified a posterior network of regions that are typically engaged during the component processes hypothesized to underlie elaborative memory retrieval processes. Support for our hypotheses would demonstrate that these more posterior regions change in the extent of their synchronization with one another from earlier to later in retrieval as more elaboration-related processes begin to predominate autobiographical memory retrieval. Overall, this study aims to provide evidence for dynamic models of AM retrieval that propose neural processing that underlies AM processes dynamically unfold from memory access-related processing to elaboration of the accessed memory.

Method

Participants

Seventeen healthy adult volunteers (ages 19-30; *M*=23; *SEM*=0.71; 11 female) were recruited from Emory University and compensated for their participation with a gift card from a local merchant. Each adult participant gave informed written consent as approved by the Emory University IRB. Sixteen adults (ages 19-30; *M*=23; *SEM*=0.76;

10 female) were included in the final analyses after 1 participant was later excluded due to opting out of the study.

Task and procedures

Materials

The study consisted of two distinct parts. The first was the elicitation of memories during an interview in the laboratory with the experimenter using cue words. The second part took place in the MRI, where fMRI was collected while participants thought about the memories they had previously described to the experimenter in the interview portion. Furthermore, during the second part, participants completed a semantic word task, which was used as a comparison contrast in later analyses. The cue words used to elicit autobiographical memories consisted of forty-five neutral concrete nouns that were selected from previous studies (Bauer, Burch, Scholin, & Güler, 2007; Rubin, 1982) A complete list of the cue words is given in Appendix A. During the autobiographical memory interview, participants saw 45 words, 30 of which were used in part 2 along with 15, which served as extra words in the event that participants were unable to generate an autobiographical memory. In order to increase the generalizability of the memories; the interviewer sought to include autobiographical memories from 3 valence categories: negative, positive, and neutral. The words were counterbalanced across three lists so that each word was used in each to elicit neutral autobiographical memories from each valence category across participants equally (e.g., the cue word *dinner* was used to elicit negative, positive and neutral autobiographical memories).

In addition to the cue words, an additional 15 neutral concrete nouns were used as semantic cue words for the fMRI task. Three semantic words were used as practice and

the remaining 12 words were used in the actual experiment. Time-locked cues were presented in PsyScope X B53 (Trieste, Italy).

Procedure

The experiment consisted of two distinct parts; an interview portion, where memories were elicited using cue words, and an MRI portion where participants were asked to think about the memories that had been elicited in the first part of the experiment. Additionally, participants completed a semantic control task, which was later contrasted with the autobiographical memory retrieval task in analyses.

Part 1: Elicitation of autobiographical memories through experimenter interview. Directly prior to the scanning session (i.e., the same day), participants met with the experimenter to generate autobiographical memories using 30 cue words. During the interview, the experimenter sat across from the participant and presented the words, one at a time, on a computer screen using Microsoft PowerPoint. Participants were instructed to read the word out loud, and describe one specific event that occurred within the past year that related to the given word (e.g. for the word *dinner:* "Last month I had dinner at my friend's house"). The first ten words presented were used to elicit memories for the neutral condition, and every five words that followed alternated between negative and positive valence conditions (i.e., Words 1-10 were used to elicit neutral memories, words 11-15 and 21-25 were used to elicit negative memories, and words 16-20 and 26-30 were used to elicit positive memories). If the participant was unable to generate a memory for a word cue, the word was skipped. Then, after going through all the experimental words, the experimenter would show the participant a list of 15 extra words to fill in the set. Participants generated memories using the extra cue words in the same order as they did

for the original 30 (i.e., first they generated neutral memories, followed by negative and positive memories respectively).

For the neutral condition, participants were given the general prompt: "Tell me about a specific one time event that this word reminds you of". They were further instructed to pick events from the past year that occurred in one place, and at one time, and supply enough detail that they would recall the event later. To ensure that participants picked memories for the appropriate time period, the experimenter provided an appropriate time marker (e.g. "It can be any single event that happened from the beginning of the school year to today"). For the negative and positive conditions, participants were given the same general instructions, but with the more specific prompts: "Tell me about a specific one time UNHAPPY/HAPPY event that this word reminds you of".

For all valance conditions, after the initial elicitation of the memory, the experimenter prompted the participant to provide more details, intended to aid later recall during the scanning session, with the general prompt; "Tell me more…" The experimenter then prompted the participant with six specific Wh- questions (e.g. "Who was there when that happened?") to ensure that participants had retrieved sufficient detail for part 2. Finally, to aid in recall during the fMRI session, the experimenter and participant collaborated to assign additional key word that would remind the participant of the target event in the scanner during part 2 of the experiment. The additional key word was a non-emotional word that was not part of the cue word set, and typically represented a specific element of the event such as a person's name (e.g. Dinner and *Sally*). Additionally, all interviews were video-recorded.

After the interview period, the participant practiced the autobiographical memory scanner task on a computer with Power Point, along with the semantic control task, which will be described in further detail in Part 2. Additionally, on the way to the scanner, the experimenter performed a fidelity check and tested the participant on their memories by providing the cue word and the key word and asking the participant to recount the specific memory associated with those words. This was to ensure that participants still remembered the memories from the interview session. If the participant was unable to recall a memory, the experimenter helped the participant recall the memory with additional prompts. All participants were able to recall all of the memories without any trouble.

Part 2: Retrieval of memories while recording BOLD response. After participants were placed in the scanner, they underwent a short practice run to familiarize them with the button box. The structure of the practice run was the same as during the experiment session. The practice run consisted of three autobiographical memory trials and one semantic control trial, with a practice cue word from each valance category and a semantic word being presented.

During the autobiographical memory trials, participants first saw a fixation cross for 12 sec. Afterwards the cue word appeared on the screen for 16 sec in upper case letters with the key word underneath in lower case letters for 4 sec. After 4 sec the key word disappeared and two wh- questions would appear, one at a time, for 6 sec each (4 and 10 sec; Fig. 1). The order and selection of the wh- questions was counterbalanced across participants. The inter-trial interval (ITI) was 12 sec (Figure 1). Participants were

instructed to press a button when they first started thinking of the memory and to continue thinking about the memory until the fixation-cross appeared.

During the semantic trial, which was modeled after the autobiographical memory trials, one of the semantic words (e.g. Gorilla) appeared on the screen for 16 sec in upper class letters with the word *think* underneath in lower case letters for 4 sec. Participants were instructed to press the button when they first started to think about the word. After 4 sec, the word *bigger* would appear in lower case letters underneath the semantic word for 6 sec. Participants were instructed to think about whether the item described by the word was bigger than their head but not make a button press. Then, after 6 sec, the word *living* would appear underneath the semantic word in lower case letters. The participants were instructed to think about whether the item was alive or not and not make a button press. The ITI was 12 seconds long.

The experimental session consisted of three runs. Each run contained 3 semantic trials and 3 memory trials from each valance category (i.e., three neutral trials, three negative trials, and three positive trials) for a total of 12 trials. Due to the low frequency of semantic retrieval trials they could not be accurately examined for change in dynamic connectivity in this study. The order of autobiographical and semantic cue words was counterbalanced across participants, however the counterbalancing was designed so that participants never ended a trial with the retrieval of a negative memory.

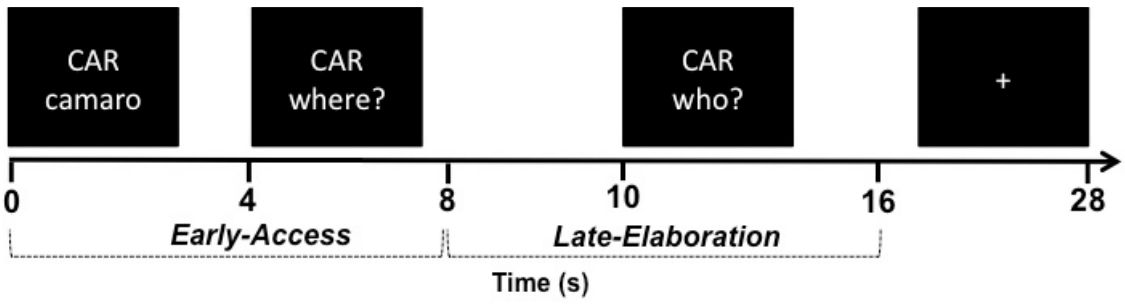


Figure 1. Illustration of an AM retrieval trial. Upon receiving the neutral cue and the pre-designated personal cue, participants were instructed to retrieve a previously rehearsed memory for 16 seconds. At 4 and 10 seconds the participant received Wh- cues to aid in construction and elaboration of the memory for the entire trial. The first half of this retrieval period is considered the early-access period and the second half of this period is considered the late-elaboration period. Semantic memory trials were similarly structured in time, but Wh- question prompts were replaced with the questions semantic retrieval cues bigger and living. The font was white (top cue font size = 54, bottom cue font size = 48) on a black background.

Data acquisition

All imaging data were acquired using a Siemens 3.0-Tesla MRI scanner. Brain imaging involved acquisition of 40 axial slices of 3 mm thickness acquired parallel to the AC–PC line. Functional scans were acquired using T2*- weighted gradient-echo, echo-planar pulse sequences (TR = 2016 msec, TE = 30 msec, 64 x 64 matrix, FA = 90°, 3 x 3 x 3 mm voxel size). A total of 158 scans were acquired in each of 3 runs (5.6 min/run). Structural images were acquired using a gradient-echo, T1-weighted pulse sequence (TR = 500 msec, TE = 20 msec, 256 x 256 matrix, 1 x 1 x 1 mm voxel size).

Movement was minimized with foam pillows placed around the head and a piece of medical tape placed across the top of the head. All participants were provided earplugs for noise reduction as well as headphones and a microphone for communication with the experimenter. Cue word stimuli were viewed through a mirror attached to the head coil and directed at a projected screen at the back of the scanner bore.

Data analysis

Data were preprocessed using Statistical Parametric Mapping software (SPM8, Wellcome Department of Cognitive Neurology; www.fil.ion.ucl.ac.uk; Penny, Friston, Ashburner, Kiebel, & Nichols, 2011), run in MATLAB2011a. Bad slices in each functional image were identified and corrected via interpolation across adjacent slices in each volumen using Art Repair software (Mazaika, Hoeft, Glover, & Reiss, 2009; Mazaika, Whitfield-Gabrieli, Reiss, & Glover, 2007). After differences in slice acquisition time were corrected (slice-timing correction) to the middle slice in time, all functional data sets were realigned and unwarped to the first image in the scanning session. Motion was further examined and corrected with Art Repair (Mazaika et al., 2009; Mazaika et al., 2007). An 'artifact' threshold is defined by Art Repair as any scanning volume in which the tool box detects a large, non-physiological global signal change between consecutive scans. An interpolation algorithm was applied across all volumes identified with superthreshold movement related changes in the global signal. Normalization parameters were derived from segmenting each participant's T1-weighted anatomical brain image into white matter, gray matter, and CSF. These normalization parameters were then applied to the respective participant's EPI images (Crinion et al., 2007). Upon normalization all functional images were smoothed at 6x6x6 FWHM. Band pass temporal filtering from 0.01 Hz to 0.08 or 0.1 Hz was not applied to the data as is commonly performed in resting state connectivity analyses because we expect there to be task-relevant brain activity that could last longer for 10 seconds and the time windows were time locked to the presentation of the cue word. Thus, if a 0.1 Hz filter was applied

during processing then any task relevant brain activity would be potentially removed from the data.

Cross-correlation analysis

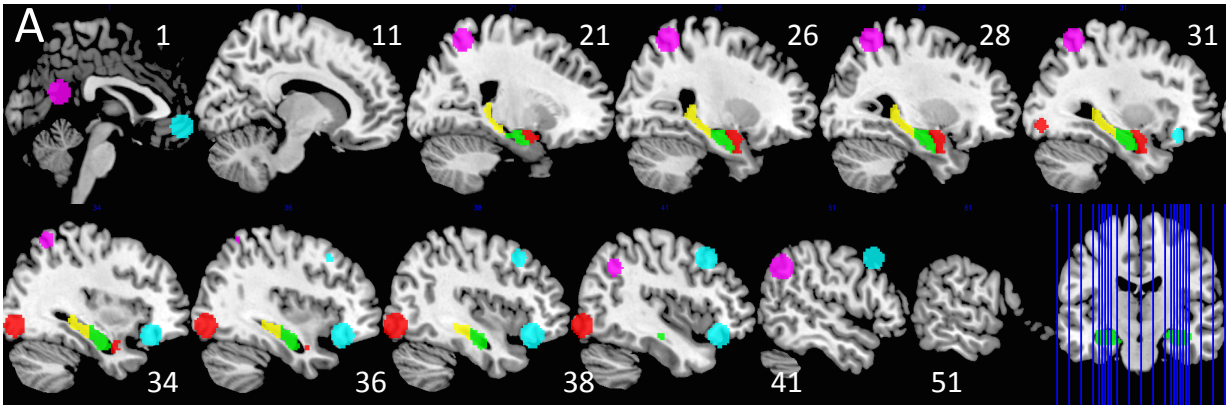
ROI identification. Regions-of-interest (ROIs) were derived from the coordinates of regions identified in the Svoboda et al. (2006) and Daselaar et al. (2008) studies as core regions in AM retrieval processes (Table 1). A 10 mm spherical ROIs was grown around the specific derived coordinates using the SPM toolbox MarsBar (Brett, Anton, Valabregue, & Poline, 2002) for all neocortical ROIs. A 10 mm sphere was chosen with the intent of ROIs of similar volumes that capture the mean signal from each ROI. In addition, this size of ROI is typical for measuring the mean signal time course in neocortical ROIs due to the fact that their functionality is more diffuse and encompasses a broader cortical area than subcortical ROIs (Inman et al., 2012; James et al., 2009). Medial temporal lobe ROIs were created using the Automatic Anatomic Labeling (AAL) system ROIs in WFU Pick Atlas toolbox for SPM (Maldjian, Laurienti, Kraft, & Burdette, 2003; Tzourio-Mazoyer et al., 2002). Specifically, the amygdala ROI was defined directly from the AAL amygdala mask. The left and right hippocampal ROIs were also derived from the AAL left and right hippocampal ROI mask. Each hippocampus was further parcellated into an anterior and posterior portion. The anterior and posterior hippocampus in either hemisphere was parcellated at the uncal apex of a standard automatic anatomical labeling (AAL) hippocampal mask derived in the WFU Pick Atlas. The whole hippocampal ROI masks were divided using the image manipulation program MRIcron (Rorden, 2007). When co-registered with a standard T1 (Colin brain), this division point was at MNI y-coordinate of -21 mm from the origin.

This coordinate corresponds to the typical distinction of the anterior and posterior hippocampus in templates or atlas ROIs used in other studies of long-axis specialization of the human hippocampus (Poppenk et al., 2013; Poppenk & Moscovitch, 2011). The exact core network ROIs are displayed in slice orientation in Figure 2 below.

Table 1

Region of Interest (ROI) hemisphere, label, and MNI coordinate.

Region of Interest	Hemisphere	ROI Label	X	Y	Z
Dorsolateral Prefrontal Cortex	Left	LDLPFC	-41	18	39
Ventrolateral Prefrontal Cortex	Left	LVLPFC	-38	30	-16
Medial Prefrontal Cortex	Medial	mPFC	0	45	-10
Dorsolateral Prefrontal Cortex	Right	RDLPFC	42	17	39
Ventrolateral Prefrontal Cortex	Right	RVLPFC	39	31	-15
Amygdala	Left	LAmyg	-24	-1	-17
Anterior Hippocampus	Left	LAntHipp	-26	-13	-17
Posterior Hippocampus	Left	LPostHipp	-26	-33	-3
Amygdala	Right	RAmyg	26	1	-18
Anterior Hippocampus	Right	RAntHipp	29	-13	-17
Posterior Hippocampus	Right	RPostHipp	26	-33	-3
Intraparietal Lobule	Left	LIPL	-26	-58	59
Temporoparietal Junction	Left	LTPJ	-49	-57	38
Posterior Cingulate Cortex	Medial	PCC	0	-57	19
Intraparietal Lobule	Right	RIPL	27	-58	59
Temporoparietal Junction	Right	RTPJ	49	-57	38
Occipital Cortex	Left	LOCC	-38	-84	-9
Occipital Cortex	Right	ROCC	39	-84	-8



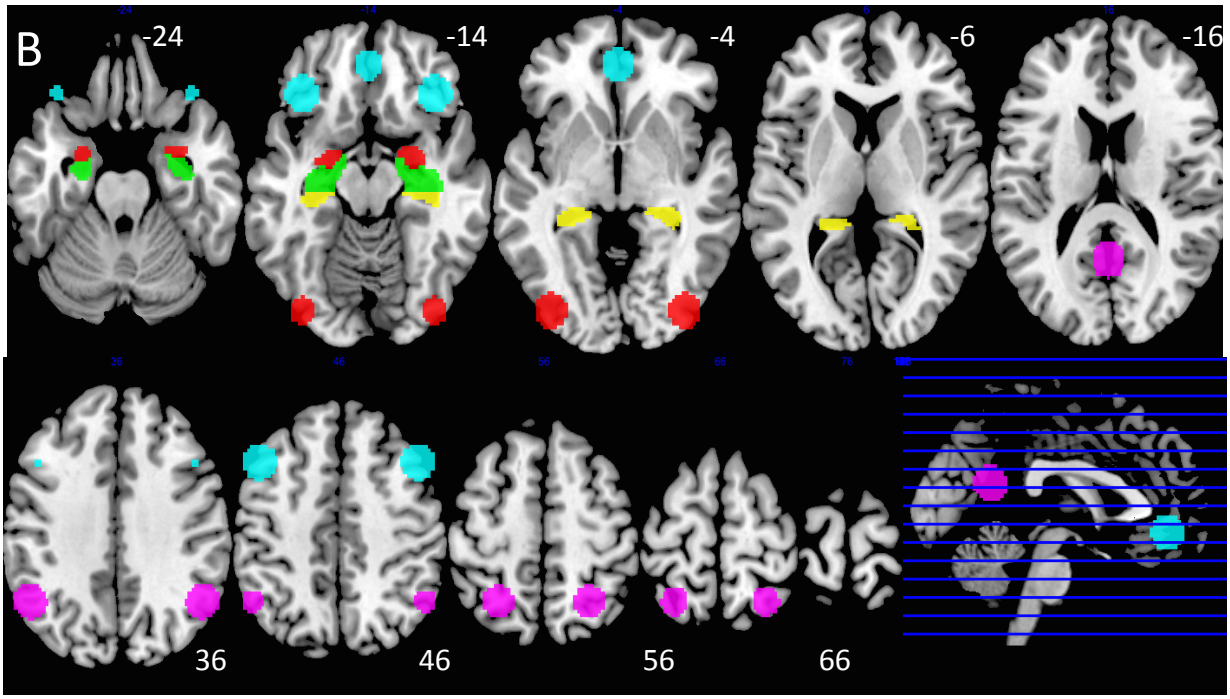


Figure 2. Illustrations of core network ROIs. A) Sagittal representation of core network ROIs overlaid on the canonical MNI brain (right hemisphere displayed; left hemisphere is mirrored). B) Axial representation of the core network ROIs overlaid on the canonical MNI brain. Cyan denotes frontal lobe ROIs. Red ROIs in the MTL denotes the amygdala ROIs. Green MTL ROIs denotes anterior hippocampus ROI. Yellow MTL ROIs denote posterior hippocampus ROIs. Purple denotes parietal lobe ROIs. Red occipital ROIs denote occipital lobe ROIs. Slice renderings were created in MRIcron (Rorden, 2007).

Time course extraction from core network ROIs. Time courses from all core AM retrieval network ROIs were extracted using the MarsBar SPM toolbox. The raw mean time course was extracted for each ROI from each participant's AM retrieval fMRI data. To account for arbitrary differences in the baseline raw signal of the scanner, each participant's time course values underwent a z-score transformation to normalize the data across participants.

Time window specification. The AM retrieval fMRI data time courses were segmented into seven, equal-width time windows across each 28-second retrieval and inter-stimulus interval (ISI) cycle. Each time window was time-locked to the memory cue onset. Time windows were specified to maximize the number of time windows within each AM retrieval trial while capturing most of hemodynamic response function (12 seconds) and allowing for resolution of the underlying dynamics in cognitive processing. Based on many previous studies of AM retrieval for rehearsed and unrehearsed memory cues (Addis et al., 2011, 2004; Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; Greenberg et al., 2005; Muscatell et al., 2010; St. Jacques et al., 2011; Velanova et al., 2003), we assumed the initial, access-related processing to unfold over the first 8 seconds on average after which elaboration-related processing would begin to predominate. Although the distinction of these processing periods as the first 8 seconds and following 8 seconds is certainly a course distinction, our overall goal was to characterize consistent patterns of connectivity within these early and late processing periods and directly contrast these time periods to uncover hypothesized differences in connectivity patterns between the processing windows. To address all of these criteria to the extent that was possible, each of the 7 time windows was defined as 8.64 seconds wide (4 TR). Each time window overlapped the preceding and succeeding time windows by 4.32 seconds (2 TR). Time windows overlapped one another by 4.32 seconds (2 TR) were created to maximize and smooth the resolution of changes over time. All statistical tests were performed on non-overlapping time windows. All time windows were lagged by a factor of 4.32 seconds (2 TR) to account for lag in the hemodynamic response. All statistical

comparisons for this study were performed between the 0-8 second and 8-16 second time windows after having accounted for the hemodynamic response lag.

Cross-correlation matrix construction. After segmenting the time courses in to the respective time windows, bivariate correlation matrixes of the connection strength between each ROI pair (153 total) were calculated for each participant. Specifically, for each participant by time course matrix was constructed by computing the bivariate correlation between each ROI time course and all of the other 17 ROI time courses within each time window. Each correlation in each time window matrix was transformed with the Fisher's Z transformation to allow for averaging of correlation values across participants. A connection was considered to be dynamic if there was a significant (bootstrap corrected $p<0.05$, two-tailed paired *t*-test) pairwise difference between the coherence of 2 ROIs in the contrasting two time windows (e.g. early versus late). Stable connections were defined as those regions with a correlation of $|r|>0.3$ across the whole retrieval period and were not significantly stronger in the early or later time window.

Statistical approach. Paired t-tests with bootstrapping were utilized to test differences in connection strength for each pairwise correlation in the early time window relative to the late time window and visa versa (Watrous, Tandon, Conner, Pieters, & Ekstrom, 2013). To account for multiple comparison issues, each t-test underwent a bootstrapping procedure with 1000 re-sampled (with replacement) permutations of the sampling distribution. This procedure also helps to maintain a fixed type 1 error rate of 5% given an $\alpha = 0.05$. *T*-statistics and Cohen's d estimates of effect size are depicted in tables for each primary *t*-contrast that showed a significant change between time windows.

Network visualization. Network visualization was performed with the BrainNet Viewer toolbox in Matlab (Xia, Wang, & He, 2013). All BrainNet figures were created with the same 18-node, AM core network configuration (Figure 3a and b). Connections or edges in BrainNet figures were constructed in two different manners depending on the connection information that best described the topological effect of interest. For stable networks, the thickness and color of connections in the BrainNet figures were displayed according to the mean Fisher's Z throughout the entire AM retrieval period (i.e., all time windows). For dynamic networks (i.e., early > late or late > early), the thickness and color of connections in the BrainNet figures were displayed according to the mean change in Fisher's Z from comparison of the two time windows. Core network connection matrixes for each of the BrainNet figures were also created using the BrainNet viewer. The color scale in each matrix corresponds to either the mean Fisher's Z for particular ROI-to-ROI connections in the case of stable networks and the mean change in Fisher's Z for particular ROI-to-ROI connections in the case of dynamic networks.

In addition to the BrainNet topological representation of changes in functional connectivity, dynamic and stable connectivity patterns were also visualized with the Social Network Image Animator (SONiA; Bender-deMoll & McFarland, 2006). Network visualizations in the SONiA format are displayed in a spring-loaded format using the Kamada-Kawai graph energy algorithm (Kamada & Kawai, 1989). The Kamada-Kawai "spring-embedding" algorithm treats each connection between two nodes as a "spring" of a specific length that corresponds to the connection strength of the two nodes. This creates a virtual dynamic system that contains "energy" in the form of the connection

strengths of all connections in the network. In the SONiA program, the Kamada-Kawai algorithm finds the optimal layout of the nodes relative to one another by determining the state in which the total spring energy of the system is minimal. The Kamada-Kawai visualization technique allows for clear visualization of modules or clustered nodes in the network and when animated allow for a dynamic representation of changes in network connectivity over time.

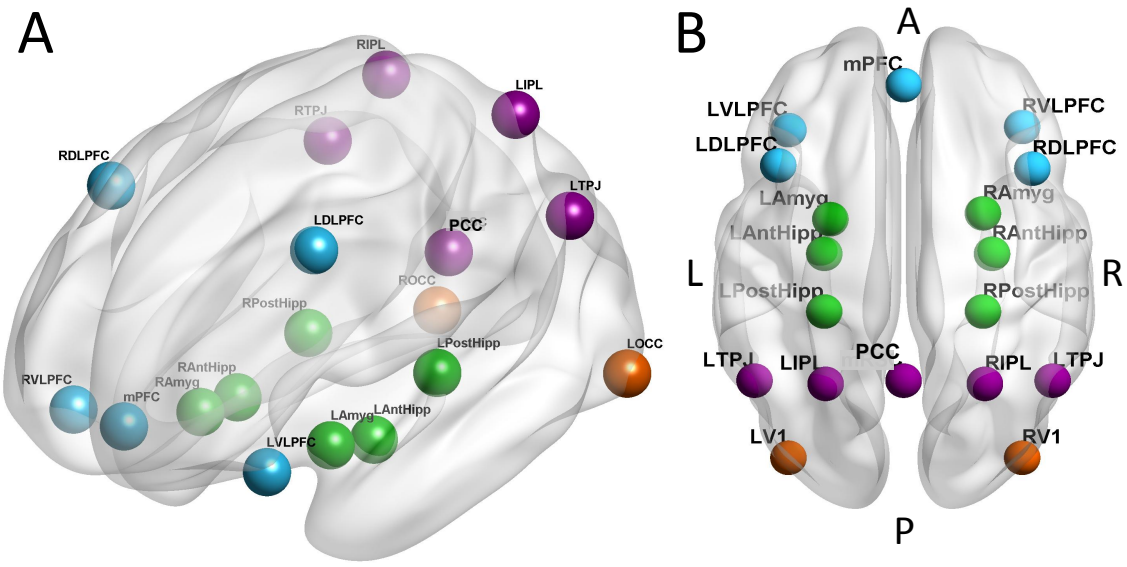


Figure 3. A) Illustration of core network ROIs from dorsal sagittal perspective. B) Illustration of core network ROIs from a ventral axial perspective. Nodes are displayed in MNI space co-registered with a smoothed and transparent representation of the ICBM152 brain surface template. Node color denotes the lobe membership of each ROI. Cyan nodes denote frontal lobe ROIs. Green nodes denote medial temporal lobe ROIs. Purple nodes denote parietal lobe ROIs. Orange nodes denote occipital lobe ROIs. A=anterior, P= posterior, L=left, R=right.

Whole brain graph theory analysis

Whole-brain ROI parcellation. A whole-brain fMRI atlas generated with spatially constrained spectral clustering of resting state fMRI functional connectivity data from a large cohort was used to parcellate each participant's fMRI data into 200 distinct ROIs (Craddock et al., 2012). This particular whole-brain atlas was selected, as opposed to an anatomically or cyto-architectonically defined atlas (i.e., AAL, Broadman's areas, etc.), because it consists of ROIs with anatomic homology, takes into account common resting state functional networks, and the volume of all 200 ROIs are normally distributed. The closest ROI by center of gravity coordinate from the 200-region parcellation to the center of gravity for the core network region was taken as a homologous core network region. In general, the coordinates for the core network regions were within 10 mm in any x, y, or z direction of the coordinates for the homologous parcellation ROI and significantly overlapped the defined core network ROI.

Time course extraction. A time course of eigenvalues calculated via singular value decomposition (SVD; i.e., principle component) was extracted from each ROI in AFNI (Cox, 1996). This measure is very similar to the mean time course approach used in the core network cross-correlation analyses, but better estimates the signal in an ROI by differentially weighting the principle voxels in the ROI. Each participant's time course values underwent a z-score transformation to normalize the data across participants.

Time window specification. All time windows were specified with the same approach as described for the cross-correlation analysis with the time courses being seven time-locked, 8-second time windows which overlapped one another by 4 seconds and were lagged by 4 seconds to account for hemodynamic lag.

Graph metric processing and calculation. Graph theory is a branch of mathematics in which mathematical structures (graphs) are used to model pairwise relations (i.e., edges or connections) between objects (i.e., nodes or in the case of fMRI ROIs; Bullmore & Sporns, 2009; Power et al., 2011; Rubinov & Sporns, 2010; Wig et al., 2011). Graphs are networks composed of a pre-determined set of functional regions involved in a task or a functional parcellation of regions throughout the whole brain. In particular, graphs are abstract representations of the components in a network that are useful in visualizing important topological properties of a networks organization and structure (Bullmore & Sporns, 2009; Wig et al., 2011). Although graphs are useful for visualizing properties of a networks structure, the matrix of a network's connections, known as an adjacency matrix, is the primary computational unit for analysis of graph properties or metrics. Graph metrics are used to help determine simple organizational features of the complex network architecture and include many objective measures node-based and network-based properties. In functional connectivity analyses, two types of adjacency matrixes can be derived from pairwise relations between a set of nodes: binary and weighted. Binary matrixes are created by applying a threshold to a correlation matrix and defining any correlations that exceed that threshold as connected during a particular time window. A value of 1 is assigned to any correlation or edge that exceeds the threshold and a value of 0 is assigned to any correlation or edge that does not exceed the threshold. A weighted adjacency matrix maintains the correlation strength or weight of each connection rather than defining each connection as a 1 or 0. Weighted adjacency matrixes are useful for computing certain graph metrics, like node strength, but most functional connectivity

graph metrics, like degree centrality and clustering coefficient, are calculated using a binary matrix (Rubinov & Sporns, 2010; Sporns et al., 2004).

Graph metrics. Two basic and common graph metrics were utilized in this study to characterize the topological properties of the core AM retrieval regions in the context of the whole brain. These metrics include measures of average node strength and node centrality (e.g. degree) in the whole-brain network. Node strength is simply calculated as the average correlation strength a node has with all of it's connected nodes. This is the only weighted measure in this graph theory analysis and is performed for each participant before any binary matrixes were created. All other graph metrics were calculated from a binarized adjacency matrix.

Metrics of functional centrality in a brain network identifies the brain regions that often interact with many other brain regions, facilitate functional integration, and are key to a network's vulnerability and resilience to damage (Sporns, Chivalo, Kaiser, & Hilgetag, 2004). Common centrality measures that are derived in almost every graph theory analysis are based on the idea that brain regions with more short paths within a network act as important information flow control (Sporns, Chivalo, Kaiser, & Hilgetag, 2004). Degree centrality is the one of the most common and basic graph theory measures for individual nodes in a network. Degree centrality is simply measured by counting the number of other nodes connected to a particular node with larger degree values reflecting the importance of that node in the network. In analyses of brain network dynamics during a task these graph metrics of a region's centrality allow for a characterizations of the regions importance during a particular period in the AM retrieval processes.

Centrality graph metrics were computed with a multi-level thresholding approach to alleviate concerns of selecting arbitrary thresholds to create each participants binarized adjacency matrix (Bassett et al., 2008; Lynall et al., 2010). Briefly, across individuals there is ample variability in the extent to which regions throughout the brain are correlated. In other words, binarization of a correlation matrix by an arbitrary value (i.e., $|r|>0.4$), some subjects would have every correlation survive while others would have an empty matrix. Thus, instead of taking an arbitrary correlation (r) threshold it is useful to take a certain top percentage of correlation strengths. This top percentage of correlation strength could also be arbitrarily defined (i.e., top 33% or 50%) based on an assumption of what might denote consistently strong connections throughout the brain. However, this method also has the issue of an arbitrary threshold. A more robust method for selecting a density threshold to define the binary adjacency matrixes is to calculate the matrixes across multiple top percentage thresholds and take the mean for each graph metric across all of the thresholded matrixes (Bassett et al., 2008; Lynall et al., 2010). A more detailed description is outlined below to further specify this procedure.

First, a correlation matrix of all 200 ROIs was created for each participant for a particular time window. Then, this subject level correlation matrix is transformed into a binarized adjacency matrix at a range of thresholds for the top 37% of correlations in the full matrix to the top 50% with a stepwise interval of 1% (14 adjacency matrixes total). Degree centrality is calculated for every node in each of the thresholded binary adjacency matrixes. Finally, the average graph metric is calculated for each node across all 14 of the thresholded binary adjacency matrixes from 37% to 50% for that participant. These

values were compiled in a participant-by-participant database for each graph metric by ROI.

Statistical approach. Paired *t*-tests with bootstrapping were utilized to test differences in graph metric for each pairwise correlation in the early time window relative to the late time window and visa versa (Watrous et al., 2013). To account for multiple comparison issues, each t-test underwent a bootstrapping procedure with 1000 re-sampled (with replacement) permutations of the sampling distribution. This procedure also helps to maintain a fixed type 1 error rate of 5% given an $\alpha = 0.05$. *T*-statistics and Cohen's d estimates of effect size are depicted in tables for each primary *t*-contrast that showed a significant change between time windows.

Results

Behavioral retrieval characteristics

Mean reaction times to beginning retrieval of the memory (once the participant had the specific prompted memory in mind) were *M*=1.83 (*SEM*=0.12) seconds for autobiographical memory retrieval according to when the participants pressed the button. In the session after the fMRI scan, all participants were able to retrieve the same memory derived for each cue word in the pre-scan session and no participants reported retrieving a different memory from the memory retrieved in the pre-scan session.

Cross-correlation strength analysis

Evaluation of network connectivity during AM retrieval revealed that nearly all (90%) core AM retrieval regions (see figure 2 for depiction of core network on a standardized brain) were at least moderately connected to one another ($r > 0.3$). Consistent with our prediction that regions within the core network would be strongly

connected with one another, 90% of these region-to-region connections maintained a strong correlation with one another that remained stable throughout all hypothesized AM retrieval processes. Possible connections that did not exceed the threshold for being considered strongly connected were primarily between regions in the MTL and parietal regions, as well as, connections between left frontal regions and the right occipital cortex. Stable connections were defined as those connections that were strong throughout AM retrieval and did not significantly change in connection strength based on pairwise t-tests between all of the contrasts of interest. The contrasts of interests for this study were for ROI-to-ROI connections that were stronger early > late 1, late 1 > early, late 2 > early, and late 3 > early. Dynamic connections were defined as those that were strong ($r > 0.3$) throughout retrieval and did significantly change in connection strength based on pair-wise t-tests between all contrasts of interest. Overall, consistent with our hypothesis, the stable network consisted of had structured, non-random topological organization. In particular, the strongest stable or non-dynamic connections were observed between regions local (i.e., within the same lobe) and contralateral to one another. A topological representation and matrix representation of the stable network is illustrated in Figure 4.

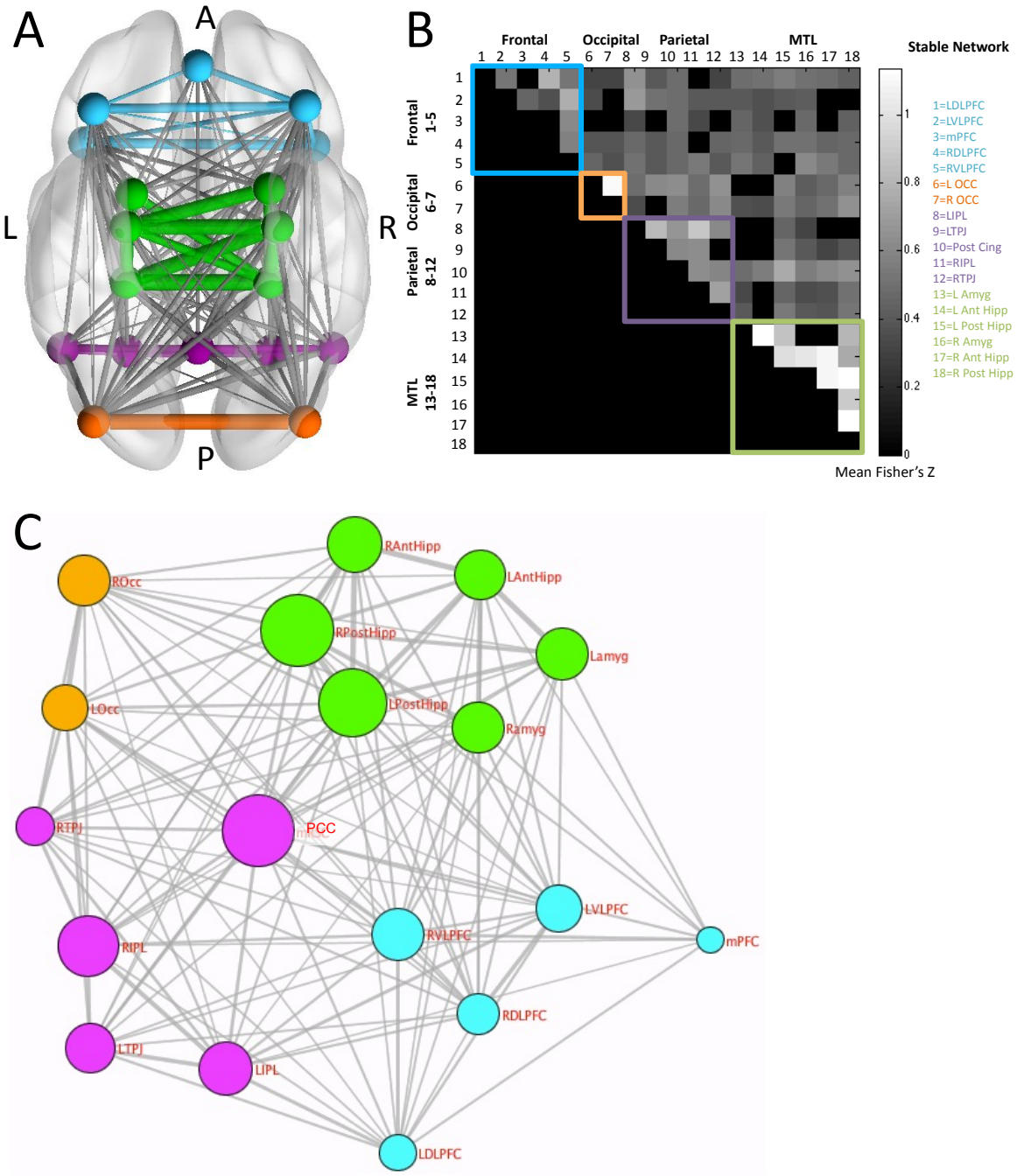


Figure 4. Stable network during AM retrieval. A) Topological representation of all connections that were at least moderately connected to one another (i.e., $r > 0.3$) and did not change during AM retrieval. Connections within the same lobe are color coded with cyan for frontal regions, green for MTL regions, purple for parietal regions, and orange for occipital regions. Thickness of the connection denotes the relative mean Fisher's Z.

Note that local and contralateral connections have stronger connections with one another than more distant connections. A = Anterior, P = Posterior, L = Left, R = Right. B) Matrix representation of stable connections. Gray color bar denotes mean Fisher's Z for each connection. Although the matrix is symmetric, only the upper triangle is displayed for ease of interpretability. Colored boxes encompass regions within each lobe with cyan for frontal regions, green for MTL regions, purple for parietal regions and orange for occipital regions. Note that connections within lobes are more strongly connected to one another (i.e., brighter) than distant connections between regions in different lobes. C) Spring embedded representation of stable network. Distance between nodes denotes an optimal configuration based on the strength of each connection between particular nodes (i.e., nodes that are more strongly connected are closer in space). Size of node denotes the relative average degree of each node across the entire retrieval period in the whole brain network (200 ROIs). Node colors represent lobe membership and are consistent with the color codes in A and B of this figure. Note that nodes from the same lobe cluster together with one another. Also note that the node degree of the PCC and MTL nodes are largest relative to other nodes in the network.

Dynamic network connectivity: Early versus Late. To assess the hypothesis that anterior connections (i.e., frontal and temporal) would be stronger during early, access-related processing than late-elaboration processing periods, bootstrapped paired t-tests were performed for every connection, contrasting connection strength (mean Fisher's Z) for the early (0-8 s) versus late (8-16 s) time period. This contrast revealed specific region-to-region connections that were significantly stronger in the early versus late time period reflecting initial strategic memory search processes and construction of memory

context and details. Consistent with our predictions that regions involved in memory access processes (strategic memory search) would be more strongly connected early relative to late in retrieval, network connectivity that was stronger early than late primarily consisted of connections between the prefrontal cortex and medial temporal lobe (Table 2). In particular, relative to the late period, the early-access period of AM retrieval exhibited stronger mPFC connections to the dorsal PFC and left posterior hippocampus. Furthermore, connections between the right VLPFC and left posterior hippocampus were stronger early versus later in retrieval (Figure 5).

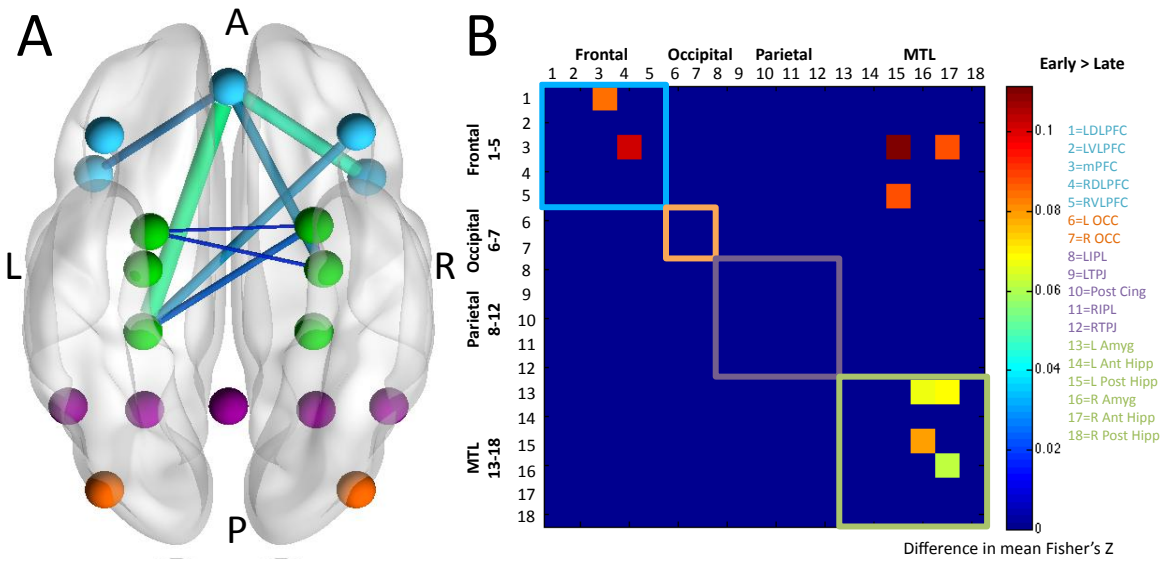


Figure 5. Stronger connections early versus late in AM retrieval. A) Topological representation of connections that were more strongly connected to one another during the early period relative to the late period of AM retrieval. Thickness of the connection denotes the relative mean difference in Fisher's Z between the early and late time periods. A = Anterior, P = Posterior, L = Left, R = Right. B) Matrix representation of connections that were more strongly connected to one another during the early period relative to the late period of AM retrieval. Although the matrix is symmetric, only the

upper triangle is displayed for ease of interpretability. The color of each connection point in the matrix denotes the difference in mean Fisher's Z. Colored boxes encompass regions within each lobe with cyan for frontal regions, green for MTL regions, purple for parietal regions and orange for occipital regions.

Table 2

Connections with stronger connectivity early versus late and late versus early.

Connection			Mean			
ROI 1	ROI 2	Contrast	Difference	*t*-score	*p*-value	Cohen's D
lDLPFC	mPFC	Early > Late	0.08	2.29	0.042	0.29
mPFC	rDLPFC	Early > Late	0.10	2.96	0.016	0.44
mPFC	lPostHipp	Early > Late	0.11	3.15	0.009	0.28
mPFC	rAntHipp	Early > Late	0.09	2.46	0.028	0.22
rVLPFC	lPostHipp	Early > Late	0.09	2.34	0.039	0.24
lAmyg	rAmyg	Early > Late	0.07	3.20	0.005	0.16
lAmyg	rAntHipp	Early > Late	0.07	2.19	0.044	0.16
lPostHipp	rAmyg	Early > Late	0.08	2.27	0.045	0.17
rAmyg	rAntHipp	Early > Late	0.06	2.33	0.046	0.17
lDLPFC	rIPL	Late > Early	0.11	3.56	0.018	-0.25
rDLPFC	rIPL	Late > Early	0.11	3.22	0.007	-0.32
rVisCor	lPrec	Late > Early	0.12	2.48	0.030	-0.30
lPrec	rPrec	Late > Early	0.12	3.49	0.018	-0.31

Dynamic network connectivity: Late versus Early. To assess the hypothesis that posterior connections (i.e., parietal and occipital) would be stronger during late, elaboration-related process than the early processing period, bootstrapped paired t-tests were performed for every connection, contrasting the late (8-16 s) versus early (0-8 s) time period. This contrast revealed specific region-to-region connections that were significantly stronger in the late versus early time period reflecting memory elaboration and reliving processes. Consistent with our predictions that posterior regions typically engaged in memory maintenance and elaboration processes would be more strongly connected to one another later relative to earlier in retrieval, network connectivity that

was stronger late than early primarily consisted of connections within the parietal cortex and between regions in fronto-parietal and parietal-occipital cortices (Table 2). In particular, the late-elaboration period of AM retrieval was predominated by stronger connections between the left and right TPJ, left TPJ and right occipital cortex. Furthermore, connections between the right TPJ and the left and right DLPFC were stronger late versus early in retrieval (Figure 6).

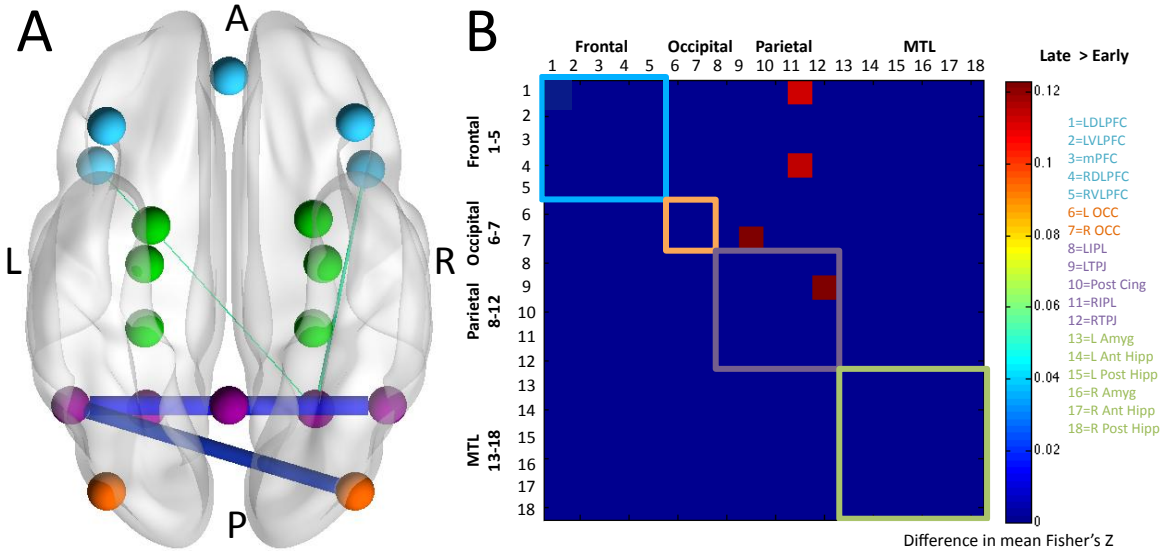


Figure 6. Stronger connections late versus early in AM retrieval. A) Topological representation of connections that were more strongly connected to one another during the late period relative to the early period of AM retrieval. Thickness of the connection denotes the relative mean difference in Fisher's Z between the late and early time periods. A = Anterior, P = Posterior, L = Left, R = Right. B) Matrix representation of connections that were more strongly connected to one another during the late period relative to the early period of AM retrieval. Although the matrix is symmetric, only the upper triangle is displayed for ease of interpretability. The color of each connection point in the matrix denotes the mean difference in Fisher's Z. Colored boxes encompass

regions within each lobe with cyan for frontal regions, green for MTL regions, purple for parietal regions and orange for occipital regions.

Dynamic graph theory analysis

Node strength. To assess the dynamic change in the average strength of connection each node in the core AM retrieval network had to one another across the retrieval period, the node strength was calculated for each ROI and submitted to a bootstrapped paired t-test. Contrasting the node strength during the early and late time periods for each ROI revealed regions whose average connection strength to all other regions in the network became stronger from early to late or late to early in retrieval. Based on previous evidence, we predicted that the VLPFC and anterior hippocampus would have stronger connections to the rest of the network during early, access-related processing than later processing. We also predicted that the occipital cortex and posterior hippocampus would have stronger connections to the rest of the network during late, elaboration-related processing than earlier processing. Inconsistent with our hypotheses, no ROIs had stronger node strength in the early relative to the late time periods or visa versa.

Centrality: Node degree o assess the extent to which regions of the core AM retrieval network changed in their topological centrality (i.e., the extent to which a region served as a network hub), degree centrality was calculated for each core network ROI in the 200 ROI whole brain network. Each region's degree centrality during the early and late time period was submitted to bootstrapped paired t-tests to test whether the degree centrality significantly increased from the early period to the late time period or visa versa. Changes in degree centrality in the early versus late time periods indicate the extent to

which regions become more or less central to integrating distributed information within the 200 ROI whole brain network during AM retrieval. Based on previous evidence that the VLPFC and anterior hippocampus are involved in strategic memory search and rebinding processes (Daselaar et al., 2008; Rugg & Vilberg, 2012; Velanova et al., 2003; Wagner, 1998; Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Tulving, 2002), we hypothesized that the VLPFC and anterior hippocampus would have a greater degree centrality in the early time period relative to the late time period. Inconsistent with our hypotheses, no ROIs had stronger node degree centrality in the early relative to the late time periods or visa versa.

Discussion

The findings of the present study support the view that autobiographical memory retrieval recruits cognitive and neural processes that change dynamically from initial processes of memory access to later processes of elaboration and re-experiencing. By using a dynamic multivariate connectivity analysis of the core AM retrieval network, changes in connectivity strength and centrality between specific regions in the core AM retrieval network and the whole brain were characterized. Consistent with current influential theories that view AM retrieval processes as changing dynamically during the extended time period of autobiographical retrieval (Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; Jacques, Kragel, & Rubin, 2011; McCormick et al., 2013), we found that early AM retrieval processes, hypothesized to involve strategic memory search and construction of the initial context and details of an AM memory, primarily recruited a frontotemporal network of connectivity between the prefrontal cortex and medial temporal lobe, as contrasted with later retrieval processes. In addition, in line with

predictions, brain network connectivity during later retrieval processes (relative to early AM retrieval) primarily included strong connections between occipital-parietal regions and fronto-parietal regions associated with mental imagery, reliving, and working memory processes. Furthermore, we predicted that most of the core AM retrieval regions would be strongly connected to one another throughout retrieval based on evidence that these regions tend to activate with one another. Consistent with this hypothesis, the present study shows that dynamic changes in neural processing and connectivity occur in the context of a strongly connected core AM retrieval network that maintains a least moderately strong ($r>0.3$) connectivity throughout retrieval. In summary, these findings provide further neuroimaging evidence in support of dynamic models of AM retrieval which propose that the cognitive processes underlying AM retrieval progress from frontotemporal, memory access-related processing early in retrieval to posterior occipito- and fronto-parietal, elaboration-related processing later in retrieval.

Dynamic networks supporting early, access-related processing

A reliable, core network of regions throughout the brain tend to be activated during AM retrieval relative to non-episodic or task active control conditions (Svoboda et al., 2006). These regions were specifically investigated in the present study to examine how the network organization of these regions might change from early to late AM retrieval. Consistent with the rich literature identifying regions engaged during AM retrieval, we found that most of the regions in this core AM retrieval network were well connected to one another throughout retrieval. In addition, the basic network organization finding that regions more local to one another (i.e. within the same lobe) were more strongly connected than more distant connections (i.e. between lobes) throughout

retrieval suggests that our sliding time window method had sufficient data points in each time period to properly estimate biologically relevant changes in network connectivity. Within this well connected network, several regions were consistently more strongly connected in either the early or late time periods of AM retrieval. The findings of this study support the general prediction that anterior connections (i.e., frontal and temporal) are stronger during early, access-related AM retrieval than later processing periods. However, the results did not support the hypothesis that frontotemporal connections would be more central to processing distributed information early relative to later in retrieval. In particular, relative to the late retrieval period, the early-access period of AM retrieval exhibited stronger mPFC connections to the dorsal PFC and left posterior hippocampus. In addition, connections between the right VLPFC and left posterior hippocampus were stronger early versus later in retrieval. The engagement and stronger functional connectivity of these fronto-temporal connections early is consistent with previous studies of neural activation and connectivity.

Through experimental manipulation of various aspects of AM retrieval, the rich literature of functional activation studies that examine AM retrieval processes has helped to characterized the hypothesized functions of regions that are co-activated by AM retrieval processes (Addis et al., 2011; Bonnici et al., 2012; Cabeza et al., 2004; Cabeza & St Jacques, 2007; Conway et al., 1999, 2002; Daselaar et al., 2008; Fink et al., 1996; Maguire, 2001; Svoboda & Levine, 2009; Svoboda et al., 2006). Functional activation studies typically refer to regions that are co-activated by AM retrieval processes as a network, but true functional networks can only be defined as brain regions whose signal covaries with other independent regions throughout the brain over time (Mcintosh, 1999).

The present study contributes to functional activation studies of AM retrieval regions by demonstrating that specific regions that tend to be significantly activated across a wide range of AM retrieval tasks form a true functional network that dynamically changes as AM retrieval processes unfold. For instance, Daselaar et al. (2008) found that the right ventrolateral PFC, right dorsolateral PFC, medial PFC, and hippocampus were significantly more active during early AM access processes than late AM elaboration processes. Consistent with Daselaar's findings these same regions (i.e., the right VLPFC, right DLPFC, mPFC, and hippocampus) form a more strongly connected network during early, access-related processes than late retrieval processes in the present study. Neuropsychological evidence (Barceló et al., 2000; Knight et al., 1999) converges with fMRI data to suggest that ventrolateral PFC implements top-down control signals to bias processing in posterior cortical regions like the parietal and late visual cortex (Ranganath and Knight, 2005; Petrides, 2002; Ranganath & Paller, 1999, 2000). Previous studies suggests that activity in the VLPFC may be material specific, with the right VLPFC engaged by the retrieval of images and the left VLPFC engaged by retrieval of verbal information (Petrides, 2002). Findings that the anterior and posterior hippocampi are strongly to connected to frontal regions during early-access processes provides further support that the MTL is not only involved in the formation but also the reactivation of memory traces during conscious memory retrieval (Addis et al., 2009; Cabeza & Moscovitch, 2013; Poppenk et al., 2013; Squire, 2004).In combination with previous functional activation and neuropsychological studies, our findings suggest that the functions of this ensemble of regions work with one another to enable strategic episodic memory search processes, also known as retrieval mode (RVLPFC; Tulving, 1983;

Velanova et al., 2003), and initial reactivation of specific memory traces from one's personal past (hippocampus and mPFC; Greenberg et al., 2005; Hoffman & McNaughton, 2002; Prince, 2005; Squire, 2004). Our findings help to bridge the findings of neural activation with those of neural connectivity studies by identifying the specific connections that change in synchrony between regions that are commonly activated relative to a baseline during AM retrieval.

The present study's findings are also consistent with recent studies of dynamic changes in neural connectivity during AM retrieval (McCormick et al., 2013; St. Jacques et al., 2011) and add to evidence of neural AM retrieval dynamics from these studies by identifying specific region-to-region connections in a large network of regions involved in AM retrieval processes. St. Jacques et al. (2011) showed that large-scale, multi-region components derived from independent components analysis (ICA) changed in their connectivity with one another as AM retrieval processes unfolded and that these inter-component connections were modulated by the extent memory accessibility and recollection. These components consisted of a medial PFC network (similar to default mode network; Buckner et al., 2008), MTL network, frontoparietal network, and cinguloopercular network. They found that all of the networks contributed to early, access-related processes with the mPFC network and MTL networks continuing to be engaged during later-elaboration processes. Our findings are mostly consistent with the findings from St. Jacques et al., but provides much more specificity to help unpack the changes in network connectivity of specific regions within and between each of St. Jacques et al's components during early and later processes of AM retrieval. The large and diverse spatial extent of each of St. Jacques et al's components (i.e. each component

contained regions throughout the brain) make it somewhat difficult to directly compare between the two studies, but our study found that regions in their MTL component, the anterior and posterior hippocampi, were strongly connected to the mPFC and right VLPFC during early AM retrieval processes relative to later am retrieval processes. This finding fits with St. Jacques finding that MTL regions are connected to regions in the PFC early in retrieval, but is inconsistent with their finding that these components are similarly engaged during later elaboration processes. This discrepancy is likely due to the spatial, multi-region form of the components and the fact that St. Jacques did not directly compare the strength of connectivity in each component during the early-access period relative to the late-elaboration period. The present study directly contrasts the region-to-region connectivity between the early and late AM retrieval periods and makes clear anatomical distinctions of ROIs that compose St. Jacques et al's multi-region components. Adding to the findings from St. Jacques et al., our findings suggest that when directly compared to the late-elaboration period, early-access related processing is predominated by stronger frontotemporal connectivity engaged in initial strategic episodic search processes and initial reconstruction of the specific memory's episodic context and details.

In another study of dynamic connectivity changes during AM retrieval, McCormick et al. (2013) found that the left anterior hippocampus was well connected to frontal areas during early, memory access or construction processes. In partial support of McCormick's findings, we found stronger connectivity between left posterior hippocampus and VLPFC early in retrieval. We did not examine one of the regions in their model of AM retrieval regions derived from their data, the dorsomedial PFC, that

was more strongly connected to the anterior hippocampus in their structural equation model early relative to later in retrieval. However, in our study we did find that the right anterior hippocampus was more strongly connected to the mPFC during early-access relative to late-elaboration during AM retrieval. Taken together, the findings of McCormick's study and our study suggest that perhaps a more comprehensive approach to exploring network connectivity during AM retrieval is needed. McCormick et al's study provides important evidence that the anterior and posterior hippocampi play distinct roles in coordinating dynamic changes in neocortical networks during both access and elaboration, but their focus on the hippocampus leaves the remaining question of how other core AM retrieval regions, including the hippocampus, interact with one another during transient AM retrieval periods. Although Daselaar et al., St. Jacques et al., and McCormick et al. provide useful findings that demonstrate dynamic neural processing during AM retrieval, our findings provide an added level of specificity and comprehensiveness by directly comparing of dynamic changes in region-to-region connectivity between the early and late time periods throughout the entire core AM retrieval network. Overall, our findings essentially fit with previous literature that have suggested the primary component processes during the early AM retrieval include strategic episodic memory search and initial reactivation of specific memory traces from one's personal past.

Dynamic networks supporting late, elaboration-related processing

Our findings also support the hypothesis that, relative to early processes, late AM retrieval processes are predominated by stronger posterior occipital-parietal and fronto-parietal connections indicative of elaboration and reliving processes. Neural activation

studies of AM retrieval have identified occipital and parietal regions, like the temporoparietal junction (TPJ) and the occipital cortex (BA19), as being involved in retrieval of spatial context of events and visual imagery processes, respectively (Daselaar et al., 2008; Ganis et al., 2004). Behavioral (Rubin, Schrauf, & Greenberg, 2003), neuropsychological (Greenberg & Rubin, 2003), and neuroimaging evidence (Cabeza et al., 2004) have shown that visual information and visual imagery are important components of AM retrieval processes (Daselaar et al., 2008). Our dynamic functional connectivity data support the view that the visual and parietal cortices work in tandem during late-elaboration processes of AM retrieval (Rubin, 2005, 2006). In addition, activation and connections of lateral fronto-parietal regions during the late-elaboration period of AM retrieval have been implicated in control of reconstruction processes and maintenance of episodic details in working memory (Velanova et al., 2003; Vincent et al., 2006, 2008; Wager & Smith, 2003). The present study further supports previous findings that posterior parietal and occipital and fronto-parietal connections are activated during late-elaboration processes of AM retrieval and adds to this literature by demonstrating that these regions are also in sync with one another after retrieval shifts from early, access-related processing to later, elaboration-related processing.

Studies of dynamic neural connectivity during AM retrieval also find that time periods after the initial access period involve posterior connections between fronto-parietal components and connections of occipito-parietal regions with the posterior hippocampus (McCormick et al., 2013; St. Jacques et al., 2011). As mentioned previously, St. Jacques et al. identified four independent components composed of multiple regions whose signal time course tended to vary together. Similar to our study,

they found that their fronto-parietal and cinguloopercular components tended to peak in engagement around 12 seconds after the onset of the cue supporting the hypothesis that posterior and fronto-parietal networks are engaged in late-elaboration processes. When examining the hippocampus's role in coordinating anterior and posterior networks during AM retrieval, McCormick et al. (2013) found that the posterior hippocampus was more strongly connected to mid-occipital regions and ventral parietal regions during the later-elaboration period than during the early period. The present study did not find direct evidence of stronger connectivity between the posterior hippocampus and parietal or occipital regions during later periods of AM retrieval. Rather, we only found that the occipito-parietal regions and fronto-parietal regions were more strongly connected to one another. This discrepancy may exist between the two studies because the occipito-parietal regions tested in the McCormick et al. study included slightly different regions (e.g., mid OCC, fusiform, and lingual gyrus) that were derived from their partial least squares analysis than those included as part of our core AM retrieval network that was derived from meta-analyses of previous AM retrieval studies. Network approaches that include a more comprehensive set of regions involved in AM retrieval to examine dynamic changes in AM retrieval network might find that the posterior hippocampus is well connected with posterior occipital regions during the late-elaboration period similar to the McCormick et al. study. Overall, our findings mostly fit with previous literature, which suggests that later periods of AM retrieval after a specific memory has been accessed primarily involve engagement and connectivity of regions involved in visuospatial re-experiencing of the past event and maintenance of retrieved information in working memory.

Limitations and Future Directions

The present study was specifically designed to examine the development of AM retrieval processes through a univariate analysis of regions activated by AM retrieval in school-aged children and adults. Thus, several experimental design qualities limit the interpretation of the results of the present study. The first limitation of the present study is the limited selection of core AM retrieval regions. These regions were selected in a principled and justifiable manner by creating core network ROIs based on previous studies of dynamic AM retrieval (Daselaar et al., 2008) and the most recent meta-analysis that reviewed neuroimaging studies of AM retrieval (Svoboda et al., 2006). The present study was also the most comprehensive inclusion of specific neural regions to date in studies of dynamic changes in functional connectivity during AM retrieval. However, a challenge for future studies will be to account for an even more comprehensive set of regions engaged in AM retrieval, whether through whole brain network analyses or a set of regions that include core, secondary, and tertiary regions involved in AM retrieval processes. More studies of the dynamic recruitment of AM retrieval regions using a range of AM retrieval characteristics and a flexible fMRI designs similar to the Daselaar et al. (2008) study are needed to better characterize the dynamic engagement of regions involved in AM retrieval. More dynamic activation studies of AM retrieval will allow for a meta-analysis of compiled findings across a range of samples and AM retrieval conditions.

Another limitation of the present study's design includes the effects of recent rehearsal imparted on the AM retrieval processes. Rehearsal effects have been shown to attenuate the activation in the autobiographical memory network (Svoboda & Levine,

2009). Thus, the extensive rehearsal of the memories immediately prior to the scanning session in this study likely reduced the time and effort needed to access the specific memory for each cue and likely attenuated the strength, timing, and extent of the core AM network connectivity during the early-access period of AM retrieval in our study. Although there seems to have been sufficient engagement of hypothesized networks during early AM retrieval, effects of rehearsal on the time to access the memory was also not optimal to examine connectivity changes relative to the point in which a specific memory is selected and elaboration processes begin.

Future studies should manipulate the timing of the transition from access-related processing to elaboration-related processing by manipulating the difficulty of retrieving a specific memory for particular cues. For instance, in preparation for a future study we have performed a pilot study in which we selected a wide range of cue words (80 in total) from many previous studies of cued AM retrieval and had participants retrieve memories without any prior rehearsal for each cue word. Once the participant had a specific memory in mind they were instructed to press a button, demarking the time to access a specific memory for each cue. We found that many of the cue words required a consistent amount time to access a specific memory across all of the participants. When examining the means of these cue words we found that the time to access across participants and words followed a linear distribution with sufficient variability to select cue words that tend to vary in the time it takes to access a specific memory for each cue word. Cues like "shopping", tended to be accessed more quickly (*M*= ~4 seconds), where as cues "field", tended to be accessed more slowly (*M*= ~12 seconds). Previous studies using button presses to denote this information have either not had sufficient variability or did not take

advantage of the variability in time to access and have tended to average across quickly and slowly accessed memories. Future studies of AM retrieval dynamics could take advantage of this variability by having participants respond via button press when a specific memory has been accessed to more accurately examine the transition between access-related processing and elaboration-related processing and establish that the strength of connections from the access to the elaboration network only change around the moment of transition between the two processes. Another approach to denoting the time to access, other than having the participant submit a button press, is to develop fMRI scanning procedures that would allow participants to retrieve AMs aloud or overtly in the scanner. This development would also allow for verification that participants are retrieving specific AMs in the scanner and examination of neuroimaging data based on the narrative content of the autobiographical memory. More generally, developments in the methods to behaviorally assess the transition from process to process is needed to more accurately and comprehensively examine the dynamic neural correlates of AM retrieval processes.

The elaboration cues introduced after the initial cue may have also contributed to attenuation of dynamic changes in neural connectivity across the AM retrieval period. In particular, elaboration cues used to prompt the participant to continue elaborating for the duration of each AM retrieval trial might have also reduced the effort needed to intrinsically elaborate upon the memory and maintain the AM in working memory. Thus, although elaboration cues likely ensured that participants continued AM retrieval for the duration of most trials, this design characteristic may have attenuated changes in the strength of connectivity during the late AM retrieval processes. In addition, the overall

trial length was shorter (16 seconds) relative to previous studies of AM retrieval (24-30 seconds). Although this study finds hypothesized patterns of occipito- and fronto-parietal connectivity late relative to early in retrieval, shorter trial lengths limited this study's capacity to examine whether these late, elaboration-related differences from the early retrieval period persist or change in configuration beyond the initial late period after access processes. The combination of the potential attenuating effects of rehearsal and elaboration prompts might have also contributed to the unexpected null findings in examining the dynamic changes of each region's average node strength in the core AM retrieval network and node degree centrality of core AM retrieval regions in the whole brain.

Although these limitations exist and need to be addressed in future experiments, this study still provides useful evidence that predictable and specific neural connections change in their strength of functional connectivity to one another as AM retrieval processes progress from access-related to elaboration-related processing. These findings can be used as a basis to create and test models of the neural mechanisms that underlie AM retrieval processes across a range of populations across development (children and adults across the lifespan) to patient populations with known issues in retrieving autobiographical memory. As mentioned before, the fMRI data for autobiographical memory retrieval in this study is only one part of a larger fMRI AM retrieval dataset that included developmental data from children ages 8-12 years old. Contrasting the similarities and differences in changes of dynamic connectivity during AM retrieval in the developmental sample to our adult data would allow us to further account for the known behavioral and neural changes in AM retrieval across development during

childhood, adolescence, and through adulthood (Bauer & Fivush, 2010; Fivush, 2011). Another interesting aspect of the full data set from which this study was derived is that memories were pre-selected as either negative, positive, or neutral in emotional valence. Although this manipulation was not taken advantage of in the present study due to insufficient power to estimate differential processing between the emotional conditions, questions of the modulation of network properties based on the emotional valence and arousal of the memory are of significant interest to researchers working to gain an understanding of the interplay between emotion and memory (Hamann, 2001). In addition, this study's approach could also be applied to studies of patients who experience memory retrieval issues of autobiographical memory, like consistent, involuntary retrieval of negative past experiences (i.e., depression, generalized anxiety disorder, post-traumatic stress disorder, etc.) or difficulty retrieving AMs from one's past (i.e., mild cognitive disorder, dementia, Alzheimer's disease, other neurological diseases, etc.), to better understand alterations in neural connectivity associated with these disorders. A few studies have started to apply similar ideas of assessing alteration in activation and connectivity of core AM retrieval regions (Jacques, Botzung, Miles, & Rubin, 2010; St Jacques, Kragel, & Rubin, 2013). Further studies into alterations in the dynamic nature of cognitive and neural processes associated with these psychiatric and neurological disorders would aid in our understanding of the neural systems we need to engage to treat the various constituent dysfunctional AM retrieval processes.

Conclusions

In conclusion, the present study provides initial evidence that the core AM retrieval network exhibits predictable changes in the connectivity of specific regions in

the core AM retrieval that unfolds over the course of dynamic and complex AM retrieval processes. By using measures of multivariate, dynamic connectivity between specific regions of an established core AM retrieval network, this study further supports previous views that patterns of neural engagement and connectivity dynamically change as AM retrieval processes progress from early, access-related processing to late, elaboration-related processing. In combination with previous evidence of dynamic changes in neural processing during AM retrieval, the present study provides helps to further refine current theories of dynamic AM retrieval processing. These findings underscore the need for more comprehensive neuroimaging examinations of the complex and dynamic neural interactions that shape our thoughts, feelings, memories, and actions.

Study 2: Large-scale functional network organization changes during autobiographical memory retrieval

The neural state of the human brain is constantly changing over time as internal and external cues influence a person to engage in a constant stream of ever fluctuating cognitive behaviors (Anderson & Fincham, 2013; Bassett et al., 2011; Newell & Simon, 1972). One such cognitive behavior that has been shown to dynamically engage multiple neural systems is autobiographical memory (AM) retrieval. AM retrieval is hypothesized to involve multiple cognitive states that engage and oscillate in their predominance of neural processing resources. Building on previous theories of memory retrieval (Moscovitch & Melo, 1997; Rugg & Wilding, 2000; Tulving, 1983, 2002), Conway and Pleydell-Pierce's (2000) self-memory system theory proposed a specific sequence in which AM retrieval processes unfold over time. In particular, Conway and Pleydell-Pierce proposed that upon receiving a cue to remember, one must first access and monitor the accuracy of the cued memory, then once accessed, the specific details are held in working memory and elaborated upon as the participant builds representations to re-experience the memory.

Empirical work has tested the self-memory system theory using various neuroimaging methodologies (slow cortical potential EEG and fMRI) and demonstrated that a reliable set of regions are differentially engaged during these early-access related time points and later-elaboration related time points (Conway et al., 2001; Daselaar et al., 2008). Furthermore, studies have shown that connectivity changes between sets of these regions over a AM retrieval (i.e., fronto-parietal component and medial temporal lobe component; St. Jacques et al., 2011) and the interaction of the anterior hippocampus with

other regions involved in AM retrieval differs from the posterior hippocampus as AM retrieval processes evolve over time (McCormick et al., 2013). However, it is still not known how specific regions within and outside these large, multi-region components change as a function of evolving cognitive processing during AM retrieval. In addition, previous research has specifically focused on characterizing the changes in activation and connectivity for time periods relative to a specific behavioral marker (i.e., a button press) to demonstrate differences between a participants assumed access and elaboration-related neural processing. Although this approach helps tie the cognitive processes to a participant perceived behavioral marker, it limits the researchers ability to describe specifically how the interactions between regions involved in AM retrieval unfold across multiple time periods in retrieval. Clarifying the relationship of dynamic changes in the functional connectivity between specific regions (i.e., anterior/posterior hippocampus, prefrontal cortex, parietal cortex) as the processing demands of AM retrieval evolve in an model-free functional connectivity analysis will help to further refine models of dynamic autobiographical memory retrieval processes.

Autobiographical memories are much more varied in their temporal and spatial context, emotional characteristics, visual imagery, relation to self, and narrative structure than laboratory controlled and encoded episodic memories (Cabeza & St Jacques, 2007; Daselaar et al., 2008; Rubin, 2005). Behaviorally, AM retrieval involves mental processes to access the memory related to an internal or external cue, as well as processes involved in elaborating on the details of the accessed memory (Conway & Pleydell-Pearce, 2000; Tulving, 1983). Initial retrieval processes are referred to as memory access or construction because they are thought to involve, strategic controlled search, memory

monitoring, and rebinding of the episodic details to the cued context of the memory. In the memory access period, upon receiving a cue, the participant first experiences a automatic memory retrieval process engaged in when a specific cue interacts with information stored in memory, referred to as ecphory (Cabeza & Moscovitch, 2013; Moscovitch & Melo, 1997; Moscovitch, 1995; Tulving, 1983). After more general and personal knowledge is accessed, various episodic elements of the memory are bound into a cohesive memory that can then be re-experienced (Conway, 2009). The retrieval goals and need for sparse or rich elaboration are determined by the situation. In many cases the memory may need to be elaborated upon by filling in details of the memory to accomplish the retrieval goal (e.g., object specific details like the kind, color, and model of the car; contextual details like where, when, how the car was received).

The time course of access or mnemonic search processes can occur relatively quickly, but significantly depends on the goals of the retrieval episode and the strength of the memory. Access of unrehearsed AMs to these generic cue words typically happens between 7 and 12 seconds from the presentation of the cue, but this may vary depending on the difficulty of retrieving a specific memory for that cue (Addis, Knapp, Roberts, & Schacter, 2011; Addis, McIntosh, Moscovitch, Crawley, & McAndrews, 2004; Addis, Pan, Vu, Laiser, & Schacter, 2009; Barsalou, 1988; Rubin & Schulkind, 1997). The time taken to elaborate varies as a function of the instructions, goal, or attention that can be allocated to the retrieval task. A few studies have utilized these estimates and participant responses to delineate the time course of memory access and elaboration, but there has not been a systematic examination of the typical time to access and richly elaborate upon

an unrehearsed AM to generic cues outside the context of fMRI study design constraints (Addis & Schacter, 2008; Daselaar et al., 2008).

Across the various fMRI AM retrieval study designs, AM retrieval processes have been shown activate a broad swath of the human brain (Addis et al., 2004; Cabeza et al., 2004; Cabeza & St Jacques, 2007; Conway et al., 1999, 2002; Daselaar et al., 2008; Greenberg et al., 2005; Maguire, 2001; Muscatell et al., 2010). On this neural systems level, activated regions throughout the brain interactively orchestrate the required operations for each of mental processes underlying AM retrieval. The core network of regions involved in autobiographical memory retrieval has been found to be relatively consistent across neuroimaging studies, although some differences and discrepancies exist. In an early meta-analysis of autobiographical memory, Maguire (2001) found that distributed networks of neural regions involved in processing declarative memory include the MTL (i.e., hippocampus, parahippocampal gyrus), retrosplenial cortex, posterior parietal regions (i.e., inferior parietal and precuneus), as well as lateral and medial PFC. Subsequent studies and meta-analyses have provided evidence in support of this core network (Addis et al., 2004; Burianova, McIntosh, & Grady, 2010; Daselaar et al., 2008; Greenberg et al., 2005), for a recent meta-analysis see Svoboda et al., 2006). In a meta-analysis of regions activated in neuroimaging studies of AM retrieval Svoboda et al. (2006) found that the core AM network also included the cerebellum and the temporoparietal junction (TPJ) along with most of regions described in earlier meta-analyses. Several secondary regions are consistently activated in studies of AM. Across studies secondary region activation tends to depend on the nature of the memory retrieval task (Svoboda et al., 2006). Studies which manipulate the emotionality of stimuli or cues

have found that the amygdala and sensory processing regions like the secondary visual cortex are active in retrieval of personally significant and contextually rich AMs (Addis et al., 2004; Cabeza et al., 2004; Fink, 2003; Rubin, 2005). Researchers have gained insight into the functions of the regions in the core network for AM retrieval through extrapolation of their typical functions across a variety of cognitive tasks in both neuropsychological and neuroimaging studies.

The dynamic AM retrieval system is comprised of many distinct processing regions that interact with one another as the component retrieval processes unfold over time. Nearly all of the meta-analyses and empirical studies to date implicate regions in the MTL as the primary hub for memory retrieval processing (Addis et al., 2011; Conway, Pleydell-Pearce, Whitecross, & Sharpe, 2002; Daselaar et al., 2008; Greenberg et al., 2005; Maguire, 2001; Svoboda et al., 2006). In particular, these neuroimaging studies of AM retrieval, as well as a rich history of neuropsychological and animal studies of episodic memory (McGaugh, 2000; McIntyre, McGaugh, & Williams, 2011; Squire, 2004; Squire & Bayley, 2007; Squire, Stark, & Clark, 2004), suggest that the hippocampus is involved in the construction and rebinding of memory details (Daselaar et al., 2008; Greenberg et al., 2005; McCormick et al., 2013; St. Jacques et al., 2011). After the MTL, the prefrontal cortex (PFC) is most often discussed as core to autobiographical memory networks. Both medial and lateral aspects of the PFC are implicated in autobiographical memory retrieval. The medial aspect of the PFC is implicated in processing and recollecting the self-relevance of a particular memory and is thought to be particular to AM retrieval (D'Argembeau et al., 2007; Gusnard et al., 2001; Markowitsch et al., 2003; Oddo et al., 2010; Simons & Spiers, 2003). The lateral aspect

of the PFC is thought to be involved in a strategic memory search process known as retrieval mode, especially in the right hemisphere (Wagner, 1998). Retrieval mode is the mental set that guides the retrieval of specific, episodic information (Velanova et al., 2003). Daselaar et al. (2008) found that the medial and right PFC are involved early in AM retrieval during the memory access period. The retrosplenial cortex (RSC) or posterior cingulate cortex (PCC) is also often described as part of the core autobiographical memory network. Daselaar et al. (2008) found that the RSC and PCC show greater activity during memory access relative to memory elaboration suggesting that these regions might help aid in memory search and retrieval of sensory details. Other regions of the core autobiographical memory network include those engaged in retrieval of sensory information (e.g., visual cortex), including mental imagery of this sensory information (e.g., precuneus and inferior parietal cortex), and goal-directed control processes. Although there is robust consistency in the regions typically active in the retrieval of autobiographical and semantic memories, there is much less consistency in the brain hemispheres to which these activations are found (Conway et al., 2002; Daselaar et al., 2008; Maguire, 2001; Svoboda et al., 2006). The consistency of activation within this core network of regions makes AM retrieval a well suited candidate for further investigation into the functional integration of each region's connectivity with other core network regions and regions throughout the brain. Across a retrieval episode, the dominant processing demands change from regions involved in accessing and constructing the memory to those involved in elaborating and maintaining the memory in working memory (Daselaar et al., 2008). Daselaar et al. (2008) demonstrated that a particular set of regions is more active during memory access (hippocampus, right

prefrontal cortex, etc.), while another set is more active during memory elaboration (parietal regions, occipital cortex).

Many cognitive neuroscientists work from the viewpoint that complex interactions between distributed objects of information processing (i.e., functional brain regions) give rise to cognitive processes (Wig et al., 2011). Analysis techniques for inferring the functional connections regions have with one another have been developed over the past two decades of neuroimaging research (i.e., seed-based connectivity; ICA; PLS; graph theory; Bullmore & Sporns, 2009; Calhoun, Adali, Pearlson, & Pekar, 2001; Hutchison et al., 2013; Mcintosh, 1999; McKeown, 2000; Rubinov & Sporns, 2010). Within the past decade, studies of functional connectivity have mostly focused on characterizing both specific (e.g., the default mode; Buckner, Andrews-Hanna, & Schacter, 2008; Fox et al., 2005) and large-scale functional connectivity in the absence of experimental demands (i.e., resting state functional connectivity fMRI). Functional connectivity is defined by the temporal relations of distinct brain areas. Although these studies have informed our knowledge of spontaneous and intrinsic resting state functional networks, studies of dynamic functional networks during the resting state cannot illuminate the specific neural mechanisms underlying particular cognitive behaviors.

To date, studies of functional connectivity during experimental tasks have mainly focused on static representations of region-to-region connectivity (e.g., seed-based functional connectivity or psycho-physiological interactions) within a small set of regions found to be active during particular task conditions. These small, static representations of connectivity between task activated regions provides insights into the coordination between these regions during tasks, but they neglect the apparent, dynamic, complex

nature of cognitive processing that occur across multiple time scales and throughout the brain as we move through the world. In other words, interactions between specific functional units in the brain's complex systems dynamically adapt to a continually changing environment over multiple temporal scales (Bassett et al., 2011). In order to generate accurate models of brain function during cognition it is essential that cognitive neuroscientists utilize the aforementioned recent advances to characterize these dynamic changes in large-scale functional networks during various cognitive tasks (i.e., problem solving, emotion regulation, memory encoding and retrieval, etc.).

Autobiographical memory retrieval is a particularly good candidate to begin to test theories of dynamic cognitive and neural processing with fMRI because established theories of AM retrieval suggests that it is composed of multiple cognitive processes that evolve over a relatively extended period of time (seconds rather than milliseconds) depending on the task demands. Approaches to examining dynamic functional connectivity have received growing attention recently as sliding-window neuroimaging analysis approaches have become more computationally feasible (Bassett et al., 2011; for thorough review see Hutchison et al., 2013). Although initial studies of functional integration during AM retrieval did not account for the dynamic nature of retrieval, they do provide important evidence that has guided theory and evidence to the point that calls for a better understanding of the dynamic neural organization that underlies AM retrieval processes.

Although the first studies establishing models of functional and effective connectivity during AM memory retrieval were very informative (Conway et al., 1999, 2001; Greenberg et al., 2005; Maguire et al., 2000), data accumulated since their

publication and developments in connectivity analyses lend the opportunity to establish more refined models of functional and effective connectivity (St. Jacques et al., 2011). St. Jacques et al. (2011) performed an initial examination of the dynamic neural networks that underlie access and elaborative processes during AM retrieval. St. Jacques study's findings added to the existing literature by showing that different large-scale, multi-region networks (i.e., medial PFC network, MTL network, frontoparietal network, and cinguloopercular network) are differentially involved in AM retrieval during access and elaboration. Following the St. Jacques study, McCormick et al. (2013) characterized how frontal, temporal, parietal and occipital regions interacted with the anterior and posterior hippocampus during the hypothesized access and elaboration periods of AM retrieval. Using fMRI and partial least squares analysis, McCormick et al. found that the left anterior hippocampus was better connected to frontal areas during construction (i.e., memory access) than elaboration. Also fitting their predictions, they found that during elaboration the posterior hippocampus, bilaterally interacted with parietal and occipital areas. Although McCormick et al's study provides important evidence that the anterior and posterior hippocampi play distinct roles in coordinating dynamic changes in neocortical networks during both access and elaboration, their focus on the hippocampus leaves the remaining question of how other core AM retrieval regions, including the hippocampus, interact with one another during transient AM retrieval periods. Multivariate techniques such as cross-correlation analysis and graph theory offer the opportunity to characterize the specific changes in region-to-region connectivity across the entire core AM retrieval network as cognitive processes transition from early access-related processing to later elaboration-related processing.

The present research specifically aims to determine the dynamic functional connectivity of specific connections between core AM retrieval brain regions across an extended AM retrieval period. An additional aim of the current study is to determine the large-scale functional network characteristics of core AM retrieval brain regions in the context of the whole brain using topological, graph theory metrics. Cross-correlation analysis is a basic approach to examining pairwise variations in inter-regional synchrony for an established network of nodes, in the present study's case, core brain regions involved in AM retrieval. This allows for both characterizations of specific changes in region-to-region connectivity and larger patterns of changes in connectivity depending on the underlying cognitive mechanism (e.g. shift from stronger connectivity between frontotemporal regions to occipito-parietal regions over time). Graph theory is a branch of mathematics in which mathematical structures (graphs) are used to model pairwise relations (i.e., edges or connections) between objects (i.e., nodes or in the case of fMRI ROIs; Bullmore & Sporns, 2009; Power et al., 2011; Rubinov & Sporns, 2010; Wig et al., 2011). Graph metrics are used to help determine simple organizational features of the complex network architecture and include many objective measures node-based and network-based properties. The primary graph properties related to functional brain connectivity are strength and centrality (Rubinov & Sporns, 2010). In graph theory terms, strength is one of the most basic metrics of a node's connectivity to the network and is defined as the average correlation coefficient between one region and all of the regions connected to it. Metrics of functional centrality in a brain network identifies the brain regions that often interact with many other brain regions, facilitate functional integration, and are key to a network's vulnerability and resilience to damage (Sporns, Chivalo,

Kaiser, & Hilgetag, 2004). Common centrality measures that are derived in almost every graph theory analysis are based on the idea that brain regions with more short paths within a network act as important information flow control (Sporns, Chivalo, Kaiser, & Hilgetag, 2004). In analyses of brain network dynamics during a task these graph metrics of a region's centrality allow for a characterizations of the regions importance during a particular period in the AM retrieval processes.

Similar to previous studies, the current study examines the dynamic changes in functional connectivity across early and late periods of AM retrieval between regions that have been consistently implicated in AM retrieval processes. In contrast to previous studies, this study was designed to investigate dynamic retrieval processes with a more naturalistic AM retrieval task in which the memory cue had to be maintained in working memory after initial presentation, additional cues to aid elaboration had to be internally generated, and each memory had sufficient time to be fully elaborated upon. Given these characteristics the present study, we were able to observe the elaboration process in a more ecologically valid manner beyond the initial elaborative period observed in previous studies. Furthermore, a model-free approach was utilized in the analysis of this data to better capture the changes in AM network connectivity across a early-access, first elaboration, second elaboration period. Conway and Pleydell-Piece's (2000) SMS theory predicts that dynamic connectivity changes relative in the later periods relative to the early retrieval period would similar to those of the first elaboration period. In relation to the first study of this dissertation we expect to a similar pattern of dynamic functional connectivity changes with AM retrieval.

Based on the evidence from studies of cognitive processing, neural activation, and brain connectivity during AM retrieval, the current study characterizes functionally connected brain networks during early, access-related and later, elaboration-related AM retrieval processing. Overall, we expect to find similar patterns of stable and dynamic functional connectivity during AM retrieval as were described in the first study of this thesis. This study aims to further characterize the changes in functional connectivity of core AM regions beyond the cognitive processing periods examined in previous studies (Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011). First, we expect the nearly all of the core AM retrieval regions to be moderately strongly connected to one another (i.e., $r > 0.3$) and that most of the network will be stable throughout AM retrieval base on the evidence that these regions tend to activate with one another (Cabeza et al., 2004; Cabeza & St Jacques, 2007; Conway et al., 1999; Muscatell et al., 2010; Svoboda et al., 2006). To confirm that each study had sufficient power (i.e., number of time points in each time window) to estimate biological relevant network organization, we would expect that the stable network would have a structured, non-random topological organization that fits with the numerous studies of functional large-scale connectivity in task and resting-state studies of the brain.

Many previous studies have found that mPFC activity is modulated by the extent of self-referential processing required by the memory being retrieved (Bonnici et al., 2012; D'Argembeau et al., 2007). Given that autobiographical memory is particularly defined as memories related to the self, we would expect that self-referential processes may be engaged to various regions throughout AM retrieval, but not necessarily be predominantly connected to certain parts of the network in either the early or late time

periods. Evidence supporting this hypothesis suggest that the medial PFC was engaged throughout retrieval and thus we expected that connectivity to the mPFC would remain stable throughout AM retrieval (St. Jacques et al., 2011). St. Jacques et al. also found that their MTL component, consisting of the hippocampus, parahippocampal gyrus, and posterior cingulate, was engaged throughout AM retrieval. Differing from the predictions of stability in mPFC connections, evidence from McCormick et al. (2013) would suggest that St. Jacques et al's MTL component did not sufficiently account for specific aspects of the medial temporal lobe (e.g., anterior and posterior hippocampus) that play different roles the earlier and later periods of AM retrieval.

Considering the findings of the research reviewed above (Conway et al., 2001; Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011), we would expect anterior connections (i.e., frontal and temporal) to be stronger and more central to integrating distributed information during early, access-related process than later processing periods. During later, elaboration-related processing we generally would expect a more distributed pattern of connectivity consisting primarily of posterior connections (i.e., parietal-occipital and frontoparietal) that persist from the initial late-elaboration period to the last elaboration period relative to early processing periods. To further describe specific predictions for each processing period, the hypothesized component processes within the each of the dynamic processing periods (i.e., early-access and late-elaboration) and the specific connections that would be predicted to underlie each component process are described below.

According to the hypothesized component processes during the early, access-related processing period of autobiographical memory retrieval we expected to see

dynamic changes in connectivity of frontal lobe to MTL and frontal lobe to parietal lobe connections. Previous evidence suggests that the ventrolateral PFC is specifically involved in memory search or retrieval mode processing (Daselaar et al., 2008; Rugg & Vilberg, 2012; Velanova et al., 2003; Wagner, 1998). Furthermore, neuropsychological evidence (Barceló et al., 2000; Knight et al., 1999) converges with fMRI data to suggest that ventrolateral PFC implements top-down control signals to bias processing in posterior cortical regions like the parietal and late visual cortex (Ranganath and Knight, 2005; Petrides, 2002; Ranganath & Paller, 1999, 2000). Thus, we expected the VLPFC to play a central role during access-related processing. Evidence in support of this prediction would show that the VLPFC had stronger connections and was more central (e.g. higher degree) in the early-access period relative to the late-elaboration period. Strong laterality predictions are not made given that neither of the present studies specifically manipulated variables known to modulate the VLPFC's laterality and the lack of consensus in the previous literature on the laterality of the VLPFC's involvement in strategic search-related processing.

In addition to lateral frontal strategic search processes, several reviews have suggested that another component process during the early-access period is construction of specific memory context and details (Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Tulving, 2002). A rich literature of hippocampal lesion studies (Addis, Moscovitch, & McAndrews, 2007; Maguire, Vargha-Khadem, & Mishkin, 2001; Squire, 2004; Tulving, 2002; Wixted & Squire, 2011) and neuroimaging studies of AM retrieval suggest that the hippocampus is involved in the construction and rebinding of memory details (Daselaar et al., 2008; Greenberg et al., 2005; McCormick et al., 2013; St. Jacques

et al., 2011). Although Greenberg et al. (2005) did not examine changes in connectivity across AM retrieval, they found that the left anterior hippocampus exhibited strong functional connectivity to the right VLPFC during AM retrieval. McCormick et al. (2013) further specifies this construction and rebinding function to involve stronger connections between the anterior hippocampus and the PFC during the early-access period. Findings from the present study that would support this previous evidence would show that the hippocampus, more specifically the anterior hippocampus, is more strongly connected to medial and lateral PFC regions earlier relative to later in retrieval. We also would expect the anterior hippocampus to play a more central role (i.e., higher degree) in the AM retrieval network during this early-access period relative to the later periods. In addition to the hippocampus, Daselaar et al. implicated the medial retrosplenial cortex or posterior cingulate cortex in memory reconstruction processes early in AM retrieval. Based on this evidence we would expect that connections between the hippocampus and the PCC would be stronger early relative to late in retrieval. In summary, early, access-related processing was predicted to be primarily characterized by a predominantly anterior network of connections that have been previously shown to underlie strategic memory search processes (i.e., retrieval mode) and initial reconstruction of the cue context with specific event details. Previous literature suggests that the strength of engagement, connectivity, and centrality of this primarily anterior, access-related network would diminish as a more posterior network of regions become engaged to process aspects of re-experiencing the specific AM found during memory access.

Once a specific memory has been identified for each AM cue, connections between regions in the parietal and occipital lobes were predicted to become stronger and

more central to the AM retrieval network as the specific memory is elaborated upon. Elaboration or reconstruction of the remembered experience is hypothesized to consist of several component processes including visual imagery and sensory processing of memory details, continuation of processes to rebind memory details and context, and maintenance of event details that have been retrieved in working memory (Addis et al., 2004; Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011). Regions throughout all lobes of the brain have been implicated in each of these component processes based on the cognitive fMRI tasks that tend to activate each region (Svoboda et al., 2006). In particular, regions in the occipital and parietal cortex have been implicated in visual imagery processing when a participant is imagining an experience or retrieving a memory (Addis et al., 2011; Daselaar et al., 2008; Ganis, Thompson, & Kosslyn, 2004). Thus, we expected to see stronger connectivity between the occipital cortex (i.e., BA19, extrastriate cortex) and both medial and lateral parietal cortex during the late-elaboration period relative to the early-access period of AM retrieval. We expected these patterns of posterior connectivity to persist through the duration of the retrieval period after the early period of retrieval.

The process of rebinding of memory context and details are thought to persist from the early-access period through to the late-elaboration period as new details are found and incorporated into the memory representation (McCormick et al., 2013). Evidence from McCormick et al. (2013) suggests that the posterior hippocampus is more strongly connected to medial and lateral parietal areas during late-elaboration processes than early-access processes. Poppenk et al. (2013) propose that the role of the posterior hippocampus in memory retrieval is to retrieve the precise spatiotemporal context and

episodic details of the remembered event. Based on the posterior hippocampi's proposed role in memory retrieval processes, we expected that the posterior hippocampus, bilaterally, would be more strongly connected to core AM retrieval regions in the parietal cortex during late-elaboration related processing relative to early-access related processing. We also predicted the posterior hippocampus would play a more central role in the later periods of processes.

Finally, connections between the dorsolateral frontal cortices and superior parietal cortices have been implicated in the process of maintaining information in working memory and representational control processes (Baddeley, 2003; Vincent et al., 2008; Wager & Smith, 2003). As the specified memory is elaborated upon the previously recalled details would likely need to be maintained in working memory, thus we predicted that frontoparietal connections would become stronger than during early-access processes. In the second late-elaboration time window, we expected that the dynamic connectivity pattern would be similar to those found in the first elaboration time window relative to the early time window. Specifically, we expected regions engaged in ongoing working memory (e.g. fronto-parietal connections) and rebinding processes (e.g. posterior hippocampus and parietal connections) would be more strongly connected to one another in the second late-elaboration period relative to the early-access time window. As reviewed above, a wealth of previous research has identified a posterior network of regions that are typically engaged during the component processes hypothesized to underlie elaborative memory retrieval processes. Support for our hypotheses would demonstrate that these more posterior regions change in the extent of their synchronization with one another from earlier to later in retrieval as more

elaboration-related processes begin to predominate autobiographical memory retrieval. The present study tests current theories of AM retrieval dynamics (i.e., self-memory system) by characterizing the changes in the connectivity strength of individual regions involved in AM retrieval and topological relationship of each core AM retrieval region to every other AM retrieval region and the whole brain.

Method

Participants

Sixteen healthy right-handed adults (8 female) were recruited on the Emory University campus. Participants were screened to have no history of neurological or psychiatric impairment. In addition, all participants spoke English as their first language. All participants were paid for their participation. Written informed consent was acquired from participants under a protocol that was approved by the Emory University Institutional Review Board. Fifteen subjects (8 female), with a mean age of 24.4 years successfully completed the fMRI session. One subject was excluded due to excessive motion.

Stimuli

In a session a few weeks prior to their fMRI session, participants were asked to select and describe 35 autobiographical memories from their recent (<3 years) and distant past (>3 years). For the purposes of a separate experiment, each memory was required to evoke one of five different basic emotions (i.e., happy, sad, fear, disgust, and anger). Each participant was asked to produce three memories for each basic emotion (15 total emotional memories). A set of 20 neutral memories was also collected from each participant to serve as a control condition relative to the emotional memories. An

experimenter reviewed all memories to ensure each memory was situated in a specific time and place, sufficiently detailed, and recollectively vivid. Emotional memories were also required to be specific to one basic emotion (e.g., memories of happy experiences should only evoke happiness and no other emotion) and emotionally arousing. Emotional and neutral memories are collapsed in the present study to ensure enough power to detect changes in measures of network organization across an autobiographical memory trial. Brief 1 to 3 word phrases were selected for each memory to act as a personal cue during the scanning session.

Procedure

Participants came into the lab for 3 sessions including a review and practice session prior to the fMRI session, the fMRI data acquisition session, and an emotional ratings session following the fMRI task. Participants reviewed the memories they had prepared and practiced the autobiographical memory task they were to complete in the fMRI scanner in the first session. In the fMRI scanning session upon entering the scanner an anatomical scan was collected from each participant. During the anatomical scan the participant practiced the experimental task. The experiment consisted of 10 runs. Each run alternated from a task in which participants watched short emotional film clips and the autobiographical memory task (5 film runs, 5 autobiographical memory runs). Four neutral memory cues and three emotional memories were interleaved with one another during each run (7 memories per run). To minimize the effects of slow drift and maximize the emotional experience of each memory, only one emotion state was presented in each run alternating with neutral memories. Run and stimulus order were counterbalanced across participants to alleviate potential order effects. The third session

consisted of psychophysiological recordings and ratings of emotional qualities of the emotional film clips that are not relevant to the present experiment, so they are not described in detail. Pertinent to the present study, after the scan, memories were check for consistency and fidelity relative to the memories associated with the personal word cues given prior to scanning to ensure that similar memories were retrieved in the scanner as prior to scanning. Participants were debriefed and compensated for their time upon completion of the third session.

Each autobiographical memory trial was a total of 42.5 seconds in duration. Trials began with a 500 msec fixation period followed by the presentation of the participant's personal cue and a 30-second retrieval period. Cues appeared on the screen for the first 3 seconds of the 30-second retrieval period and participants pressed a button when they began to feel an emotion. After the retrieval period, three emotional rating screens were presented for 3 seconds per rating (emotional valence, arousal, and typicality). Trials were separated by a consistent 3-second inter-trial interval. Each run ended with a 6-second buffer period to ensure completion of the hemodynamic response in the time course (Figure 1).

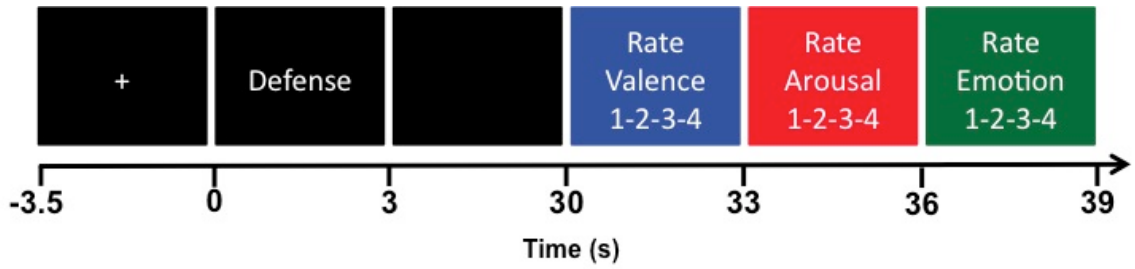


Figure 1. Illustration of an AM retrieval trial. Upon receiving the pre-designated personal cue, participants were instructed to retrieve a previously rehearsed memory for 30 seconds. The cue disappeared after being presented for the first 3 seconds of the trial.

The first 8 seconds (0-8 s) of the trial is considered the early-access period, the second 8 seconds (8-16 s) of the trial is considered the late 1-elaboration period, the third 8 seconds (16-24 s) of the trial is considered the late 2-elaboration period, and the forth 8 seconds (24-32 s) of the trial is considered the late 3-elaboration period. The font was white (cue font size = 54) on a black background. Valence, arousal, and emotional typicality ratings screens were presented on blue, red, and green backgrounds, respectively (font size = 54).

MRI acquisition parameters

Anatomical and functional whole-brain imaging data were obtained using a Siemens 3T Trio MRI scanner. High resolution structural scans were acquired using a gradient 256 x 256 matrix, 1 x 1 x 1 mm voxel size. For functional imaging, 40 3mm-thick axial slices were acquired approximately parallel to the anterior-posterior commissures in order to capture cortical and subcortical regions involved in AM processing. Functional scans were acquired using T2*-weighted gradient-echo sequences (TR = 2160ms, TE = 30ms, 64 x 64 matrix, 3 x 3 x 3mm voxel size). Head movement was limited by placing foam padding and medical tape places across the participant's forehead.

Data analysis

Data were preprocessed using Statistical Parametric Mapping software (SPM8, Wellcome Department of Cognitive Neurology; Penny, Friston, Ashburner, Kiebel, & Nichols, 2011), run in MATLAB2013a. After differences in slice acquisition time were corrected (slice-timing correction) to middle slice in time, all functional data sets were realigned to the first image in the scanning session. Motion was further examined and

corrected with Art Repair (Mazaika, Hoeft, Glover, & Reiss, 2009; Mazaika, Whitfield-Gabrieli, Reiss, & Glover, 2007). An 'artifact' threshold is defined by Art Repair as any scanning volume in which the tool box detects a large, non-physiological global signal change between consecutive scans. An interpolation algorithm was applied across all volumes identified with superthreshold movement related changes in the global signal. Normalization parameters were derived from segmenting each participant's T1-weighted anatomical brain image into white matter, gray matter, and CSF. These normalization parameters were then applied to the respective participant's EPI images (Crinion et al., 2007) to normalize all of the images into MNI space. Upon normalization all functional images were smoothed at 6x6x6 FWHM. Band pass temporal filtering from 0.01 Hz to 0.08 or 0.1 Hz was not applied to the data as is commonly performed in resting state connectivity analyses because we expect there to be task-relevant brain activity that could last longer for 10 seconds and the time windows were time locked to the presentation of the cue word. Thus, if a 0.1 Hz filter was applied during processing then any task relevant brain activity would be potentially removed from the data.

Cross-correlation analysis

ROI identification. Regions-of-interest (ROIs) were derived from the coordinates of regions identified in the Svoboda et al. (2006) and Daselaar et al. (2008) studies as core regions in AM retrieval processes (Table 1). A 10 mm spherical ROIs was grown around the specific derived coordinates using the SPM toolbox MarsBar (Brett et al., 2002) for all neocortical ROIs. A 10 mm sphere was chosen with the intent of ROIs of similar volumes that capture the mean signal from each ROI. In addition, this size of ROI is typical for measuring the mean signal time course in neocortical ROIs due to the fact that

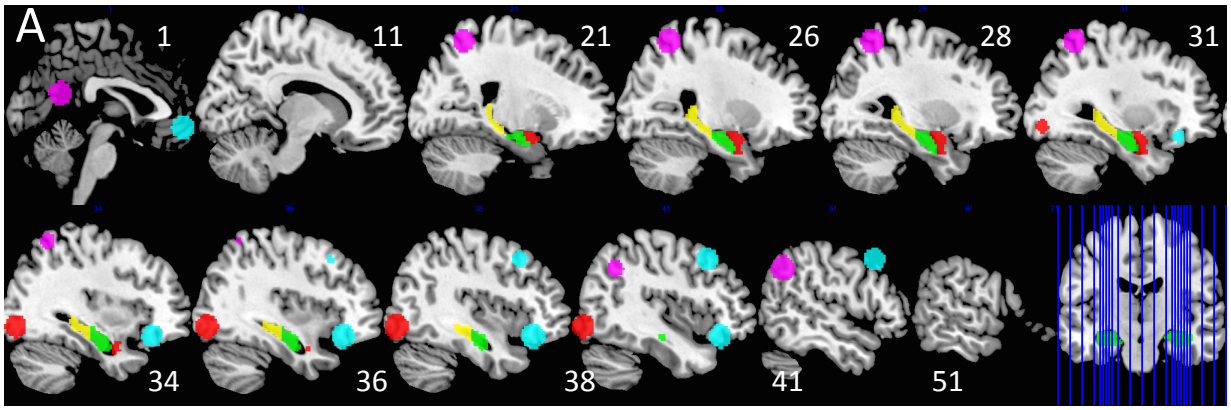
their functionality is more diffuse and encompasses a broader cortical area than subcortical ROIs (Inman et al., 2012; James et al., 2009). Medial temporal lobe ROIs were created using the Automatic Anatomic Labeling (AAL) system ROIs in WFU Pick Atlas toolbox for SPM ((Maldjian et al., 2003; Tzourio-Mazoyer et al., 2002). Specifically, the amygdala ROI was defined directly from the AAL amygdala mask. The left and right hippocampal ROIs were also derived from the AAL left and right hippocampal ROI mask. Each hippocampus was further parcellated into an anterior and posterior portion. The anterior and posterior hippocampus in either hemisphere was parcellated at the uncal apex of a standard automatic anatomical labeling (AAL) hippocampal mask derived in the WFU Pick Atlas. The whole hippocampal ROI masks were divided using the image manipulation program MRIcron (Rorden, 2007). When co-registered with a standard T1 (Colin brain), this division point was at MNI y-coordinate of -21 mm from the origin. This coordinate corresponds to the typical distinction of the anterior and posterior hippocampus in templates or atlas ROIs used in other studies of long-axis specialization of the human hippocampus (Poppenk et al., 2013; Poppenk & Moscovitch, 2011). The exact core network ROIs are displayed in slice orientation in Figure 2 below.

Table 1

Region of Interest (ROI) hemisphere, label, and MNI coordinate

Region of Interest	Hemisphere	ROI Label	X	Y	Z
Dorsolateral Prefrontal Cortex	Left	LDLPFC	-41	18	39
Ventrolateral Prefrontal Cortex	Left	LVLPFC	-38	30	-16
Medial Prefrontal Cortex	Medial	mPFC	0	45	-10
Dorsolateral Prefrontal Cortex	Right	RDLPFC	42	17	39
Ventrolateral Prefrontal Cortex	Right	RVLPFC	39	31	-15
Amygdala	Left	LAmyg	-24	-1	-17
Anterior Hippocampus	Left	LAntHipp	-26	-13	-17

Posterior Hippocampus	Left	LPostHipp	-26	-33	-3
Amygdala	Right	RAmyg	26	1	-18
Anterior Hippocampus	Right	RAntHipp	29	-13	-17
Posterior Hippocampus	Right	RPostHipp	26	-33	-3
Intraparietal Lobule	Left	LIPL	-26	-58	59
Temporoparietal Junction	Left	LTPJ	-49	-57	38
Posterior Cingulate Cortex	Medial	PCC	0	-57	19
Intraparietal Lobule	Right	RIPL	27	-58	59
Temporoparietal Junction	Right	RTPJ	49	-57	38
Occipital Cortex	Left	LOCC	-38	-84	-9
Occipital Cortex	Right	ROCC	39	-84	-8



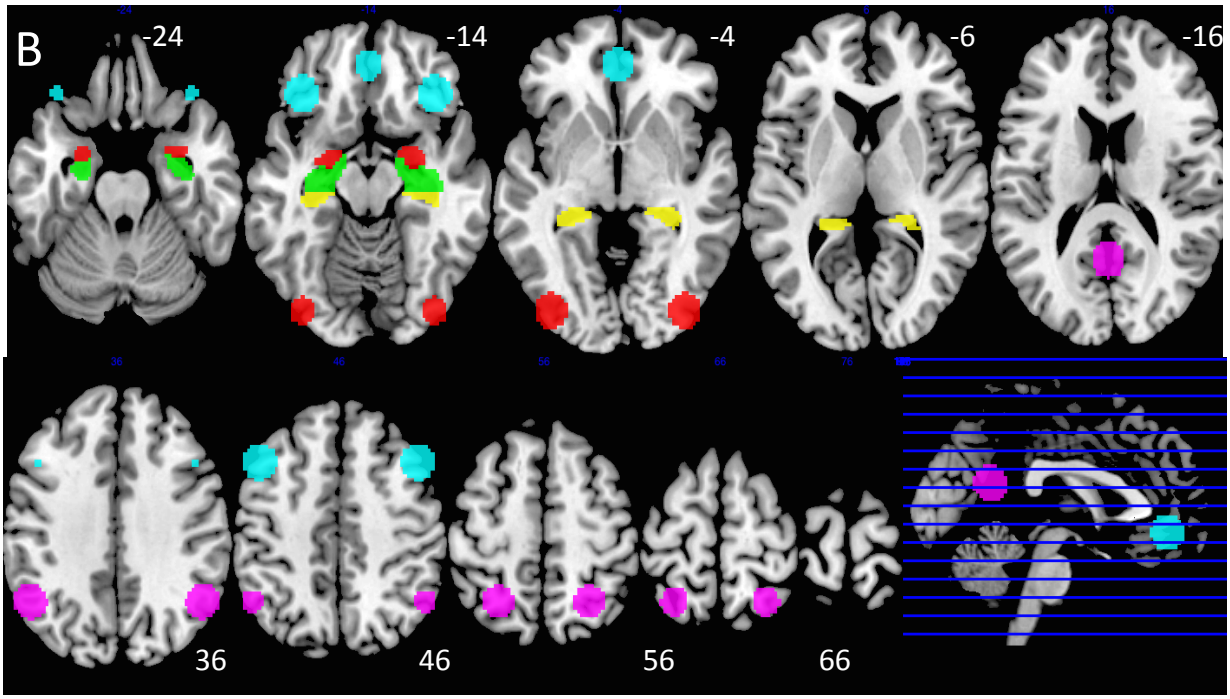


Figure 2. Illustrations of core network ROIs. A) Sagittal representation of core network ROIs overlaid on the canonical MNI brain. B) Axial representation of the core network ROIs overlaid on the canonical MNI brain. Cyan denotes frontal lobe ROIs. Red ROIs in the MTL denotes the amygdala ROIs. Green MTL ROIs denotes anterior hippocampus ROI. Yellow MTL ROIs denote posterior hippocampus ROIs. Purple denotes parietal lobe ROIs. Red occipital ROIs denote occipital lobe ROIs. Slice renderings were created in MRIcron (Rorden, 2007).

Time course extraction from core network ROIs. Time courses from all core AM retrieval network ROIs were extracted using the MarsBar SPM toolbox. The raw mean time course was extracted for each ROI from each participant's AM retrieval fMRI data. To account for arbitrary differences in the baseline raw signal of the scanner, each participant's time course values underwent a z-score transformation to normalize the data across participants.

Time window specification. The AM retrieval fMRI data time courses were segmented into ten, equal-width time windows across each 42.5-second retrieval and inter-stimulus interval (ITI) cycle. Each time window was time-locked to the memory cue onset for each trial. Time windows were specified to maximize the number of time windows within each AM retrieval trial while capturing most of hemodynamic response function (12 seconds) and allowing for resolution of the underlying dynamics in cognitive processing. Based on many previous studies of AM retrieval for rehearsed and unrehearsed memory cues (Addis et al., 2011, 2004; Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; Greenberg et al., 2005; Muscatell et al., 2010; St. Jacques et al., 2011; Velanova et al., 2003), we assumed the initial, access-related processing to unfold over the first 8 seconds on average after which elaboration-related processing would begin to predominate. Although participants were only asked to press a button once they began to feel the target emotion for each cued memory in this experiment, this button can be used as a proxy for when the memory had been accessed if we assume that emotion would not have begun to be experienced until the specific memory was retrieved. Given this assumption, on average participants made this button press around 6.28 seconds after the onset of the cue, which is similar to the timing of memory access in previous studies of AM retrieval processes. The distinction of these processing periods as the first 8 seconds and following 8 seconds is certainly a course distinction, however, our overall goal was to characterize consistent patterns of connectivity within these early and late processing periods and directly contrast these time periods to uncover hypothesized differences in connectivity patterns between the processing windows. To address all of these criteria as best we could, each of the 10 time windows was defined as 8.64 seconds wide (4 TR). Each time

window overlapped the preceding and succeeding time windows by 4.32 seconds (2 TR). Time windows overlapped one another by 4.32 seconds (2 TR) were created to maximize and smooth the resolution of changes over time. All statistical tests were performed on non-overlapping time windows. All time windows were lagged by a factor of 4.32 seconds (2 TR) to account for lag in the hemodynamic response. All statistical comparisons for this study were performed between the 0-8 second (early), 8-16 second (late 1), and 16-24 second (late 2) time windows after having accounted for the hemodynamic response lag.

Cross-correlation matrix construction. After segmenting the time courses in to the respective time windows, bivariate correlation matrixes of the connection strength between each ROI pair (153 total) were calculated for each participant. Specifically, for each participant by time course matrix was constructed by computing the bivariate correlation between each ROI time course and all of the other 17 ROI time courses within each time window. Each correlation in each time window matrix was transformed with the Fisher's Z transformation to allow for averaging of correlation values across participants. A connection was considered to be dynamic if there was a significant (bootstrap corrected $p<0.05$, two-tailed paired *t*-test) pairwise difference between the coherence of 2 ROIs in the contrasting two time windows (e.g. early versus late). Stable connections were defined as those regions with a correlation of $|r|>0.3$ across the whole retrieval period and were not significantly stronger in the early or later time window.

Statistical approach. Paired t-test with bootstrapping were utilized to test differences in connection strength for each pairwise correlation in the early time window relative to the late time window and visa versa (Watrous et al., 2013). To account for multiple

comparison issues, each t-test underwent a bootstrapping procedure with 1000 re-sampled (with replacement) permutations of the sampling distribution. This procedure maintained a fixed type 1 error rate of 5% given an $\alpha = 0.05$. *T*-statistics and Cohen's d estimates of effect size are depicted in tables for each primary *t*-contrast that showed a significant change between time windows.

Network visualization. Network visualization was performed with the BrainNet Viewer toolbox in Matlab (Xia et al., 2013). All BrainNet figures were created with the same 18-node, AM core network configuration (Figure 3a and b). Connections or edges in BrainNet figures were constructed in two different manners depending on the connection information that best described the topological effect of interest. For stable networks, the thickness and color of connections in the BrainNet figures were displayed according to the mean Fisher's Z throughout the entire AM retrieval period (i.e., all time windows). For dynamic networks (i.e., early > late or late > early), the thickness and color of connections in the BrainNet figures were displayed according to the mean change in Fisher's Z from comparison of the two time windows. Core network connection matrixes for each of the BrainNet figures were also created using the BrainNet viewer. The color scale in each matrix corresponds to either the mean Fisher's Z for particular ROI-to-ROI connections in the case of stable networks and the mean change in Fisher's Z for particular ROI-to-ROI connections in the case of dynamic networks. In addition to the BrainNet topological representation of changes in functional connectivity, dynamic and stable connectivity patterns were also visualized with the Social Network Image Animator (SONiA; Bender-deMoll & McFarland, 2006). Network visualizations in the SONiA format are displayed in a spring-loaded format using the

Kamada-Kawai graph energy algorithm (Kamada & Kawai, 1989). The Kamada-Kawai "spring-embedding" algorithm treats each connection between two nodes as a "spring" (i.e., line) of a specific length that corresponds to the connection strength of the two nodes. This creates a virtual dynamic system that contains "energy" in the form of the connection strengths of all connections in the network. In the SONiA program, the Kamada-Kawai algorithm finds the optimal layout of the nodes relative to one another by determining the state in which the total spring energy of the system is minimal. The Kamada-Kawai visualization technique allows for clear visualization of modules or clustered nodes in the network and when animated allow for a dynamic representation of changes in network connectivity over time.

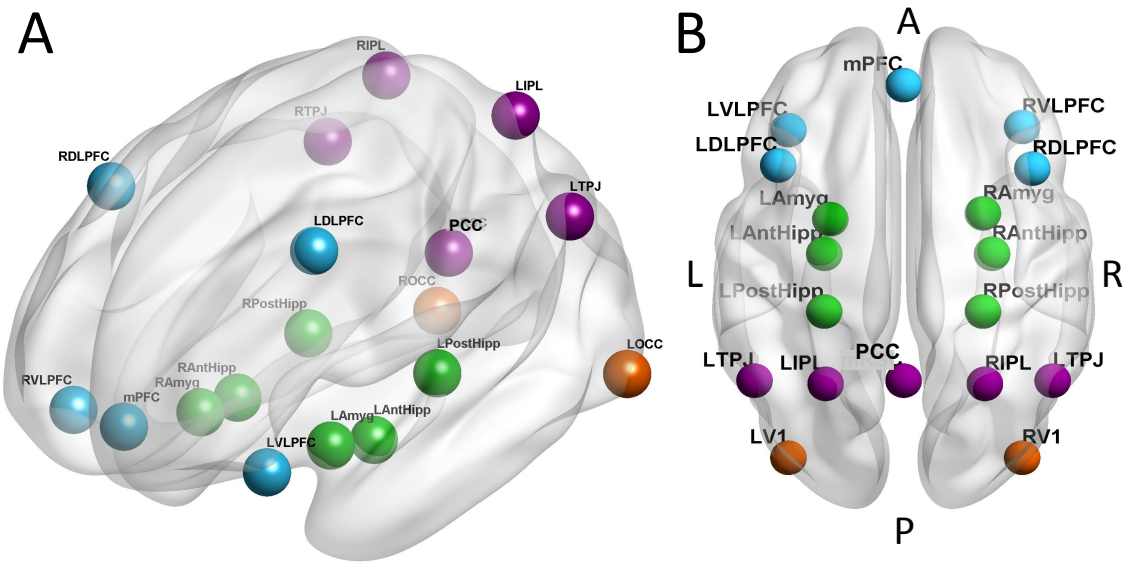


Figure 3. A) Illustration of core network ROIs from dorsal sagittal perspective. B) Illustration of core network ROIs from a ventral axial perspective. Nodes are displayed in MNI space co-registered with a smoothed and transparent representation of the ICBM152 brain surface template. Node color denotes the lobe membership of each ROI. Cyan nodes denote frontal lobe ROIs. Green nodes denote medial temporal lobe ROIs. Purple

nodes denote parietal lobe ROIs. Orange nodes denote occipital lobe ROIs. A = Anterior, P = Posterior, L = Left, R = Right.

Whole brain graph theory analysis

Whole-brain ROI parcellation. A whole-brain fMRI atlas generated with spatially constrained spectral clustering of resting state fMRI functional connectivity data from a large cohort was used to parcellate each participant's fMRI data into 200 distinct ROIs (Craddock et al., 2012). This particular whole-brain atlas was selected, as opposed to an anatomically or cyto-architectonically defined atlas (i.e., AAL, Broadman's areas, etc.), because it consists of ROIs with anatomic homology, takes into account common resting state functional networks, and the volume of all 200 ROIs are normally distributed. The closest ROI by center of gravity coordinate from the 200-region parcellation to the center of gravity for the core network region was taken as a homologous core network region. In general, the coordinates for the core network regions were within 10 mm in any x, y, or z direction of the coordinates for the homologous parcellation ROI and significantly overlapped the defined core network ROI.

Time course extraction. A time course of eigenvalues calculated via singular value decomposition (SVD; i.e., principal component) was extracted each ROI in AFNI (Cox, 1996). This measure is very similar to the mean time course approach used in the core network cross-correlation analyses, but better estimates the signal by differentially weighting the voxels in the ROI that contributed most to the ROI's signal. Each participant's time course values underwent a z-score transformation to normalize the data across participants.

Time window specification. All time windows were specified with the same approach as described for the cross-correlation analysis with the time courses being 5 time-locked, 8-second time windows and were lagged by 4 seconds to account for hemodynamic lag. Time windows of interest for statistical comparison consisted of the 0-8 second (early), 8-16 second (late 1), and 16-24 second (late 2) time windows.

Graph metric processing and calculation. Graph theory is a branch of mathematics in which mathematical structures (graphs) are used to model pairwise relations (i.e., edges or connections) between objects (i.e., nodes or in the case of fMRI ROIs; Bullmore & Sporns, 2009; Power et al., 2011; Rubinov & Sporns, 2010; Wig et al., 2011). Graphs are networks composed of a pre-determined set of functional regions involved in a task or a functional parcellation of regions throughout the whole brain. In particular, graphs are abstract representations of the components in a network that are useful in visualizing important topological properties of a networks organization and structure (Bullmore & Sporns, 2009; Wig et al., 2011).

Although graphs are useful for visualizing properties of a networks structure, the matrix of a network's connections, known as an adjacency matrix, is the primary computational unit for analysis of graph properties or metrics. Graph metrics are used to help determine simple organizational features of the complex network architecture and include many objective measures node-based and network-based properties. In functional connectivity analyses, two types of adjacency matrixes can be derived from pairwise relations between a set of nodes: binary and weighted. Binary matrixes are created by applying a threshold to a correlation matrix and defining any correlations that exceed that threshold as connected during a particular time window. A value of 1 is assigned to any

correlation or edge that exceeds the threshold and a value of 0 is assigned to any correlation or edge that does not exceed the threshold. A weighted adjacency matrix maintains the correlation strength or weight of each connection rather than defining each connection as a 1 or 0. Weighted adjacency matrixes are useful for computing certain graph metrics, like node strength, but most functional connectivity graph metrics, like degree centrality, are calculated using a binary matrix (Rubinov & Sporns, 2010; Sporns et al., 2004). In the present study, weighted adjacency matrixes were used to calculate the average connection strength for each node (i.e., node strength) and binary adjacency matrixes were used to calculate the number of connections between each node and the rest of the network (i.e., node degree centrality).

Graph metrics. Two basic, commonly used graph metrics were utilized in this study to characterize the topological properties of the core AM retrieval regions in the context of the whole brain. These metrics include measures of average node strength and node centrality (e.g. degree) in the whole-brain network. Node strength is simply calculated as the average correlation strength a node has with all of its connected nodes. Node strength was the only weighted measure in this graph theory analysis, and this analysis was performed for each participant before any binary matrixes were created. The node degree centrality metric was calculated from a binarized adjacency matrix.

Metrics of functional centrality in a brain network identify the brain regions that most frequently interact with many other brain regions. Brain regions with high centrality facilitate functional integration and are therefore locations where the network is most vulnerable to disruption from damage (Rubinov & Sporns, 2010; Sporns, 2013). Common centrality measures that are derived in almost every graph theory analysis are

based on the idea that brain regions with a larger number of short paths within a network act as important for information flow throughout the network (Sporns, Chivalo, Kaiser, & Hilgetag, 2004). Degree centrality is the one of the most common and basic graph theory measures for individual nodes in a network. For a given node, its degree centrality is measured by summing the number of other nodes to which it is connected. Nodes with larger degree values indicate greater importance of that node in the network. For example, in the context of AM retrieval, nodes with higher centrality are thought to be more central to integrating distributed information from the rest of the network. In analyses of brain network dynamics during a task, these graph metrics of a region's centrality allow for a characterization of the regions importance during a particular period in the AM retrieval processes. The present study utilized the node degree graph metric as a measure of centrality for each of the 18 core network ROIs within a 200 region whole brain network to examine the extent to which the core AM regions become more or less central to integrating distributed information during each time period of AM retrieval. This whole brain centrality approach was taken because examining each core network ROI's network connectivity in the whole brain is a more comprehensive and complete description of each ROI's role in neural information processing throughout the whole brain network during AM retrieval than only examining each core network ROI's centrality in the 18 node core network.

An important consideration regarding the binarization procedure is that there is no generally agreed on method for determining single threshold to use for binarization, and thus the use of a single threshold would necessarily be arbitrary. Therefore, centrality graph metrics were computed with a multi-level thresholding approach to alleviate

concerns of selecting arbitrary thresholds to create each participants binarized adjacency matrix (Bassett et al., 2008; Lynall et al., 2010). To briefly summarize this procedure, the first step involves accounting for inter-subject variability in average correlation values. Across individuals there is substantial variability in the extent to which regions throughout the brain are correlated. In other words, binarization of a correlation matrix by an arbitrary value (i.e., $|r|>0.4$), some subjects would have every correlation survive while others would have an empty matrix. Thus, instead of taking an arbitrary correlation (r) threshold it is useful to take a certain top percentage of correlation strengths. A widely used and recommended method for selecting a density threshold to define the binary adjacency matrixes is to calculate the matrices across multiple top percentage thresholds and take the mean for each graph metric across all of the thresholded matrixes (Bassett et al., 2008; Lynall et al., 2010). To describe this method in greater detail, a correlation matrix for all 200 ROIs was first created for each participant for a particular time window. Next, this subject-level correlation matrix was transformed into a binarized adjacency matrix at a range of thresholds for the top 37% of correlations in the full matrix to the top 50% with a stepwise interval of 1% (14 adjacency matrixes total). Degree centrality was calculated for every node in each of the thresholded binary adjacency matrixes. Finally, the average graph metric was calculated for each node across all 14 of the thresholded binary adjacency matrixes from 37% to 50% for that participant. These values were compiled in a participant-by-participant database for each graph metric by ROI.

One benefit of examining the degree centrality of each ROI in the whole brain network is that it allowed exploration of the regions throughout the brain that changed the

most in degree centrality from the early to late processing periods. To assess which brain changed the most in degree centrality from the early to late processing periods, an exploratory rank analysis was performed on the extent of change in degree centrality between each time window. This analysis will help guide selection of network nodes and modeling network connectivity in future analyses by examining the regions in the whole brain network with the most change in degree centrality from one time window to the next. Furthermore, this descriptive analysis allows for a characterization of which and how many core AM regions were among the top regions throughout the brain in the extent of change in mean degree centrality. Specifically, the mean change in degree centrality was calculated by contrasting the early time window with the later time windows. Then, for each time window, the ROIs were sorted by the mean change in degree, from regions that had the largest change in degree to regions that had the smallest change in degree. Finally, we evaluated which of the core AM retrieval network ROIs were among the top 20% of all regions for most positive change in mean degree centrality for each contrast of interest (i.e., early vs. late 1, late 1 vs. early, late 2 vs. early, late 3 vs. early).

Statistical approach. Paired *t*-tests with bootstrapping were utilized to test differences in graph metric for each pairwise correlation in the early time window relative to the late time window and visa versa (Watrous et al., 2013). To account for potential inflation of the false positive rate due to multiple comparisons, each t-test involved a bootstrapping procedure with 1000 re-sampled (with replacement) permutations of the sampling distribution. This procedure also maintains a fixed type 1 error rate of 5% given an $\alpha =$

0.05. *T*-statistics and Cohen's d estimates of effect size are depicted in tables for each primary *t*-contrast that showed a significant change between time windows.

Results

Cross-correlation strength analysis

Evaluation of network connectivity during AM retrieval revealed that all core AM retrieval regions (see Figure 2 for depiction of core network in the brain) were at least moderately connected to one another ($r > 0.3$). Consistent with our prediction that regions within the core network would be strongly connected with one another, all of the region-to-region connections maintained a strong correlation with one another during all time periods of AM retrieval. Stable connections were defined as those connections that were strong throughout every AM retrieval period and did not significantly change in connection strength based on bootstrapped paired t-tests between all of the contrasts of interest. The contrasts of interest for this study were for ROI-to-ROI connections that were stronger early > late 1, late 1 > early, late 2 > early, and late 3 > early. Dynamic connections were defined as those that were at least moderately strong ($r > 0.3$) throughout retrieval and significantly changed in connection strength based on paired t-tests between all contrasts of interest. Although many of the paths were stable throughout all hypothesized AM retrieval processes (30%), most of the paths dynamically changed in their connection strength throughout retrieval. A topological representation and matrix representation of the stable network is illustrated in Figure 4.

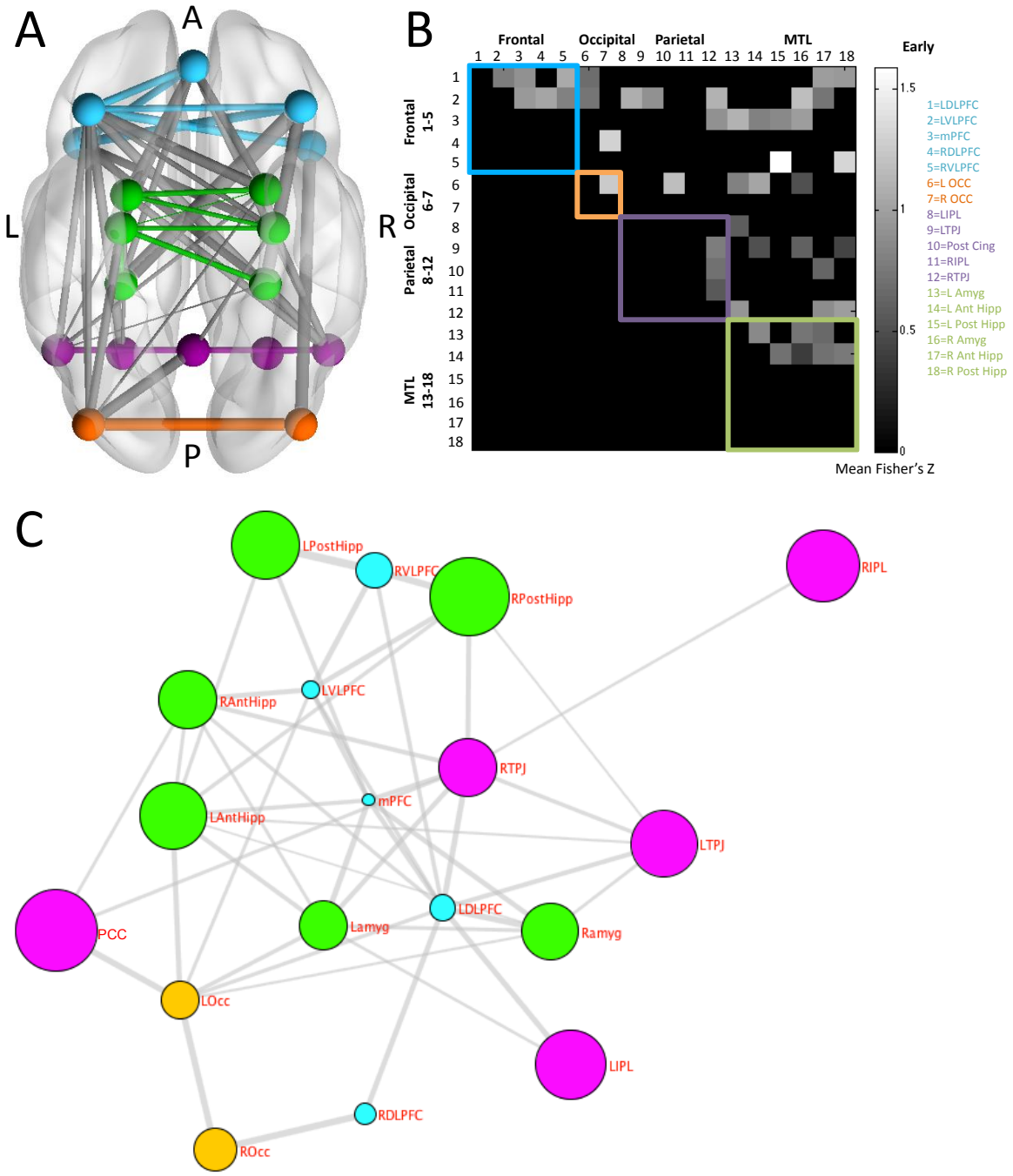


Figure 4. Stable network during AM retrieval. A) Topological representation of all connections that were at least moderately connected to one another (i.e., $r > 0.3$) and did not change during AM retrieval. Connections within the same lobe are color coded with cyan for frontal regions, green for MTL regions, purple for parietal regions, and orange for occipital regions. Thickness of the connection denotes the relative mean Fisher's Z. A

= Anterior, P = Posterior, L = Left, R = Right. B) Matrix representation of stable connections. Gray color bar denotes mean Fisher's Z for each connection. Although the matrix is symmetric, only the upper triangle is displayed for ease of interpretability. Colored boxes encompass regions within each lobe with cyan for frontal regions, green for MTL regions, purple for parietal regions and orange for occipital regions. C) Spring loaded representation of stable network. Distance between nodes denotes an optimal configuration based on the strength of each connection between particular nodes (i.e., nodes that are more strongly connected are closer in space). Size of node denotes the relative average degree of each node across the entire retrieval period in the whole brain network (200 ROIs). Node colors represent lobe membership and are consistent with the color codes in A and B of this figure. Note that nodes from the same lobe cluster together with one another. Also note that the node degree of the PCC and MTL nodes are largest relative to other nodes in the network.

Dynamic network connectivity: Early versus Late 1. To assess the hypothesis that anterior connections (i.e., involving the frontal and temporal lobes) would be stronger during early, access-related processing than late-elaboration processing periods, bootstrapped paired t-tests were performed for every connection, contrasting connection strength (mean Fisher's Z) for the early (0-8 s) versus late 1 (8-16 s) time periods. This contrast revealed specific region-to-region connections that were significantly stronger in the early versus late time period, potentially reflecting initial strategic memory search processes and initial reconstruction of memory context and details. Consistent with our prediction that regions involved in memory access processes (strategic memory search; VLPFC) would be more strongly connected early relative to late in retrieval, network

connectivity that was stronger early than late primarily consisted of connections between the lateral prefrontal cortex, medial temporal lobe, and parietal cortex (Table 2). Consistent with our specific predictions that the VLPFC and anterior hippocampus are involved in strategic memory search and rebinding processes (Daselaar et al., 2008; Rugg & Vilberg, 2012; Velanova et al., 2003; Wagner, 1998; Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Tulving, 2002), connections between the right VLPFC and left anterior hippocampus were stronger early versus later in retrieval (Figure 5). Also consistent with the prediction that the VLPFC implements top-down control signals to bias processing in posterior cortical regions like the parietal and late visual cortex, relative to the late period, the early-access period of AM retrieval exhibited stronger connections between the right VLPFC and the bilateral parietal and occipital regions of the core AM retrieval network. Consistent with the PCC's known structural connections to the hippocampus and role in generating a coherent mental scene (i.e., scene construction), the early period was also characterized by stronger connections between the PCC and the left anterior and posterior hippocampus relative to the late period. However, inconsistent with our predictions that the posterior hippocampus and parietal regions would be primarily more strongly connected to regions throughout the network later in retrieval, several connections were stronger between the posterior hippocampus, frontal, and parietal regions during the early period relative to the late period of retrieval.

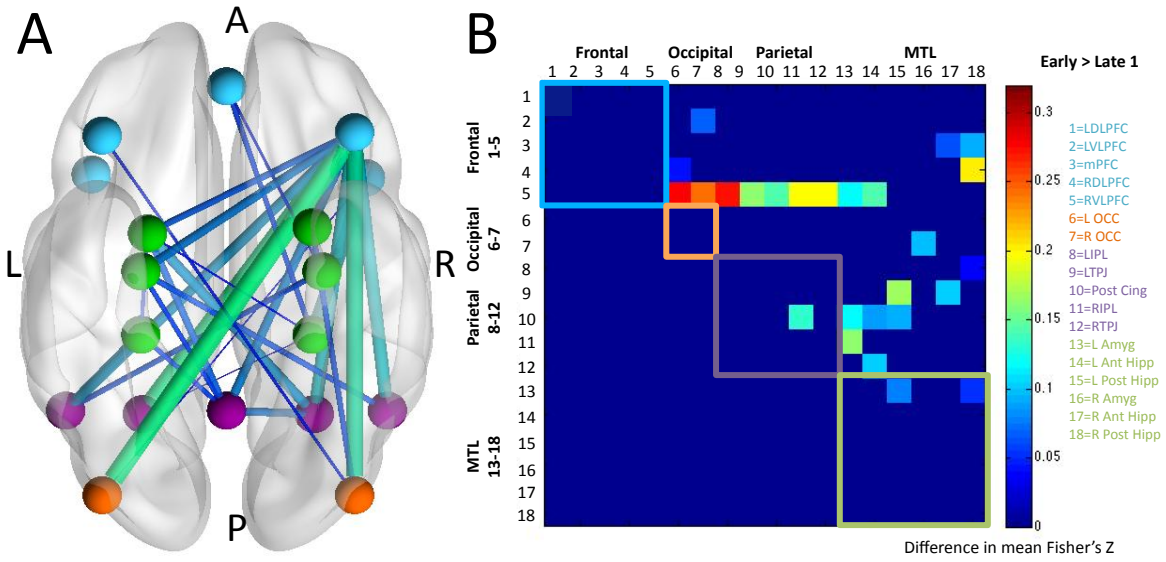


Figure 5. Stronger connections early versus late 1 in AM retrieval. A) Topological representation of connections that were more strongly connected to one another during the early period relative to the late 1 period of AM retrieval. Thickness of the connection denotes the relative mean difference in Fisher's Z between the early and late 1 time periods. A = Anterior, P = Posterior, L = Left, R = Right. B) Matrix representation of connections that were more strongly connected to one another during the early period relative to the late period of AM retrieval. Although the matrix is symmetric, only the upper triangle is displayed for ease of interpretability. The color of each connection point in the matrix denotes the difference in mean Fisher's Z. Colored boxes encompass regions within each lobe with cyan for frontal regions, green for MTL regions, purple for parietal regions and orange for occipital regions.

Table 2

Connections with stronger connectivity during the early versus late 1 period.

Connection			Mean			
ROI 1	ROI 2	Contrast	Difference	*t*-score	*p*-value	Cohen's D
lVLPFC	rVisCor	Early > Late 1	0.07	2.30	0.048	0.10
mPFC	rAntHipp	Early > Late 1	0.06	3.20	0.029	0.18
mPFC	rPostHipp	Early > Late 1	0.09	2.54	0.029	0.19
rDLPFC	lVisCor	Early > Late 1	0.04	3.27	0.010	0.09
rDLPFC	rPostHipp	Early > Late 1	0.20	4.16	0.002	0.30
rVLPFC	lVisCor	Early > Late 1	0.28	5.75	0.001	0.92
rVLPFC	rVisCor	Early > Late 1	0.24	9.74	0.001	1.11
rVLPFC	lIPL	Early > Late 1	0.27	9.22	0.001	1.00
rVLPFC	lPrec	Early > Late 1	0.16	5.12	0.002	0.62
rVLPFC	PCC	Early > Late 1	0.14	6.42	0.002	0.65
rVLPFC	rIPL	Early > Late 1	0.20	7.39	0.001	0.51
rVLPFC	rPrec	Early > Late 1	0.20	6.45	0.001	0.70
rVLPFC	lAmyg	Early > Late 1	0.12	4.49	0.013	0.32
rVLPFC	lAntHipp	Early > Late 1	0.14	5.29	0.001	0.31
rVisCor	rAmyg	Early > Late 1	0.10	2.61	0.027	0.20
lIPL	rPostHipp	Early > Late 1	0.04	2.47	0.034	0.10
lPrec	lPostHipp	Early > Late 1	0.17	4.93	0.002	0.60
lPrec	rAntHipp	Early > Late 1	0.10	2.28	0.040	0.27
PCC	rIPL	Early > Late 1	0.13	2.78	0.017	0.49
PCC	lAmyg	Early > Late 1	0.12	2.91	0.022	0.33
PCC	lAntHipp	Early > Late 1	0.09	2.35	0.045	0.42
PCC	lPostHipp	Early > Late 1	0.09	2.95	0.019	0.21
rIPL	lAmyg	Early > Late 1	0.16	4.60	0.002	0.49
rPrec	lAntHipp	Early > Late 1	0.10	2.63	0.026	0.50
lAmyg	lPostHipp	Early > Late 1	0.08	2.97	0.015	0.23
lAmyg	rPostHipp	Early > Late 1	0.05	2.79	0.018	0.31

Dynamic network connectivity: Late 1 versus Early. To assess the hypothesis that posterior connections (i.e., parietal and occipital) would be stronger during late, elaboration-related process than the early processing period, bootstrapped paired t-tests were performed for every connection, contrasting the late 1 (8-16 s) versus early (0-8 s) time period. These contrasts revealed specific region-to-region connections that were

significantly stronger in the late 1 versus the early time period, potentially reflecting initial memory elaboration processes like visual imagery and maintenance of retrieved mnemonic details. Consistent with our predictions that posterior regions typically engaged in memory maintenance and elaboration processes would be more strongly connected to one another later relative to earlier in retrieval, network connectivity that was stronger in the late 1 time period than early time period primarily consisted of connections connections between posterior regions (in the parietal and occipital lobe) and other regions in the frontal and parietal lobes (Table 3). In particular, relative to the early period, the late-elaboration period of AM retrieval exhibited a larger number of connections between the all of the parietal regions and the bilateral occipital regions. In addition, connections between the right DLPFC and all parietal regions were stronger during the late 1 versus early periods of AM retrieval (Figure 6). Consistent with previous evidence that the left lateral PFC is engaged during elaboration processes, the left VLPFC was also more strongly connected to all parietal ROIs during the late 1 time period relative to the early time period. In addition to these primarily posterior connections, connections were also stronger during the late 1 time period relative to the early time period within the MTL, including the left and right anterior hippocampus.

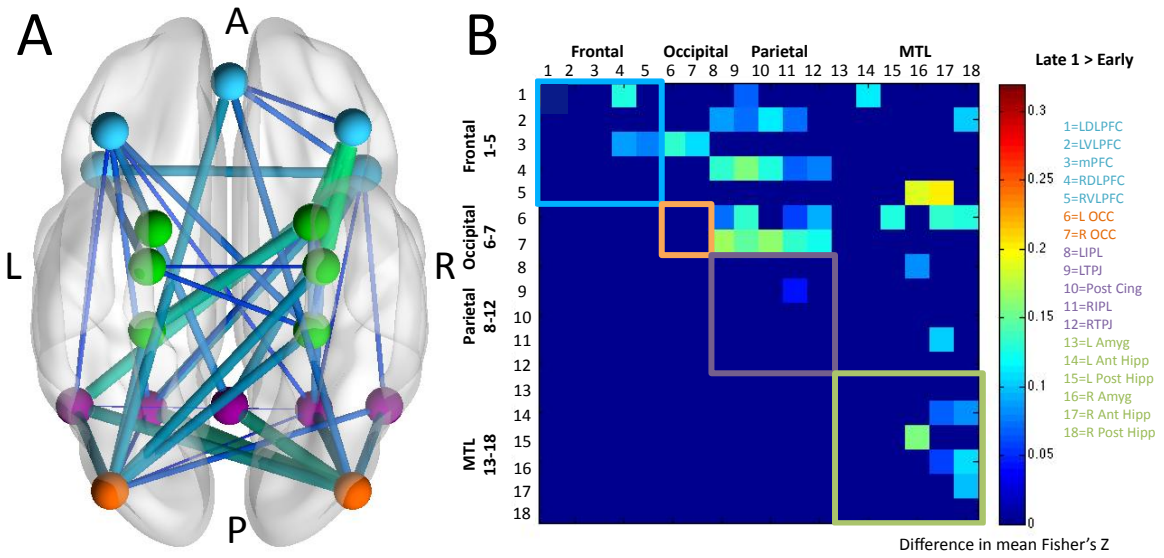


Figure 6. Stronger connections late 1 versus early in AM retrieval. A) Topological representation of connections that were more strongly connected to one another during the late period relative to the early period of AM retrieval. Thickness of the connection denotes the relative mean difference in Fisher's Z between the late 1 and early time periods. B) Matrix representation of connections that were more strongly connected to one another during the late 1 period relative to the early period of AM retrieval. Although the matrix is symmetric, only the upper triangle is displayed for ease of interpretability. The color of each connection point in the matrix denotes the mean difference in Fisher's Z. Colored boxes encompass regions within each lobe with cyan for frontal regions, green for MTL regions, purple for parietal regions and orange for occipital regions.

Table 3

Connections with stronger connectivity during the late 1 versus early period.

Connection			Mean			
ROI 1	ROI 2	Contrast	Difference	*t*-score	*p*-value	Cohen's D
lDLPFC	rDLPFC	Late 1 > Early	0.13	4.14	0.014	0.36
lDLPFC	lPrec	Late 1 > Early	0.07	2.72	0.020	0.25
lDLPFC	rPrec	Late 1 > Early	0.08	2.63	0.019	0.18
lDLPFC	lAntHipp	Late 1 > Early	0.11	5.07	0.002	0.31
lVLPFC	rPostHipp	Late 1 > Early	0.10	4.11	0.003	0.26
mPFC	rDLPFC	Late 1 > Early	0.09	2.94	0.012	0.22
mPFC	rVLPFC	Late 1 > Early	0.08	2.46	0.027	0.19
mPFC	lVisCor	Late 1 > Early	0.13	6.44	0.001	0.62
mPFC	rVisCor	Late 1 > Early	0.11	4.35	0.003	0.35
mPFC	lIPL	Late 1 > Early	0.09	4.13	0.004	0.19
mPFC	lPrec	Late 1 > Early	0.07	4.48	0.009	0.34
mPFC	PCC	Late 1 > Early	0.11	5.73	0.001	0.41
mPFC	rIPL	Late 1 > Early	0.07	2.57	0.042	0.14
rDLPFC	lIPL	Late 1 > Early	0.13	5.69	0.001	0.43
rDLPFC	lPrec	Late 1 > Early	0.16	5.26	0.003	0.53
rDLPFC	PCC	Late 1 > Early	0.13	3.79	0.010	0.40
rDLPFC	rIPL	Late 1 > Early	0.07	2.26	0.048	0.18
rVLPFC	rAmyg	Late 1 > Early	0.19	5.30	0.001	0.59
rVLPFC	rAntHipp	Late 1 > Early	0.20	3.47	0.025	0.70
lVisCor	lIPL	Late 1 > Early	0.07	3.94	0.006	0.13
lVisCor	lPrec	Late 1 > Early	0.13	3.04	0.009	0.31
lVisCor	rIPL	Late 1 > Early	0.06	2.63	0.039	0.18
lVisCor	rPrec	Late 1 > Early	0.09	2.54	0.034	0.20
lVisCor	lPostHipp	Late 1 > Early	0.13	3.01	0.015	0.40
lVisCor	rAntHipp	Late 1 > Early	0.13	4.08	0.006	0.28
lVisCor	rPostHipp	Late 1 > Early	0.13	3.23	0.010	0.28
rVisCor	lIPL	Late 1 > Early	0.17	4.56	0.001	0.29
rVisCor	lPrec	Late 1 > Early	0.15	4.68	0.003	0.25
rVisCor	PCC	Late 1 > Early	0.16	4.05	0.002	0.29
rVisCor	rIPL	Late 1 > Early	0.13	3.01	0.012	0.21
rVisCor	rPrec	Late 1 > Early	0.12	4.00	0.004	0.15
lIPL	rAmyg	Late 1 > Early	0.08	3.97	0.001	0.12
lPrec	rIPL	Late 1 > Early	0.04	3.36	0.015	0.32
rIPL	rAntHipp	Late 1 > Early	0.10	2.17	0.042	0.36
lAntHipp	rAntHipp	Late 1 > Early	0.07	2.32	0.036	0.13
lAntHipp	rPostHipp	Late 1 > Early	0.08	2.68	0.021	0.13
lPostHipp	rAmyg	Late 1 > Early	0.16	7.41	0.001	0.25
rAmyg	rAntHipp	Late 1 > Early	0.06	4.65	0.007	0.30
rAmyg	rPostHipp	Late 1 > Early	0.11	3.82	0.013	0.21
rAntHipp	rPostHipp	Late 1 > Early	0.10	3.27	0.018	0.15

Dynamic network connectivity: Late 2 versus Early. To assess the hypothesis that posterior connections (i.e., connections between parietal and occipital regions) would continue to be stronger during the elaboration-related processes in the late 2 period (relative to the early period), bootstrapped paired t-tests were performed for every connection between ROIs, contrasting the late 2 (16-24 s) versus early (0-8 s) time period. This contrast revealed specific region-to-region connections that were significantly stronger in the late 2 time period versus early time period, potentially reflecting continuing memory elaboration processes and maintenance of retrieved mnemonic details. Overall, stronger fronto-parietal connectivity persisted from the late 1 time period into the late 2 time period relative to the early time period with less occipital-parietal connections than in the late 1 versus early contrast. Specifically, 53% of the connections that were stronger in the late 1 time period relative to early were stronger in the late 2 time period relative to early. Partially consistent with our predictions, network connectivity that was stronger during the late 2 period than the early period primarily consisted of frontal cortex connections to the parietal regions, as well as, regions in the MTL (Table 4). The largest functional connectivity changes in the late 2 period relative to the early period were between the right DLPFC and all of the parietal cortices. The connection strength of the right DLPFC to all of the MTL regions also increased in the late 2 time period relative to the early time period. Finally, connections of the left and right IPL to regions in the medial temporal lobe were stronger in the late 2 time period relative to the early time period (Figure 7).

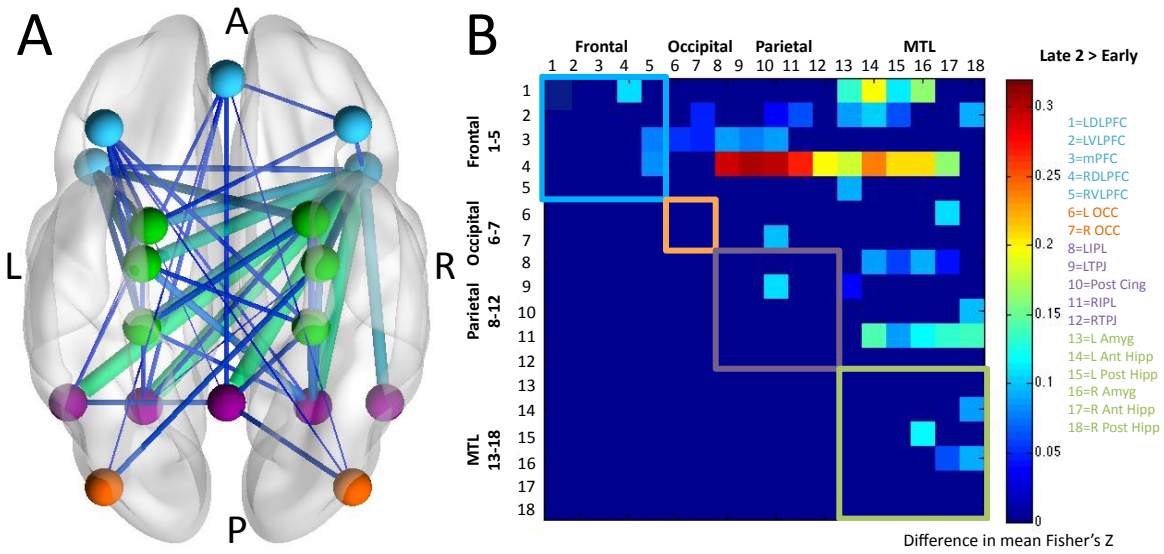


Figure 7. Stronger connections late 2 versus early in AM retrieval. A) Topological representation of connections that were more strongly connected to one another during the late 2 period relative to the early period of AM retrieval. Thickness of the connection denotes the relative mean difference in Fisher's Z between the late 2 and early time periods. A = Anterior, P = Posterior, L = Left, R = Right. B) Matrix representation of connections that were more strongly connected to one another during the late 2 period relative to the early period of AM retrieval. Although the matrix is symmetric, only the upper triangle is displayed for ease of interpretability. The color of each connection point in the matrix denotes the mean difference in Fisher's Z. Colored boxes encompass regions within each lobe with cyan for frontal regions, green for MTL regions, purple for parietal regions and orange for occipital regions.

Table 4

Connections with stronger connectivity late 2 versus early period.

Connection			Mean			
ROI 1	ROI 2	Contrast	Difference	*t*-score	*p*-value	Cohen's D
lDLPFC	rDLPFC	Late 2 > Early	0.36	2.82	0.017	0.30
lDLPFC	lAmyg	Late 2 > Early	0.32	3.71	0.003	0.42
lDLPFC	lAntHipp	Late 2 > Early	0.36	5.34	0.001	0.55
lDLPFC	lPostHipp	Late 2 > Early	0.42	3.85	0.004	0.27
lDLPFC	rAmyg	Late 2 > Early	0.44	3.43	0.012	0.36
lVLPFC	rVisCor	Late 2 > Early	0.66	2.30	0.033	0.08
lVLPFC	PCC	Late 2 > Early	0.69	2.27	0.043	0.06
lVLPFC	rIPL	Late 2 > Early	0.58	2.53	0.028	0.11
lVLPFC	lAmyg	Late 2 > Early	0.59	3.77	0.015	0.15
lVLPFC	lAntHipp	Late 2 > Early	0.61	4.44	0.002	0.17
lVLPFC	lPostHipp	Late 2 > Early	0.70	3.37	0.011	0.09
lVLPFC	rPostHipp	Late 2 > Early	0.40	5.85	0.002	0.23
mPFC	rVLPFC	Late 2 > Early	0.43	2.57	0.032	0.18
mPFC	lVisCor	Late 2 > Early	0.22	4.17	0.005	0.23
mPFC	rVisCor	Late 2 > Early	0.29	2.47	0.042	0.16
mPFC	lIPL	Late 2 > Early	0.46	3.25	0.019	0.19
mPFC	lPrec	Late 2 > Early	0.21	5.04	0.002	0.37
mPFC	PCC	Late 2 > Early	0.30	4.66	0.003	0.29
rDLPFC	rVLPFC	Late 2 > Early	0.38	2.74	0.029	0.23
rDLPFC	lIPL	Late 2 > Early	0.27	11.85	0.001	1.09
rDLPFC	lPrec	Late 2 > Early	0.29	10.19	0.001	1.06
rDLPFC	PCC	Late 2 > Early	0.29	7.76	0.001	1.02
rDLPFC	rIPL	Late 2 > Early	0.36	6.25	0.001	0.75
rDLPFC	rPrec	Late 2 > Early	0.36	4.76	0.002	0.56
rDLPFC	lAmyg	Late 2 > Early	0.25	4.76	0.003	0.74
rDLPFC	lAntHipp	Late 2 > Early	0.36	6.50	0.001	0.66
rDLPFC	lPostHipp	Late 2 > Early	0.33	5.26	0.001	0.64
rDLPFC	rAmyg	Late 2 > Early	0.38	5.25	0.001	0.54
rDLPFC	rAntHipp	Late 2 > Early	0.38	4.08	0.007	0.42
rVLPFC	rAmyg	Late 2 > Early	0.32	2.52	0.034	0.29
lVisCor	rAntHipp	Late 2 > Early	0.47	2.96	0.032	0.23
rVisCor	PCC	Late 2 > Early	0.57	2.70	0.033	0.17
lIPL	lAntHipp	Late 2 > Early	0.75	3.24	0.012	0.12
lIPL	lPostHipp	Late 2 > Early	0.76	2.80	0.011	0.07
lIPL	rAmyg	Late 2 > Early	0.71	3.14	0.016	0.13
lIPL	rAntHipp	Late 2 > Early	1.14	2.48	0.034	0.04

lPrec	PCC	Late 2 > Early	0.68	4.98	0.001	0.16
lPrec	lAmyg	Late 2 > Early	0.72	2.38	0.043	0.06
PCC	rPostHipp	Late 2 > Early	0.23	2.25	0.044	0.43
rIPL	lAntHipp	Late 2 > Early	0.09	4.25	0.006	1.48
rIPL	lPostHipp	Late 2 > Early	0.26	2.46	0.046	0.34
rIPL	rAmyg	Late 2 > Early	0.28	3.02	0.010	0.42
rIPL	rAntHipp	Late 2 > Early	0.29	2.62	0.022	0.46
rIPL	rPostHipp	Late 2 > Early	0.40	3.35	0.005	0.35
lAntHipp	rPostHipp	Late 2 > Early	0.57	2.58	0.025	0.16
lPostHipp	rAmyg	Late 2 > Early	0.64	4.40	0.001	0.19
rAmyg	rAntHipp	Late 2 > Early	0.19	3.52	0.005	0.34
rAmyg	rPostHipp	Late 2 > Early	0.51	3.84	0.007	0.18

Dynamic network connectivity: Late 3 period versus early period. To assess the hypothesis that posterior connections (i.e., between parietal and occipital regions) would continue to be stronger during late, elaboration-related process than the early processing period, bootstrapped paired t-tests were performed for every connection, contrasting the late 2 (16-24 s) versus early (0-8 s) time period. This contrast revealed specific region-to-region connections that were significantly stronger in the late 3 time period versus early time period reflecting continuing memory elaboration processes and maintenance of retrieved mnemonic details. Overall, in the late 3 time period, stronger fronto-parietal connectivity persisted from the late 1 and late 2 time periods relative to the early time period with less occipital-parietal and parietal-to-parietal connections than in the late 1 versus early contrast. Specifically, 68% of the connections that were stronger in the late 1 time period relative to early were stronger in the late 3 time period relative to early. Mostly consistent with our predictions that relative to early time periods, later time periods would be predominated connectivity patterns reflecting elaboration and memory maintenance processes, stronger connectivity during the late 3 period than early period primarily consisted of frontal cortex connections to the parietal and temporal lobes (Table

5). The strongest changes in the late 3 period relative to the early period were between the left DLPFC and all of the MTL regions. As predicted, the connection strength of the right DLPFC to all of the parietal regions also increased in the late 3 time period relative to the early time period. Finally, several connections in the medial temporal lobe were stronger in the late 3 time period relative to the early time period, including connections between the bilateral anterior hippocampus and bilateral posterior hippocampi (Figure 8).

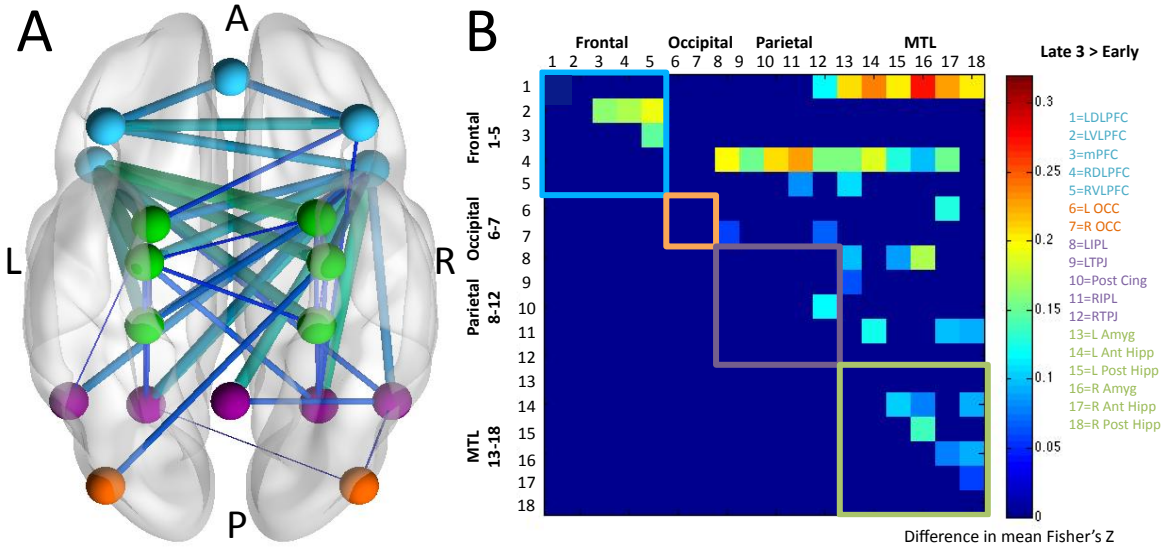


Figure 8. Stronger connections late 3 versus early in AM retrieval. A) Topological representation of connections that were more strongly connected to one another during the late 3 period relative to the early period of AM retrieval. Thickness of the connection denotes the relative mean difference in Fisher's Z between the late 3 and early time periods. A = Anterior, P = Posterior, L = Left, R = Right. B) Matrix representation of connections that were more strongly connected to one another during the late 3 period relative to the early period of AM retrieval. Although the matrix is symmetric, only the upper triangle is displayed for ease of interpretability. The color of each connection point in the matrix denotes the mean difference in Fisher's Z. Colored boxes encompass

regions within each lobe with cyan for frontal regions, green for MTL regions, purple for parietal regions and orange for occipital regions.

Table 5

Connections with stronger connectivity late 3 versus early period.

Connection			Mean			
ROI 1	ROI 2	Contrast	Difference	*t*-score	*p*-value	Cohen's D
lDLPFC	rPrec	Late 3 > Early	0.12	2.39	0.037	0.28
lDLPFC	lAmyg	Late 3 > Early	0.21	8.20	0.001	0.74
lDLPFC	lAntHipp	Late 3 > Early	0.24	12.79	0.001	0.71
lDLPFC	lPostHipp	Late 3 > Early	0.20	11.44	0.001	0.49
lDLPFC	rAmyg	Late 3 > Early	0.27	10.15	0.001	0.72
lDLPFC	rAntHipp	Late 3 > Early	0.23	5.95	0.001	0.61
lDLPFC	rPostHipp	Late 3 > Early	0.20	8.79	0.001	0.41
lVLPFC	mPFC	Late 3 > Early	0.16	4.06	0.003	0.35
lVLPFC	rDLPFC	Late 3 > Early	0.17	6.48	0.001	0.42
lVLPFC	rVLPFC	Late 3 > Early	0.19	6.12	0.003	0.36
mPFC	rVLPFC	Late 3 > Early	0.15	4.27	0.002	0.32
rDLPFC	lIPL	Late 3 > Early	0.20	7.85	0.003	0.76
rDLPFC	lPrec	Late 3 > Early	0.15	6.98	0.001	0.50
rDLPFC	PCC	Late 3 > Early	0.21	5.18	0.001	0.64
rDLPFC	rIPL	Late 3 > Early	0.23	5.72	0.003	0.59
rDLPFC	rPrec	Late 3 > Early	0.16	4.19	0.002	0.42
rDLPFC	lAmyg	Late 3 > Early	0.16	4.65	0.001	0.56
rDLPFC	lAntHipp	Late 3 > Early	0.19	5.43	0.001	0.49
rDLPFC	lPostHipp	Late 3 > Early	0.13	3.53	0.008	0.37
rDLPFC	rAmyg	Late 3 > Early	0.10	2.50	0.031	0.25
rDLPFC	rAntHipp	Late 3 > Early	0.15	3.98	0.001	0.37
rVLPFC	rIPL	Late 3 > Early	0.08	2.60	0.020	0.21
rVLPFC	lAmyg	Late 3 > Early	0.11	2.61	0.027	0.30
lVisCor	rAntHipp	Late 3 > Early	0.13	4.17	0.002	0.25
rVisCor	lIPL	Late 3 > Early	0.06	2.29	0.046	0.09
rVisCor	rPrec	Late 3 > Early	0.07	2.32	0.046	0.08
lIPL	lAmyg	Late 3 > Early	0.10	3.47	0.011	0.18
lIPL	lPostHipp	Late 3 > Early	0.09	4.73	0.002	0.12
lIPL	rAmyg	Late 3 > Early	0.17	7.40	0.003	0.24
lPrec	lAmyg	Late 3 > Early	0.06	3.26	0.009	0.08
PCC	rPrec	Late 3 > Early	0.12	3.15	0.006	0.32
rIPL	lAntHipp	Late 3 > Early	0.12	3.31	0.008	0.92
rIPL	rAntHipp	Late 3 > Early	0.10	2.57	0.040	0.33
rIPL	rPostHipp	Late 3 > Early	0.09	2.41	0.029	0.21

lAntHipp	lPostHipp	Late 3 > Early	0.10	2.95	0.013	0.34
lAntHipp	rAmyg	Late 3 > Early	0.08	2.26	0.045	0.19
lAntHipp	rPostHipp	Late 3 > Early	0.09	2.43	0.037	0.16
lPostHipp	rAmyg	Late 3 > Early	0.14	6.34	0.001	0.23
rAmyg	rAntHipp	Late 3 > Early	0.08	3.33	0.011	0.40
rAmyg	rPostHipp	Late 3 > Early	0.09	3.85	0.003	0.18
rAntHipp	rPostHipp	Late 3 > Early	0.06	2.65	0.024	0.09

Dynamic graph theory analysis

Node strength. To assess dynamic changes in the average connection strength among the nodes in the core AM retrieval network across the AM retrieval period, the node strength for each ROI in this network was calculated for each retrieval time period, and differences in ROI node strength between the early period and each of the subsequent AM retrieval periods (i.e., Late 1, Late 2, and Late 3) were compared using bootstrapped paired t-tests. In this way, contrasting the node strength during the early and late time periods for each ROI identified regions whose average connection strength to all other regions in the network became stronger from early to late, or, conversely, late to early in AM retrieval. Based on previous evidence, we predicted that the VLPFC and anterior hippocampus would have stronger connections to the rest of the network during the earliest time period relative to later periods, potentially reflecting the greater influence of access-related processing in the early period. Partially consistent with our hypotheses, the right VLPFC was the only region in the 18 node network to show stronger connectivity with the rest of the core AM retrieval network in the early time period than then late 1 time period, $t(14) = 6.15$, $p = .001$; $d = .43$, as assessed by node strength. However, contrary to our predictions, the node strength of the left anterior hippocampus did not significantly change from the early to late 1 or late 2 time periods during retrieval, $t(14) = 1.81$, $p = .09$. In addition, the right anterior hippocampus increased in node strength from

the early to late time periods, $t(14) = 3.93$, $p = .004$; $d = .35$. We also predicted that the occipital cortex and posterior hippocampus would have stronger connections to the rest of the network during late, elaboration-related processing than earlier processing. Of the regions hypothesized to have stronger node strength later in retrieval, partially consistent with our hypotheses, the left and right occipital cortex (BA19) increased in node strength early to later in retrieval, $t(14) = 6.08$, $p = .001$; $d = .73$ and $t(14) = 2.25$, $p = .05$; $d = .08$, respectively. Inconsistent with our hypotheses, the node strength of the left or right posterior hippocampus did not significantly increase later relative to early in AM retrieval, $t(14) = .11$, $p = .92$ and $t(14) = .81$, $p = .43$, respectively.

Centrality: Node degree. To assess the extent to which regions of the core AM retrieval network changed in their topological centrality (i.e., the extent to which a region served as a network hub), degree centrality was calculated for each of the 18 core network ROIs with respect to the larger 200 ROI whole brain network. Each region's degree centrality during the early and late time period was submitted to bootstrapped paired t-tests to test whether the degree centrality significantly increased from the early period to the late time period or visa versa. Changes in degree centrality in the early versus late time periods indicate the extent to which regions become more or less central to integrating distributed information within the 200 ROI whole brain network during AM retrieval.

Based on previous evidence that the VLPFC and anterior hippocampus are involved in strategic memory search and rebinding processes (Daselaar et al., 2008; Rugg & Vilberg, 2012; Velanova et al., 2003; Wagner, 1998; Cabeza & St Jacques, 2007; Conway & Pleydell-Pearce, 2000; Tulving, 2002), we hypothesized that the VLPFC and

anterior hippocampus would have a greater degree centrality in the early time period relative to the late time period. Consistent with our hypotheses, the right VLPFC and left anterior hippocampus exhibited significantly greater degree centrality in the early relative to the late 1 and late 2 time periods, $t(14) = 3.5$, $p = .02$; $d = .14$ and $t(14) = 2.46$, $p = .04$; $d = .13$, respectively. Consistent with their designation as core AM retrieval network regions, the right VLPFC and left anterior hippocampus were also among the top 6% of all ROIs in the whole brain network, based on the amount of change in degree centrality from the early to the late 1 time period. In addition, we hypothesized that the occipital cortex and posterior hippocampus would have greater degree centrality during the late time periods relative to the early time period. Partially consistent with our hypotheses, the left and right occipital cortex exhibited significantly greater degree centrality in the late 1 and late 2 time periods relative to the early time period, $t(14) = 2.36$, $p = .03$; $d = .51$ and $t(14) = 3.07$, $p = .02$; $d = .68$, respectively. Consistent with their designation as core AM retrieval network regions, the left and right occipital cortex were also among the top 3% of all ROIs in the whole brain network for change in degree centrality during the late 1 and late 2 time period relative to the early time period. However, contrary to predictions, there was no significant change in the degree centrality for the left or right posterior hippocampus later in retrieval relative to early in retrieval, $t(14) = .75$, $p = .46$ and $t(14) = .60$, $p = .55$, respectively.

Descriptive analysis of change in degree for all 200 whole brain nodes. In addition to the inferential analyses of dynamic changes in centrality for the core AM retrieval region during AM retrieval, we performed an exploratory rank analysis of the change in degree centrality for all brain regions in the whole brain network. This whole

brain centrality approach was taken because it offered a more comprehensive and complete description of each ROI's role in neural information processing throughout the whole brain during each period of AM retrieval than only examining each core network ROI's centrality in the 18 node core network. This exploratory analysis revealed several nodes that became more central in the brain during each time period beyond nodes in the core AM retrieval network (Table 6). The regions with the greatest degree during the early time period relative to the late time periods were in the right mid-cingulate cortex, right supramarginal gyrus, and medial frontal cortex. The regions with the greatest degree during the late time periods relative to the early time period were all in the occipital cortex, with the core network occipital cortex bilaterally having the greatest degree in the late time periods relative to the early time period.

Table 6

Top 10% most change in degree centrality for whole brain network nodes by time period.

Whole Brain AAL Label	Core node Label	Coordinate X	Y	Z	Change in Degree	Time Window	Percent
Cingulum_Mid_R		2	-38	32	13.6	Early	1%
SupraMarginal_R		55	-47	41	8.9	Early	1%
Angular_L	LTPJ	-43	-67	40	8.5	Early	2%
Frontal_Mid_R		33	-78	30	7.5	Early	2%
SupraMarginal_R		61	-31	26	7.4	Early	3%
Frontal_Inf_Tri_L		-45	27	26	7.4	Early	3%
Precentral_L		-43	2	48	6.3	Early	4%
Frontal_Inf_Orb_R	RVLPFC	44	30	-10	5.8	Early	4%
Thalamus_L		-9	-18	10	5.8	Early	5%
Precentral_L		-45	33	-9	5.4	Early	5%
Precuneus_R		10	-63	56	5.3	Early	6%
Cingulum_Ant_L		0	21	-9	5.2	Early	6%
Hippocampus_L	LAntHipp	-32	-21	-19	5.1	Early	7%
Angular_R		53	-55	23	4.9	Early	7%
Supp_Motor_Area_L		-8	1	66	4.9	Early	8%
Postcentral_R		43	-20	53	4.8	Early	8%
Precuneus_L		-8	-75	41	4.7	Early	9%
Insula_L		-40	-13	12	4.7	Early	9%

Parietal_Inf_R		40	-43	48	4.6	Early	10%
SupraMarginal_L		-57	-28	36	4.4	Early	10%
Occipital_Inf_L	LOCC	-22	-92	-13	24.6	Late 1	1%
Occipital_Inf_R		43	-73	-11	14.9	Late 1	1%
Calcarine_R		13	-94	2	13.2	Late 1	2%
Calcarine_L		-7	-93	1	12.6	Late 1	2%
Occipital_Inf_R	ROCC	30	-87	-11	12.1	Late 1	3%
Fusiform_L		-36	-78	-15	10.0	Late 1	3%
Supp_Motor_Area_R		2	-23	68	8.9	Late 1	4%
Occipital_Mid_L		-26	-92	12	6.7	Late 1	4%
Fusiform_L		-44	-52	-19	6.1	Late 1	5%
Paracentral_Lobule_L		-9	-38	69	6.1	Late 1	5%
Cingulum_Ant_R		7	43	5	5.8	Late 1	6%
Lingual_R		8	-86	-13	5.7	Late 1	6%
Pons		3	-27	-36	5.5	Late 1	7%
Insula_L		-47	5	2	5.2	Late 1	7%
Frontal_Mid_L		-27	12	56	5.0	Late 1	8%
Frontal_Inf_Orb_L	LVLPFC	-28	32	-16	4.7	Late 1	8%
Frontal_Sup_L		-22	31	47	4.6	Late 1	9%
Frontal_Mid_Orb_L		-29	50	-13	4.6	Late 1	9%
Rolandic_Oper_R		61	-17	12	4.5	Late 1	10%
Supp_Motor_Area_R		1	-15	51	4.4	Late 1	10%
Occipital_Inf_L	LOCC	-22	-92	-13	32.7	Late 2	1%
Occipital_Inf_R	ROCC	30	-87	-11	21.1	Late 2	1%
Occipital_Inf_R		43	-73	-11	20.1	Late 2	2%
Calcarine_L		-7	-93	1	17.6	Late 2	2%
Occipital_Mid_L		-26	-92	12	14.0	Late 2	3%
Calcarine_R		13	-94	2	13.9	Late 2	3%
Fusiform_L		-36	-78	-15	12.0	Late 2	4%
Supp_Motor_Area_R		2	-23	68	11.2	Late 2	4%
Lingual_R		8	-86	-13	10.4	Late 2	5%
Occipital_Mid_L		-40	-85	1	9.5	Late 2	5%
Postcentral_L		-52	-14	40	9.0	Late 2	6%
Cuneus_L		-6	-87	25	8.7	Late 2	6%
Paracentral_Lobule_L		-9	-38	69	7.6	Late 2	7%
Precentral_R		44	2	49	7.4	Late 2	7%
Occipital_Sup_R		17	-89	22	7.2	Late 2	8%
Precentral_L		-18	-16	70	7.0	Late 2	8%
Rolandic_Oper_R		61	-17	12	6.8	Late 2	9%
Fusiform_L		-44	-52	-19	6.1	Late 2	9%
Temporal_Sup_R		58	-7	-9	5.5	Late 2	10%
Temporal_Sup_L		-59	-27	16	5.2	Late 2	10%
Rolandic_Oper_R		55	6	5	15.5	Late 3	1%

Precentral_R		59	-1	26	14.7	Late 3	1%
Precentral_R		44	2	49	12.4	Late 3	2%
Temporal_Sup_L		-59	-27	16	12.3	Late 3	2%
Rolandic_Oper_R		61	-17	12	10.7	Late 3	3%
Fusiform_L		-44	-52	-19	10.0	Late 3	3%
Cingulum_Mid_R		1	17	32	9.3	Late 3	4%
Postcentral_L		-52	-14	40	9.1	Late 3	4%
Cingulum_Mid_L		0	0	42	8.6	Late 3	5%
Temporal_Mid_L		-59	-48	-9	8.4	Late 3	5%
Pons		3	-27	-36	8.3	Late 3	6%
Supp_Motor_Area_R		2	-23	68	8.3	Late 3	6%
Occipital_Inf_R		43	-73	-11	8.1	Late 3	7%
Parietal_Sup_L	LIPL	-19	-52	65	7.7	Late 3	7%
Postcentral_L		-59	-8	26	7.3	Late 3	8%
Vermis		-1	-77	-24	6.7	Late 3	8%
Temporal_Sup_L		-57	-10	5	6.7	Late 3	9%
Precentral_L		-18	-16	70	6.5	Late 3	9%
Supp_Motor_Area_R		10	2	66	6.5	Late 3	10%
Cuneus_R		13	-77	39	6.0	Late 3	10%

Discussion

The findings from the present study provide evidence that accessing and reconstructing memories from one's personal past involves dynamic changes in neural network connectivity as a specific memory is accessed, selected, elaborated upon, and maintained in working memory. A dynamic multivariate connectivity analysis of the core AM retrieval network was utilized to characterize changes in connectivity strength and centrality between specific regions in the core AM retrieval network and the whole brain. Overall, consistent with previous fMRI regional activation and functional connectivity studies (Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011), both region-to-region bivariate correlations and network graph analyses showed that early, access-related processing involved a primarily anterior, fronto-temporal network and later, elaboration-related processing involved a primarily posterior, occipital-parietal and

fronto-parietal network. Specifically, the right VLPFC and left anterior hippocampus were more strongly connected to one another and more central to the component processes of strategic search and integration of distributed information in the early, access-related period than later in AM retrieval. Current theories and previous research also predict that dynamic AM retrieval processes following memory access involve elaboration and reliving of the accessed memory (Conway & Pleydell-Pearce, 2000; Conway et al., 2001; Daselaar et al., 2008; Jacques et al., 2011; McCormick et al., 2013). Consistent with this prediction, neural networks that were stronger during later retrieval processes relative to early AM retrieval processes primarily included connections between occipital-parietal regions and fronto-parietal regions. Most of the connections within the parietal lobe and between the parietal and frontal lobes were found to persist from the initial late-elaboration time periods through the last retrieval time windows relative to early processing periods.

In a separate set of connectivity analyses, we further characterized the relations of specific nodes in the core AM retrieval network to one another and to the whole brain using two graph theory metrics of a node's role in the functional integration of network information (i.e., node strength and node degree centrality). Consistent with predictions of stronger connections between ventrolateral frontal regions and the rest of the brain during early AM retrieval, we found that the right VLPFC had stronger connections on average to all other nodes in the 18-node core network during the early period than during later retrieval periods. Also fitting with our predictions of stronger connections to occipital and parietal regions late in AM retrieval, both occipital cortices exhibited stronger connections on average to all other nodes in the core network during late-

elaboration processes than early-access processes. We did not find support for all of our hypotheses of node-specific changes in average connectivity to the rest of the core AM retrieval network. However, these dynamic graph theory findings suggest that, as predicted, specific nodes in the core network increase in their overall synchrony with the entire AM retrieval network during early and later AM retrieval processes.

Complementary to measures of dynamic changes in each node's strength in the core AM retrieval network, we also measured the dynamic changes in the extent to which each node in the AM retrieval network became more or less central to integrating distributed information in a 200 region whole brain network as AM retrieval unfolded. This metric is known as node degree centrality. Our findings for node degree centrality were consistent with our predictions that frontotemporal regions would play a more central role in the early time period (reflecting memory access) whereas occipital-parietal regions would be more central in the later time periods (reflecting elaboration and maintenance). These whole brain degree centrality findings are in agreement with previously described cross-correlation and node strength analyses. Specifically, the findings of the whole-brain centrality analyses revealed that the right VLPFC and left anterior hippocampus were more central in the early, access-related processing period than the initial late processing period. In addition, relative to the early-access-period, both occipital cortices were more central to connection throughout the whole brain during the late-elaboration period. Finally, an exploratory descriptive analysis of changes in centrality for regions all regions in the whole brain network suggests that these core network regions (i.e. RVLPFC and anterior hippocampus, early retrieval period; occipital cortex, later retrieval periods) are among the top 10% of regions throughout the whole

brain in the extent of change in centrality from the early period to the later periods and visa versa. These node centrality findings support the proposal that frontotemporal regions are integral to controlling and integrating distributed information throughout the whole brain early in AM retrieval during memory access processes, whereas occipital regions are integral to integrating distributed visual and spatiotemporal information later in AM retrieval as the specific memory is elaborated upon.

In summary, findings from both dynamic cross-correlation analyses and graph theory analyses provide further neuroimaging evidence in support of dynamic models of AM retrieval which propose that the cognitive processes underlying AM retrieval progress from memory access-related processing early in retrieval to elaboration-related processing later in retrieval. This study particularly helps refine and extend dynamic neural processing models of AM retrieval, such as the self-memory system theory, by providing evidence of the specific connections throughout the brain that change in their synchrony with one another as processing progresses from access of specific events in the past to elaborative reliving of the past event.

Dynamic networks supporting early, access-related processing

A reliable, core network of regions throughout the brain tend to be activated during AM retrieval relative to non-episodic or task active control conditions (Svoboda et al., 2006). These regions were specifically examined in the present study to determine how the network organization of these regions changed from early to late AM retrieval. Consistent with the rich literature identifying regions engaged during AM retrieval, we found that all of the regions in this core AM retrieval network were well connected to one another throughout retrieval. In addition, the basic network organization finding that

regions more local to one another (e.g., within the same lobe) were more strongly connected than more distant connections (e.g., between lobes) throughout retrieval suggests that our sliding time window method had sufficient data points in each time period to properly estimate biologically relevant changes in network connectivity. Within this organized network, several regions were consistently more strongly connected during either the early or late time periods of AM retrieval.

Consistent with current theories and evidence of dynamic AM retrieval processes (Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; Jacques et al., 2011; McCormick et al., 2013), this study found that strategic memory search and construction of the initial context and details of a memory during the early AM retrieval period primarily recruited a frontotemporal network of connectivity between the lateral prefrontal cortex and anterior hippocampus relative to neural processes later in retrieval. Specifically, the right VLPFC and left anterior hippocampus were more strongly connected to one another and posterior parietal regions early relative to late in retrieval. Both regions were also more central to the component processes of strategic search and integration of distributed information in the early, access-related period than later in AM retrieval. The early, access-related network (relative to later retrieval periods) was also characterized by stronger connectivity between MTL regions and parietal regions such as the posterior cingulate cortex (PCC).

Functional activation studies of AM retrieval have helped to characterize the functions of regions that are activated by AM retrieval processes (Addis et al., 2011; Bonnici et al., 2012; Cabeza et al., 2004; Cabeza & St Jacques, 2007; Conway et al., 1999, 2002; Daselaar et al., 2008; Fink et al., 1996; Maguire, 2001; Svoboda & Levine,

2009; Svoboda et al., 2006). Although many such studies refer to the set of regions commonly activated during AM retrieval as "networks", it is important to note that studies which only consider regional brain activations do not provide evidence that a set of activated regions form a network. Evidence for functional networks, defined as brain regions whose activity covaries with other spatially independent regions throughout the brain over time, requires evidence of significant covariation between regions comprising a putative network (Mcintosh, 1999). The present study thus complements regional activation studies of AM retrieval by showing how regions recruited during AM retrieval form functional network thats dynamically change as AM retrieval processes unfold.

Daselaar et al. (2008) found that the right ventrolateral PFC, right dorsolateral PFC, medial PFC, posterior cingulate cortex, and hippocampus were significantly more active during early AM access processes than late AM elaboration processes. Consistent with the findings of that study and Greenberg et al. (2005), in the present study the right VLPFC and left anterior hippocampus formed a more strongly connected network with one another and to posterior regions during the early retrieval period relative to later periods. Additionally, the early period was characterized by stronger connections between the mRSC and the left anterior and posterior hippocampus relative to the late period. These connectivity findings are consistent with evidence from neuropsychological studies of memory deficits caused by lesions in specific regions of memory retrieval networks as well as other neuroimaging studies of AM and episodic memory retrieval. For instance, patients with damage to the VLPFC or white matter connections between the VLPFC and the anterior MTL (i.e., the uncinate fasciculus) exhibit marked retrograde amnesia (Petrides, 2002). In addition, electrophysiological studies of the causal effects of

prefrontal lesions in the VLPFC on visual processing in the extrastriate cortex of non-human primates and humans suggest that that the VLPFC modulates information in the visual processing system (Barceló et al., 2000; Knight et al., 1999; Markowitsch, 1995). Stronger early connections of the right VLPFC to posterior regions fits well with converging neuropsychological (Petrides, 2002), electrophysiological (Barceló et al., 2000; Knight et al., 1999; Markowitsch, 1995), and fMRI data (Ranganath & Paller, 1999, 2000), which suggest that the ventrolateral PFC implements top-down control signals to modulate processing in posterior cortical regions like the parietal and late visual cortex (Ranganath and Knight, 2005; Petrides, 2002; Ranganath & Paller, 1999, 2000). Previous neuroimaging studies also suggest that activity in the VLPFC may be material specific, with the right VLPFC engaged by the retrieval of images and the left VLPFC engaged by retrieval of verbal information (Petrides, 2002). Given this previous literature, findings that the right VLPFC had particularly strong connections to the parietal and occipital cortices during early retrieval might reflect strategic memory search and verification processes that exert top-down control by influencing operations of visuospatial information processing systems in parietal and occipital regions as a specific episodic memory is accessed.

In parallel, findings that the anterior hippocampus was strongly connected to frontal regions like the VLPFC during early-access processes provides further evidence that the MTL is not only involved in the formation, but also the retrieval of memory traces (Addis et al., 2009; Cabeza & Moscovitch, 2013; Poppenk et al., 2013; Squire, 2004). The increased connectivity between right VLPFC and the left anterior hippocampus during the early time period is also consistent with Greenberg et al's (2005)

finding that these regions are more strongly functionally connected to one another during AM retrieval relative to semantic memory retrieval. Greenberg et al. suggested that connectivity between the right VLPFC and hippocampus is consistent with neuropsychological studies that show damage to the main white matter connection between the VLPFC and anterior MTL regions, the uncinate fasciculus, is associated with retrograde amnesia (Markowitsch, 1995). Converging evidence from previous literature and this study suggest that the VLPFC and hippocampus act in concert with one another and parietal regions to enable search, selection, and initial reactivation of specific autobiographical memories from one's personal past.

The anterior hippocampus was also more strongly connected to the posterior cingulate early in retrieval relative to late in retrieval, indicating that these two regions which were both reported to more active during early vs. later AM retrieval in a previous study (Daselaar et al., 2008) are also more functionally connected within the AM retrieval network. Lesion studies of the retrosplenial cortex have found that damage to this region leads to similar memory deficits to those following damage to MTL regions (Valenstein et al., 1987). Furthermore, the hippocampus and PCC are structurally well connected to one another (Daselaar et al., 2008; Kobayashi & Amaral, 2003; Shibata & Yukie, 2003). These neuropsychological and anatomical findings suggest that the retrosplenial portion of the PCC is an essential communication hub between the hippocampus and thalamus. The stronger functional coupling between the left hippocampus and PCC during the early relative to late AM retrieval we observed in the current study may indicate that the PCC is preferentially involved in the initial reconstruction of the episodic context and details as a memory is selected and accessed.

In combination with previous functional activation and neuropsychological studies, our findings suggest that the functions of this ensemble of regions work with one another to enable strategic episodic memory search processes, also known as retrieval mode (RVLPFC; Tulving, 1983; Velanova et al., 2003), and initial reactivation of specific memory traces from one's personal past (anterior hippocampus and PCC; Greenberg et al., 2005; Hoffman & McNaughton, 2002; Prince, 2005; Squire, 2004; Valenstein et al., 1987; Van Der Werf et al., 2003). The present study's findings help to extend the findings of regional activation studies by identifying the specific connections that change in synchrony between regions that are commonly activated during AM retrieval.

The findings of the current study are also consistent with recent studies of dynamic changes in neural connectivity during AM retrieval (McCormick et al., 2013; St. Jacques et al., 2011). St. Jacques et al. (2011) showed that large-scale, multi-region components derived from independent components analysis (ICA) changed in their connectivity with one another as AM retrieval processes unfolded and that these inter-component connections were modulated by the extent memory accessibility and recollection. These components consisted of a medial PFC network (similar to default mode network; Buckner et al., 2008), MTL network, frontoparietal network, and cinguloopercular network. They found that all of the networks contributed to early, access-related processes with the mPFC network and MTL networks continuing to be engaged during later-elaboration processes. The current study extends these previous ICA-based findings by identifying connections between specific brain regions within a network of regions involved in AM retrieval processes. Because each of the multi-regional ICA components of this previous study (St. Jacques et al., 2011) included

multiple regions across the brain, it is difficult to directly compare the findings between this previous study and the current study in a quantitative manner.

In another study of dynamic connectivity changes during AM retrieval, McCormick et al. (2013) found that the left anterior hippocampus was significantly more strongly connected to frontal areas during early, memory access or construction processes. Consistent with McCormick's findings, we found stronger connectivity between left hippocampus and right VLPFC early in retrieval. Because this prior study determined the locations of their ROIs in part from a data-driven PLS analysis of their fMRI data, the number, location, and size of their ROIs differed to varying degrees from those used in the current study. Consequently, in the current study, we did not examine a dorsomedial PFC (DMPFC) ROI that this previous study found was more strongly connected to the anterior hippocampus (based on their structural equation model) early relative to later in retrieval. However, in our study we did find that the right anterior and posterior hippocampus was more strongly connected to the mPFC (i.e., the closest ROI we had to their DMPFC ROI) during early-access relative to late-elaboration during AM retrieval.

In summary, each of the approaches applied in the literature to date have provided important information regarding AM retrieval networks (McCormick et al., 2013; St. Jacques et al., 2011). The present study adopted a different approach focusing on cross-correlation and graph theoretic analyses. This approach yielded many additional insights into the characteristics and dynamics in the AM retrieval network, at the levels of specific regional connections and network dynamics. Though essentially different in scope from

prior relevant studies, the findings of our study are broadly consistent with the findings of these previous studies.

Dynamic networks supporting late, elaboration-related processing

Current theories and previous research also predict that, after initial memory access has occurred dynamic AM retrieval processes involve elaboration and reliving of the accessed memory (Conway & Pleydell-Pearce, 2000; Conway et al., 2001; Daselaar et al., 2008; Jacques et al., 2011; McCormick et al., 2013). Previous neuroimaging findings regarding this later period of AM retrieval suggest that elaboration and reliving processes engage a predominantly posterior network of connections between lateral parietal, occipital regions, and dorsolateral frontal regions (Conway et al., 1999, 2001; Daselaar et al., 2008). Consistent with this, neural networks that predominated later retrieval processes relative to early AM retrieval processes in the current study primarily included strong connections between occipital-parietal regions and fronto-parietal regions. Occipital-parietal regions have reliably been shown to be involved in the elaboration-related component processes of mental imagery, reliving, while fronto-parietal connections are reliably engaged by working memory processes (Baddeley, 2003; Daselaar et al., 2008; Ganis et al., 2004; Metzler-Baddeley, Jones, Belaroussi, Aggleton, & O'Sullivan, 2011; Vincent et al., 2008).

In line with the hypothesis that episodic details must be maintained in working memory as an AM is retrieved, the pattern of stronger parietal and fronto-parietal connectivity found in the initial time period after accessing the memory persisted throughout retrieval following the beginning of elaboration processes. Specifically, the posterior and fronto-parietal networks were not more strongly connected during the initial

late-elaboration period (i.e., late 1 period) relative to the early AM retrieval period. Moreover, most of these stronger posterior and fronto-parietal connections persisted into the later elaboration periods (i.e., late 2 and late 3 periods), as would be expected if these connections reflected maintenance of previously retrieved episodic information. Although most of the connections in this posterior elaboration network persisted from initial elaboration processes through later elaboration processes, it should be noted that several connections did not persist through elaboration processes including occipito-parietal connections.

Our dynamic functional connectivity data support the view that the visual and parietal cortices work in tandem during late-elaboration processes of AM retrieval (Rubin, 2005, 2006). The largest changes in connectivity strength from the early period to the initial late-elaboration period were between parietal and occipital regions. Neural activation studies of AM retrieval have identified occipital and parietal regions, like the temporoparietal junction (TPJ) and the occipital cortex (BA19), as being involved in retrieval of spatial context of events and visual imagery processes, respectively (Daselaar et al., 2008; Ganis et al., 2004). Behavioral (Rubin, Schrauf, & Greenberg, 2003), neuropsychological (Greenberg & Rubin, 2003), and neuroimaging evidence (Cabeza et al., 2004) have shown that visual information and visual imagery are important components of AM retrieval processes (Daselaar et al., 2008). Activation and connections of lateral fronto-parietal regions during the late-elaboration period of AM retrieval have also been implicated in control of reconstruction processes and maintenance of episodic details in working memory (Velanova et al., 2003; Vincent et al., 2006, 2008; Wager & Smith, 2003). The present study further supports previous findings that posterior parietal

and occipital and fronto-parietal connections are activated during late-elaboration processes of AM retrieval and adds to this literature by demonstrating that these regions are also in sync with one another after retrieval shifts from early, access-related processing to later, elaboration-related processing.

When examining the hippocampus's role in coordinating anterior and posterior networks during AM retrieval, McCormick et al. (2013) found that the posterior hippocampus was more strongly connected to mid-occipital regions and ventral parietal regions during the later-elaboration period than during the early period of memory retrieval. Overall, we did not find evidence in support for this limited role of the posterior hippocampus's connections during only the late-elaboration period. Rather, we found that the bilateral posterior hippocampus tended to be more strongly connected to different frontal, parietal, medial temporal, and occipital regions depending on the period of retrieval. As noted in the previous section, the posterior hippocampi were more strongly connected to the mPFC and right dorsolateral PFC, as well as the PCC and right IPL early relative to late in retrieval. During later-elaboration periods of AM retrieval, we found stronger connections between the posterior hippocampus, intraparietal lobule, and bilateral anterior hippocampi relative to the early time period. Although McCormick et al. found that the posterior hippocampus is primarily connected to posterior parietal regions in later-elaboration processes than early AM retrieval processes, our findings suggest that the posterior hippocampus is engaged in different connections to regions throughout AM retrieval network during both early and late retrieval processes. This difference in results may reflect the different approaches used in these two studies. Specifically, whereas McCormick et al. used a data-driven approach to select ROIs (st-PLS) to test with a

confirmatory SEM analysis, the present study used a well-established and independent core network of ROIs determined from previous studies of regional activation during AM retrieval. Overall, our findings mostly fit with previous literature with several key differences in the role of fronto-parietal connections and the posterior hippocampus during late, elaboration-related AM retrieval processing. This study's findings suggests that later periods of AM retrieval after a specific memory has been accessed primarily involve engagement and connectivity of regions involved in visuospatial re-experiencing of the past event and maintenance of retrieved information in working memory.

Limitations and Future Directions

The present study was specifically designed to examine the neural engagement of regions throughout the brain to different basic emotional states through having participants internally generate these emotions with autobiographical memories while being scanned with fMRI. Thus, several experimental design features limit the interpretation of the results of the present study. The first limitation of the present study is the limited selection of core AM retrieval regions. These regions were selected in a principled manner by creating core network ROIs based on previous studies of dynamic AM retrieval (Daselaar et al., 2008) and the most recent meta-analysis that reviewed neuroimaging studies of AM retrieval (Svoboda et al., 2006). The current study also had the most comprehensive inclusion of specific neural regions to date in studies of dynamic changes in functional connectivity during AM retrieval. However, future studies need to account for an even more comprehensive set of regions engaged in AM retrieval, whether through whole brain network analyses or a set of regions that include core, secondary, and tertiary regions involved in AM retrieval processes. More studies of the dynamic

recruitment of AM retrieval regions using a range of AM retrieval characteristics and a flexible fMRI designs similar to the Daselaar et al. (2008) study are needed to better characterize the dynamic engagement of regions involved in AM retrieval. More dynamic activation studies of AM retrieval will allow for a meta-analysis of compiled findings across a range of samples and AM retrieval conditions.

Although memories in the current study were rehearsed to a lesser extent than was the case in several previous studies of AM retrieval, another limitation of the present study's design includes the potential effects of recent rehearsal on the AM retrieval processes. Rehearsal effects have been shown to attenuate activation in the autobiographical memory network after many repetitions of the memory prior to scanning with prefrontal and occipital activations having a significantly reduced engagement during AM retrieval after multiple repetitions (Svoboda & Levine, 2009). This attenuation effect might have been more prominent in Study 1 because memories were generated and rehearsed just prior to scanning in Study 1 to ensure that both the children and adults could retrieve the same selected memory, whereas in study 2 memories were generated several weeks prior to scanning and only rehearsed once immediately prior to scanning. Thus, rehearsal of the memories immediately prior to the scanning session may have reduced the time and effort needed to access the specific memory for each cue and might have attenuated the strength, timing, and extent of the core AM network connectivity during the early-access period of AM retrieval in our study.

Future studies could manipulate the timing of the transition from access-related processing to elaboration-related processing by manipulating the difficulty of retrieving a

specific memory for particular cues. Previous studies using button presses to denote this information have either not had sufficient variability or not take advantage of the variability in time to access and have tended to average across quickly and slowly accessed memories. Future studies of AM retrieval dynamics could take advantage of this variability by having participants respond via button press when a specific memory has been accessed to more accurately examine the transition between access-related processing and elaboration-related processing and establish that the strength of connections from the access to the elaboration network only change around moment of transition between the two processes. Another approach to denoting the time to access, other than having the participant submit a button press, is to develop fMRI scanning procedures that would allow participants to retrieve AMs aloud or overtly in the scanner. This development would also allow for verification that participants are retrieving specific AMs in the scanner and examination of neuroimaging data based on the narrative content of the autobiographical memory. More generally, developments in the methods to behaviorally assess the transition from process to process is needed to more accurately and comprehensively examine the dynamic neural correlates of AM retrieval processes.

Finally, this study would have benefitted from a more suitable pre-cue baseline that would allow for characterization of changes in the access period relative to the period just before the cue appeared. In this study the pre-cue period consisted of several ratings scales and a short 3.5-second fixation screen. In the present study, we did not use this pre-cue baseline period because of concerns that ratings and fixation processes would engage memory systems in a manner that would be difficult to predict. Resting state connectivity is known to spontaneously vary in predictable ways (Buckner et al., 2008;

Fox et al., 2005) and is particularly characterized by increased activation and connectivity of the default mode network. The default mode network has been extensively examined recently and has been shown to significantly overlap with the core AM retrieval network (Spreng & Grady, 2009; Spreng, Mar, & Kim, 2009). Although it would have been desirable to examine the changes in dynamic neural connectivity during the early and late AM retrieval processes relative to a pre-cue baseline, this known overlap in the default mode and AM retrieval networks precluded our ability to interpret any differences between changes in AM retrieval neural processing relative to this pre-cue period. Development of an adequate active baseline that engages non-memory systems throughout the brain prior to the AM retrieval trial would be beneficial for future studies of spatiotemporal dynamic of AM retrieval processes in the brain.

The current findings showed that specific neural connections change in their strength of functional connectivity to one another as AM retrieval processes progress from access-related to elaboration-related processing. These findings can be used as a basis to create and test models of the neural mechanisms that underlie AM retrieval processes across a range of populations across development (children and adults across the lifespan) to patient populations with impairments in retrieving autobiographical memory. In addition, this study's findings and approaches could also be applied to clinical studies of patients who have conditions that impair autobiographical memory, such as depression, generalized anxiety disorder, and post-traumatic stress disorder, to better understand alterations in neural connectivity associated with these disorders. A few studies have started to apply similar ideas of assessing alteration in activation and connectivity of core AM retrieval regions (Jacques, Botzung, Miles, & Rubin, 2010; St

Jacques, Kragel, & Rubin, 2013). Our examination of the extent to which specific regions in the core AM retrieval network become more or less central to integrating distributed information throughout the brain during certain periods of AM retrieval processing is particularly useful with respect to identifying key nodes that change due to developmental and neuropsychiatric influences over a lifetime. Measures of node centrality throughout dynamic whole brain networks are particularly important in these developmental and neuropsychiatric populations because regions which are reliably central to processing through the brain have been shown to not only facilitate functional integration, by are key to a network's vulnerability and resilience to damage (Power et al., 2011; Rubinov & Sporns, 2010; Sporns et al., 2004). Further studies into alterations in the dynamic nature of cognitive and neural processes associated with these psychiatric and neurological disorders would aid in our understanding of the neural systems we need to engage to treat the various constituent dysfunctional AM retrieval processes. With new techniques and approaches to examining dynamic changes in the neural mechanisms underlying various cognitive behaviors and disorders become available regularly, this study supports provides initial evidence of the utility in examining the dynamic nature of cognition

Conclusion

In conclusion, the present study provides evidence that the core AM retrieval network exhibits changes in the connectivity of specific regions that unfolds over the course of dynamic and complex AM retrieval processes. By using measures of multivariate, dynamic connectivity between specific regions of an established core AM retrieval network, this study provides evidence that patterns of neural engagement and

connectivity dynamically changes as AM retrieval processes progress from early, access-related processing to late, elaboration-related processing. In particular, this study's findings provide evidence to suggest that frontotemporal connectivity associated with access of a specific memory initially predominates AM retrieval processes, followed by initial changes in occipito-parietal and fronto-parietal connectivity associated with engagement of memory elaboration processes that continue to be engaged until the AM retrieval demands to continue elaborating upon a specific memory are updated or end. Together with previous studies of dynamic changes in neural processing during AM retrieval, the present study helps to further extend current theories of dynamic AM retrieval processing. These findings underscore the need for more comprehensive neuroimaging examinations of the complex and dynamic neural interactions that shape our thoughts, feelings, memories, and actions.

General Discussion

The present research aimed to examine the brain networks involved in AM retrieval that change as a function of the dynamic cognitive processes that progress from early, access-related processing to late, elaboration-related processing. Autobiographical memory retrieval is a particularly good candidate to begin to test theories of dynamic cognitive and neural processing with fMRI because established theories of AM retrieval suggest that it is composed of multiple cognitive processes that evolve over a relatively extended period of time (seconds rather than milliseconds) depending on the task demands. In two fMRI studies of AM retrieval processes in adults, we utilized sliding-window, cross-correlation analyses and graph metric analyses of core AM retrieval regions to determine the dynamic network changes associated with AM retrieval processes. Overall, we predicted anterior connections (i.e., frontal and temporal) to be stronger and more central to integrating distributed information during early, access-related processing than later processing periods. During later, elaboration-related processing we predicted a more distributed pattern of connectivity that predominantly consists of posterior connections (i.e., parietal-occipital and frontoparietal). Neural connectivity findings from both studies were generally consistent with this dynamic model of AM retrieval processes. Taken together, these studies provide evidence in support of current theories of dynamic AM retrieval processes (i.e., self-memory system; Conway & Pleydell-Pearce, 2000) by demonstrating specific region-to-region connections that change over time as AM retrieval processes unfold.

The goal of study 1 was to examine the dynamic changes in functional connectivity across early and late periods of AM retrieval between regions that have been

consistently implicated in AM retrieval processes. In contrast to previous studies of AM retrieval that apply an event-related general linear model according to a participants report of accessing the memory, a model-free approach was utilized in the analysis of this data to better capture the changes in AM network connectivity across the entire retrieval condition. The experimental design for study 1 consisted of AM retrieval after the presentation of a personal and neutral cue word for a shorter duration relative to some previous studies of AM retrieval (e.g. 16 seconds vs. 24+ seconds). In this iteration of the AM retrieval procedure, additional prompts were given after the cue word to aid and remind participants to continue to elaborate on a given memory for the duration of each AM retrieval trial.

Consistent with current influential theories that view AM retrieval processes as changing dynamically during the extended time period of autobiographical retrieval (Conway & Pleydell-Pearce, 2000; Daselaar et al., 2008; Jacques et al., 2011; McCormick et al., 2013), Study 1 found that early AM retrieval processes, hypothesized to involve strategic memory search and construction of the initial context and details of an AM memory, primarily recruited a frontotemporal network of connectivity between the prefrontal cortex and medial temporal lobe, as contrasted with later retrieval processes. In addition, in line with predictions, brain network connectivity during later retrieval processes in study 1 (relative to early AM retrieval) primarily included strong connections between occipital-parietal regions and fronto-parietal regions associated with mental imagery, reliving, and working memory processes. Furthermore, we predicted that most of the core AM retrieval regions would be strongly connected to one another throughout retrieval based on evidence that these regions tend to activate with one

another. Consistent with this hypothesis, the present study shows that dynamic changes in neural processing and connectivity occured in the context of a strongly connected core AM retrieval network that maintained a least moderately strong ($r>0.3$) connectivity throughout retrieval.

The goal of study 2 was to examine the dynamic changes in functional connectivity across the AM retrieval processes as well, but was designed to examine AM retrieval processes for a longer duration (30 seconds), with a shorter presentation of the memory cue, and without supplementary elaboration prompts. These changes in experimental design were made to allow for a more naturalistic AM retrieval condition in which the memory cue had to be maintained in working memory, additional cues to aid elaboration had to be internally generated, and each memory had sufficient time to be fully elaborated upon. Given these characteristics for study 2, we were able to observe the elaboration process beyond the initial elaboration period observed in study 1, to test whether changes in connectivity patterns between the initial late period and early period persist throughout the rest of AM retrieval.

Study 2's findings were also consistent with previous fMRI activation and connectivity studies (Daselaar et al., 2008; McCormick et al., 2013; St. Jacques et al., 2011), both region-to-region and network analyses showed that early, access-related processing involved a primarily anterior, fronto-temporal network and later, elaboration-related processing involved a primarily posterior, occipital-parietal and fronto-parietal network. Specifically, the right VLPFC and left anterior hippocampus were more strongly connected to one another and more central to the component processes of strategic search and integration of distributed information in the early, access-related

period than later in AM retrieval. Current theories and previous research also predict that dynamic AM retrieval processes following memory access involve elaboration and reliving of the accessed memory (Conway & Pleydell-Pearce, 2000; Conway et al., 2001; Daselaar et al., 2008; Jacques et al., 2011; McCormick et al., 2013).

Consistent with this prediction, neural networks that predominated later retrieval processes relative to early AM retrieval processes primarily included strong connections between occipital-parietal regions and fronto-parietal regions. Most of the connections within the parietal lobe and between the parietal and frontal lobes were found to persist from the initial late-elaboration time periods through the last retrieval time windows relative to early processing periods. In a distinct set of connectivity analyses with similar methodical goals, we further characterized the relations of specific nodes in the core AM retrieval network to one another and to the whole brain using two graph theory metrics of a node's role in the functional integration of network information (i.e., node strength and node degree centrality).

Consistent with predictions of stronger connections between lateral frontal regions and the rest of the brain during early AM retrieval, we found that the right VLPFC had stronger connections on average to all other nodes in the core network during early-access processes than later-elaboration processes. Also fitting with our predictions of stronger connections to occipital and parietal regions late in AM retrieval, both occipital cortices exhibited stronger connections on average to all other nodes in the core network during late-elaboration processes than early-access processes.

Comparing results between study 1 and study 2 we found similar general patterns that were in line with our hypotheses. However, some discrepancies in the specific

connections within these general connectivity patterns were found between the two studies. First, study 1 had many fewer connections that changed in connectivity strength between the early and late time periods as compared to study 2. We speculate that this difference in the robustness of dynamic connectivity changes between time periods can be accounted for by the extent to which the AM retrieval task guided the participant through retrieval for each AM. That is, we posit that the additional retrieval and elaboration prompts given in study 1 might have attenuated the dynamic changes that might occur in a more naturalistic AM retrieval task. Further research is needed to determine whether guiding AM retrieval with additional prompts attenuates functional activation or connectivity. We also suspect that the null results for some of the dynamic changes in graph theory metrics in study 1 might also be the consequence attenuated network dynamics. Because the overall patterns of stronger connectivity were consistent with our hypotheses in both studies, we speculate that many of the differences in specific findings from the two studies were due to this attenuation of dynamic connectivity changes in study 1.

Turning to specific findings, in study 1, stronger connections during early AM retrieval processes relative to late-elaboration processes included connections between the mPFC, VLPFC, and both the anterior and posterior hippocampus. Whereas, Study 2 found a similar fronto-temporal network connected early in retrieval, the early period was also characterized by large strength differences from the late period in rVLPFC connections to parietal regions, which fits with the rVLPFC's hypothesized function and connectivity. Taken together, the patterns of stronger connectivity during the early time period relative to the late time periods support the hypothesis that a more anterior,

frontotemporal network is engaged as the memory is initially accessed, selected, and rebound into a specific episode that took place in one's personal past.

During the late, elaboration-related processing period of AM retrieval both studies supported the hypothesis that specific connections in a more posterior network of occipito-parietal and fronto-parietal connections would be more strongly connected to one another relative to early AM retrieval processes. Study 1 revealed four of these parietal connections that were stronger relative in the late relative to the early period. Study 2 found a much more robust set of connection strength changes across nearly all of the predicted fronto- and occipito-parietal connections, as well as connection strength changes in parietal connections to regions in the MTL. Study 2 also had the added advantage of being able to assess whether the initial changes in connectivity strength that occurred in the first late time periods persisted throughout the rest of the AM retrieval period. Findings during the late periods for study 2 support this hypothesis that connectivity patterns associated with elaboration processes persist until the retrieval goals are met, the memory has been fully elucidated, or a new memory is cued and accessed. Combining the findings of study 1 and 2, our findings for the late time periods relative to early time periods support the hypothesis that occipito-parietal connections involved in mentally re-experiencing previous episodes and fronto-parietal connections associated with maintaining episodic details that have already been retrieved in working memory.

Several experimental design qualities limit the interpretation of the results of the present studies and could be improved in future studies of dynamic AM retrieval. The first limitation of the present study was the limited selection of core AM retrieval regions. These regions were selected in a principled way by creating core network ROIs based on

previous studies of dynamic AM retrieval (Daselaar et al., 2008) and the most recent meta-analysis that reviewed neuroimaging studies of AM retrieval (Svoboda et al., 2006). The present studies also provided the most comprehensive inclusion of specific neural regions to date in studies of dynamic changes in functional connectivity during AM retrieval. However, future studies would benefit by selecting an even more comprehensive set of regions engaged in AM retrieval, whether accomplished through whole brain network analyses or selection of a set of regions that include core, secondary, and tertiary regions involved in AM retrieval processes. More studies of the dynamic recruitment of AM retrieval regions using a range of AM retrieval characteristics and a flexible fMRI designs similar to the Daselaar et al. (2008) study are needed to better characterize the dynamic engagement of regions involved in AM retrieval. More dynamic activation studies of AM retrieval will allow for a meta-analysis of compiled findings across a range of samples and AM retrieval conditions.

Another limitation of both studies includes the potential effects of recent rehearsal imparted on the AM retrieval processes. Rehearsal effects have been shown to attenuate the activation in the autobiographical memory network (Svoboda & Levine, 2009). Thus, rehearsal of the memories immediately prior to the scanning session may have reduced the time and effort needed to access the specific memory for each cue and might have attenuated the strength, timing, and extent of the core AM network connectivity during the early-access period of AM retrieval in our study, although our analyses suggest that there was substantial engagement of hypothesized networks during early AM retrieval, despite possible attenuation effects.

A promising direction for future study would be to manipulate the timing of the transition from access-related processing to elaboration-related processing by manipulating the difficulty of retrieving a specific memory for particular cues. For instance, in preparation for a future study we have performed a pilot study in which we selected a wide range of cue words (80 in total) from many previous studies of cued AM retrieval and had participants retrieve memories without any prior rehearsal for each cue word. Once the participant had a specific memory in mind they were instructed to press a button, demarking the time to access a specific memory for each cue. We found that many of the cue words required a consistent amount time to access a specific memory across all of the participants. When examining the means of these cue words we found that the time to access across participants and words followed a linear distribution with sufficient variability to select cue words that tend to vary in the time it takes to access a specific memory for each cue word. Cues like "shopping", tended to be accessed more quickly (*M*= ~4 seconds), whereas cues like "field", tended to be accessed more slowly (*M*= ~12 seconds). Previous studies using button presses to denote this information have either not had sufficient variability or did not take advantage of the variability in time to access and have tended to average across quickly and slowly accessed memories.

Future studies of AM retrieval dynamics could take advantage of this variability by having participants respond via button press when a specific memory has been accessed to more accurately examine the transition between access-related processing and elaboration-related processing and establish that the strength of connections from the access to the elaboration network only change around moment of transition between the two processes. Another approach to denoting the time to access, other than having the

participant submit a button press, is to develop fMRI scanning procedures that would allow participants to retrieve AMs aloud or overtly in the scanner. This development would also allow for verification that participants are retrieving specific AMs in the scanner and examination of neuroimaging data based on the narrative content of the autobiographical memory. More generally, developments in the methods to behaviorally assess the transition from process to process is needed to more accurately and comprehensively examine the dynamic neural correlates of AM retrieval processes.

In preparation to continue this line of research we have fully designed a follow-up fMRI study that addresses most of the limitations of the studies described in this thesis. The main advances of the designed follow-up study are a high temporal resolution fMRI sequence, manipulation of the time to access by using piloted cues described above, and overt or narrated retrieval of AMs in the scanner. In particular, we will be using a novel fMRI sequence (i.e., multi-band sequence) that will reduce the temporal resolution of fMRI data from the whole brain from 2.16 seconds to 1 second per time point by acquiring multiple slices of the brain at one time. In addition, we plan to use the slow and fast access cues mentioned above to test whether the strength of connections from the access to the elaboration network only change around moment of transition between the two processes. We expect the timing of the change in network connectivity strength (among other metrics) to correlate with when the participant responds that they have fully accessed the memory (e.g., memories which are slower to be accessed will show early-access network connectivity for longer than more quickly accessed memories). This finding would demonstrate that changes in coordination between regions in the AM retrieval network underlie changes in AM retrieval processes. Furthermore, we plan to

examine differences in neural connectivity states between covert, silent retrieval of AMs and overt, narrated retrieval of AMs. We expect networks involved in overt, narrated retrieval of AMs to involve stronger connections in left-lateralized regions involved in language production. This aim is exploratory in nature and will contribute to the existing literature on AM retrieval by determining whether there are significant differences in the coordination and guidance of neural activity in conditions that require a narrative or story to be constructed versus conditions that only require construction of the AM in one's mind. Our long-term goal is to use dynamic functional connectivity analyses to examine the constantly changing networks that underlie various cognitive processes, in particular declarative memory retrieval processes.

Finally, this study would have benefitted from a pre-cue baseline that would allow for characterization of changes in the access period relative to the period just before the cue appeared. In this study the pre-cue period was a 12-second resting inter-trial interval. Resting state connectivity is known to spontaneously vary in predictable ways (Buckner et al., 2008; Fox et al., 2005) and is particularly characterized by increased activation and connectivity of the default mode network. The default mode network has been extensively examined recently and has been shown to significantly overlap with the core AM retrieval network (Spreng & Grady, 2009; Spreng, Mar, & Kim, 2009). Although we would have liked to examine the changes in dynamic neural connectivity during the early and late AM retrieval processes relative to a pre-cue baseline, this known overlap in the default mode and AM retrieval networks precluded our ability to interpret any differences between changes in AM retrieval neural processing relative to this pre-cue period. This issue is relevant all studies published to date of neural dynamics in AM retrieval

processes (McCormick et al., 2013; St. Jacques et al., 2011; Daselaar et al., 2008). Development of an improved active baseline that engages non-memory systems throughout the brain prior to the AM retrieval trial is needed in future studies of spatiotemporal dynamics of AM retrieval processes in the brain.

Although these limitations exist and need to be addressed in future experiments, this study still provides useful evidence that predictable and specific neural connections change in their strength of functional connectivity to one another as AM retrieval processes progress from access-related to elaboration-related processing. These findings can be used as a basis to create and test models of the neural mechanisms that underlie AM retrieval processes across a range of populations from developmental (children and adults across the lifespan) to patient populations with known issues in retrieving autobiographical memory. Examinations of the changes in dynamic connectivity during AM retrieval in both young and old samples relative to our data from young adults would contribute to models of AM retrieval processes based the known behavioral and neural changes in declarative memory capabilities across development during childhood, adolescence, and through adulthood (Bauer & Fivush, 2010; Fivush, 2011).

In addition, this study's approach could also be applied to studies of patients who experience memory issues of autobiographical memory, like consistent, involuntary retrieval of negative past experiences (i.e., depression, generalized anxiety disorder, post-traumatic stress disorder, etc.) or difficulty retrieving AMs from one's past (i.e., mild cognitive disorder, dementia, Alzheimer's disease, other neurological diseases, etc.), to better understand alterations in neural connectivity associated with these disorders. A few studies have started to apply similar ideas of assessing alteration in activation and

connectivity of core AM retrieval regions (Jacques, Botzung, Miles, & Rubin, 2010; St Jacques, Kragel, & Rubin, 2013). Our examination of the extent to which specific regions in the core AM retrieval network become more or less central to integrating distributed information throughout the brain during certain periods of AM retrieval processing is particularly useful with respect to identifying key nodes that change due to developmental and neuropsychiatric influences over a lifetime. Measures of node centrality throughout dynamic whole brain networks are particularly important in these developmental and neuropsychiatric populations because regions which are reliably central to processing through the brain have been shown to not only facilitate functional integration, by are key to a network's vulnerability and resilience to damage (Power et al., 2011; Rubinov & Sporns, 2010; Sporns et al., 2004). Further studies investigating alterations in the dynamic nature of cognitive and neural processes associated with these psychiatric and neurological disorders would aid in our understanding of the neural systems we need to engage to treat the various constituent dysfunctional AM retrieval processes.

Finally, a limitation in all fMRI studies of dynamic cognitive processes is the relatively coarse temporal resolution to examine changes in cognitive processing that are known to change on a millisecond time scale. Even though recent developments in fMRI acquisition sequences have reduced the temporal resolution by half (i.e., from 2 s to 1 s; multiband sequences), it is unclear whether fMRI will ever have the capacity to examine changes in neural signals throughout the whole brain at the millisecond timescale. Future studies of the evolution of dynamic cognitive processing, including AM retrieval, might be attempted with the assistance of patients undergoing intracranial electrocorticography

(iEEG) to localize the foci of epileptic activity in their brain. Studies utilizing iEEG or eCog have qualities of temporal and spatial resolution that are entirely unattainable with current neuroimaging methods. In particular, the increase temporal resolution in cognitive studies of iEEG patients allows for examinations of neural network dynamics on the time scale of milliseconds in highly localized segments of the brain. Relative to fMRI, one draw back to iEEG is that iEEG electrodes are only able to sample from a relatively sparse selection of brain regions in each patient and, although there is some consistency in the typical placement of iEEG electrodes, electrodes in each patient are placed in different locations depending on clinical inquiries. The most powerful approach to address the temporal issues in fMRI and the spatial sparsity issues in iEEG is to take advantage of the comprehensive spatial resolution and recent faster fMRI sequences to establish models of dynamic AM retrieval processes across many individuals and then test these models in willing iEEG patients with electrodes that reasonably sample the electrophysiological changes from established core AM retrieval regions. Our study provides an initial model from which to derive further fMRI and experiments with other neuroimaging methodologies of dynamic neural connectivity changes across changing AM retrieval processes.

In conclusion, these findings provide novel neuroimaging evidence in support of current dynamic models of AM retrieval which propose that the cognitive processes underlying AM retrieval evolve from early memory access-related processing to elaboration-related processing later in retrieval. Taken together, the current findings help refine and extend dynamic neural processing models of AM retrieval by providing evidence of the specific connections throughout the brain that change in their synchrony

with one another as processing progresses from access of specific events in the past to elaborative reliving of the past event. Findings from these studies underscore the need for more comprehensive neuroimaging examinations of the specific complex and dynamic neural interactions that shape our thoughts, feelings, memories, and actions.

References

Addis, D. R., Knapp, K., Roberts, R. P., & Schacter, D. L. (2011). Routes to the past: Neural substrates of direct and generative autobiographical memory retrieval. *Neuroimage*, 1–15. doi:10.1016/j.neuroimage.2011.09.066

Addis, D. R., Leclerc, C. M., Muscatell, K. A., & Kensinger, E. A. (2010). There are age-related changes in neural connectivity during the encoding of positive, but not negative, information. *Cortex*, *46*(4), 425–433. doi:10.1016/j.cortex.2009.04.011

Addis, D. R., McIntosh, A. R., Moscovitch, M., Crawley, A. P., & McAndrews, M. P. (2004). Characterizing spatial and temporal features of autobiographical memory retrieval networks: a partial least squares approach. *NeuroImage*, *23*(4), 1460–1471. doi:10.1016/j.neuroimage.2004.08.007

Addis, D. R., Moscovitch, M., & McAndrews, M. P. (2007). Consequences of hippocampal damage across the autobiographical memory network in left temporal lobe epilepsy. *Brain*, *130*(9), 2327–2342. doi:10.1093/brain/awm166

Addis, D. R., Pan, L., Vu, M.-A., Laiser, N., & Schacter, D. L. (2009). Constructive episodic simulation of the future and the past: Distinct subsystems of a core brain network mediate imagining and remembering. *Neuropsychologia*, *47*(11), 2222–2238. doi:10.1016/j.neuropsychologia.2008.10.026

Addis, D. R., & Schacter, D. L. (2008). Constructive episodic simulation: Temporal distance and detail of past and future events modulate hippocampal engagement. *Hippocampus*, *18*(2), 227–237. doi:10.1002/hipo.20405

Aggleton, J. P., & Pearce, J. M. (2001). Neural systems underlying episodic memory: insights from animal research. *Philosophical Transactions of the Royal Society of*

London. Series B: Biological Sciences, *356*(1413), 1467–1482. doi:10.1098/rstb.2001.0946

Anderson, A. K., & Phelps, E. A. (2001). Lesions of the human amygdala impair enhanced perception of emotionally salient events. *Nature*, *411*(6835), 305–309. doi:10.1038/35077083

Anderson, J. R., & Fincham, J. M. (2013). Discovering the Sequential Structure of Thought. *Cognitive Science*, n/a–n/a. doi:10.1111/cogs.12068

Andreasen, N. C., O'Leary, D. S., Cizadlo, T., Arndt, S., Rezai, K., Watkins, G. L., … Hichwa, R. D. (1995). Remembering the past: two facets of episodic memory explored with positron emission tomography. *The American Journal of Psychiatry*, *152*(11), 1576–1585.

Andreasen, N. C., O'Leary, D. S., Paradiso, S., Cizadlo, T., Arndt, S., Watkins, G. L., … Hichwa, R. D. (1999). The cerebellum plays a role in conscious episodic memory retrieval. *Human Brain Mapping*, *8*(4), 226–234. doi:10.1002/(SICI)1097-0193(1999)8:4<226::AID-HBM6>3.0.CO;2-4

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829–839. doi:10.1038/nrn1201

Barceló, F., Suwazono, S., & Knight, R. T. (2000). Prefrontal modulation of visual processing in humans. *Nature Neuroscience*, *3*(4), 399–403. doi:10.1038/73975

Barsalou, L. (1988). The content and organization of autobiographical memories. In U. Neisser & E. Winograd (Eds.), *Remembreing Reconsidered: Ecological and traditional approaches to the study of memory.* (pp. 193–239). New York: Cambridge University Press.

Bassett, D. S., Bullmore, E., Verchinski, B. A., Mattay, V. S., Weinberger, D. R., & Meyer-Lindenberg, A. (2008). Hierarchical Organization of Human Cortical Networks in Health and Schizophrenia. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *28*(37), 9239–9248. doi:10.1523/JNEUROSCI.1929-08.2008

Bassett, D. S., Wymbs, N. F., Porter, M. A., Mucha, P. J., Carlson, J. M., & Grafton, S. T. (2011). Dynamic reconfiguration of human brain networks during learning. *PNAS*, *108*(18), 7641–7646. doi:10.1073/pnas.1018985108/-/DCSupplemental/Appendix.pdf

Bauer, P. J. (2007). Toward a neuro-developmental account of the development of declarative memory. *Developmental Psychobiology*, *50*(1), 19–31. doi:10.1002/dev.20265

Bauer, P. J., Burch, M. M., Scholin, S. E., & Güler, O. E. (2007). Using Cue Words to Investigate the Distribution of Autobiographical Memories in Childhood. *Psychological Science*, *18*(10), 910–916. doi:10.1111/j.1467-9280.2007.01999.x

Bauer, P. J., & Fivush, R. (2010). Context and consequences of autobiographical memory development. *Cognitive Development*, 1–6. doi:10.1016/j.cogdev.2010.08.001

Bauer, P. J., Stevens, J. S., Jackson, F. L., & Souci, P. S. (2012). Electrophysiological indices of emotion processing during retrieval of autobiographical memories by school-age children. *Cognitive, Affective, & Behavioral Neuroscience*, *12*(1), 99–114. doi:10.3758/s13415-011-0073-7

Bender-deMoll, S., & McFarland, D. (2006). The art and science of visualizing networks. *Journal of Social Structure*, *7*(2), 1–47.

Bonnici, H. M., Chadwick, M. J., Lutti, A., Hassabis, D., Weiskopf, N., & Maguire, E. A. (2012). Detecting Representations of Recent and Remote Autobiographical Memories in vmPFC and Hippocampus. *Journal of Neuroscience*, *32*(47), 16982–16991. doi:10.1523/JNEUROSCI.2475-12.2012

Botzung, A., Rubin, D. C., Miles, A., Cabeza, R., & LaBar, K. S. (2010). Mental Hoop Diaries: Emotional Memories of a College Basketball Game in Rival Fans. *Journal of Neuroscience*, *30*(6), 2130–2137. doi:10.1523/JNEUROSCI.2481-09.2010

Brett, M., Anton, J.-L., Valabregue, R., & Poline, J.-B. (2002). Region of interest analysis using an SPM toolbox (pp. 1–1). Presented at the Presented at the 8th International Conference on Functional Mapping of the Human Brain.

Brewer, W. F. (1996). What is recollective memory? In *Remembering our past*. Cambridge University Press. Retrieved from http://dx.doi.org/10.1017/CBO9780511527913.002

Buchel, C., Coull, J., & Friston, K. (1999). The predictive value of changes in effective connectivity for human learning. *Science*, *283*(5407), 1538.

Buckner, R. L., Andrews-Hanna, J. R., & Schacter, D. L. (2008). The Brain's Default Network: Anatomy, Function, and Relevance to Disease. *Annals of the New York Academy of Sciences*, *1124*(1), 1–38. doi:10.1196/annals.1440.011

Bullmore, E., & Sporns, O. (2009). Complex brain networks: graph theoretical analysis of structural and functional systems. *Nature Reviews Neuroscience*, *10*(3), 186–198. doi:10.1038/nrn2575

Burianova, H., McIntosh, A. R., & Grady, C. L. (2010). A common functional brain network for autobiographical, episodic, and semantic memory retrieval. *Neuroimage*, *49*(1), 865–874. doi:10.1016/j.neuroimage.2009.08.066

Cabeza, R., & Moscovitch, M. (2013). Memory Systems, Processing Modes, and Components: Functional Neuroimaging Evidence. *Perspectives on Psychological Science*, *8*(1), 49–55. doi:10.1177/1745691612469033

Cabeza, R., Prince, S. E., Daselaar, S. M., Greenberg, D. L., Budde, M., Dolcos, F., … Rubin, D. C. (2004). Brain activity during episodic retrieval of autobiographical and laboratory events: an fMRI study using a novel photo paradigm. *Journal of Cognitive Neuroscience*, *16*(9), 1583–1594.

Cabeza, R., & St Jacques, P. (2007). Functional neuroimaging of autobiographical memory. *Trends in Cognitive Sciences*, *11*(5), 219–227. doi:10.1016/j.tics.2007.02.005

Cahill, L., Haier, R. J., Fallon, J., Alkire, M. T., Tang, C., Keator, D., … McGaugh, J. L. (1996). Amygdala activity at encoding correlated with long-term, free recall of emotional information. *Proceedings of the National Academy of Sciences*, *93*(15), 8016–8021.

Calhoun, V. d., Adali, T., Pearlson, G. d., & Pekar, J. j. (2001). A method for making group inferences from functional MRI data using independent component analysis. *Human Brain Mapping*, *14*(3), 140–151. doi:10.1002/hbm.1048

Canli, T., Zhao, Z., Brewer, J., E, D., & Cahill, L. (2000). Event-related activation in the human amygdala associates with later memory for individual emotional response. *The Journal of Neuroscience*, *20*(19), RC99.

Conway, M. A. (2009). Episodic memories. *Neuropsychologia*, *47*(11), 2305–2313. doi:10.1016/j.neuropsychologia.2009.02.003

Conway, M. A., & Pleydell-Pearce, C. W. (2000). The construction of autobiographical memories in the self-memory system. *Psychological Review*, *107*(2), 261–288. doi:10.1037/0033-295X.107.2.261

Conway, M. A., Pleydell-Pearce, C. W., & Whitecross, S. E. (2001). The Neuroanatomy of Autobiographical Memory: A Slow Cortical Potential Study of Autobiographical Memory Retrieval. *Journal of Memory and Language*, *45*(3), 493–524. doi:10.1006/jmla.2001.2781

Conway, M. A., Pleydell-Pearce, C. W., Whitecross, S., & Sharpe, H. (2002). Brain imaging autobiographical memory. In Brian H. Ross (Ed.), *Psychology of Learning and Motivation* (Vol. Volume 41, pp. 229–263). Academic Press. Retrieved from http://www.sciencedirect.com/science/article/pii/S0079742102800081

Conway, M. A., Turk, D. J., Miller, S. L., Logan, J., Nebes, R. D., Meltzer, C. C., & Becker, J. T. (1999). A Positron Emission Tomography (PET) Study of Autobiographical Memory Retrieval. *Memory*, *7*(5-6), 679–703. doi:10.1080/096582199387805

Cox, R. W. (1996). AFNI: Software for Analysis and Visualization of Functional Magnetic Resonance Neuroimages. *Computers and Biomedical Research*, *29*(3), 162–173. doi:10.1006/cbmr.1996.0014

Craddock, R. C., James, G. A., Holtzheimer, P. E., Hu, X. P., & Mayberg, H. S. (2012). A whole brain fMRI atlas generated via spatially constrained spectral clustering. *Human Brain Mapping*, *33*(8), 1914–1928. doi:10.1002/hbm.21333

Crinion, J., Ashburner, J., Leff, A., Brett, M., Price, C., & Friston, K. (2007). Spatial normalization of lesioned brains: Performance evaluation and impact on fMRI analyses. *Neuroimage*, *37*(3), 866–875. doi:10.1016/j.neuroimage.2007.04.065

Crovitz, H. F., & Schiffman, H. (1974). Frequency of episodic memories as a function of their age. *Bulletin of the Psychonomic Society*, *4*(5), 517–518. doi:10.3758/BF03334277

D'Argembeau, A., Ruby, P., Collette, F., Degueldre, C., Balteau, E., Luxen, A., … Salmon, E. (2007). Distinct Regions of the Medial Prefrontal Cortex Are Associated with Self-referential Processing and Perspective Taking. *Journal of Cognitive Neuroscience*, *19*(6), 935–944.

Daselaar, S. M., Rice, H. J., Greenberg, D. L., Cabeza, R., LaBar, K. S., & Rubin, D. C. (2008). The Spatiotemporal Dynamics of Autobiographical Memory: Neural Correlates of Recall, Emotional Intensity, and Reliving. *Cerebral Cortex*, *18*(1), 217–229. doi:10.1093/cercor/bhm048

Denkova, E., Chakrabarty, T., Dolcos, S., & Dolcos, F. (2011). Brain Imaging Investigation of the Neural Correlates of Emotional Autobiographical Recollection. *Journal of Visualized Experiments*, (54). doi:10.3791/2396

Eichenbaum, H., Sauvage, M., Fortin, N., Komorowski, R., & Lipton, P. (2012). Towards a functional organization of episodic memory in the medial temporal lobe.

Neuroscience and Biobehavioral Reviews, *36*(7), 1597–1608. doi:10.1016/j.neubiorev.2011.07.006

Fink, G. R. (2003). In search of one's own past: the neural bases of autobiographical memories. *Brain*, *126*(7), 1509–1510. doi:10.1093/brain/awg212

Fink, G. R., Markowitsch, H. J., Reinkemeier, M., Bruckbauer, T., Kessler, J., & Heiss, W.-D. (1996). Cerebral Representation of One's Own Past: Neural Networks Involved in Autobiographical Memory. *The Journal of Neuroscience*, *16*(13), 4275–4282.

Fivush, R. (2011). The Development of Autobiographical Memory. *Annual Review of Psychology*, *62*(1), 559–582. doi:10.1146/annurev.psych.121208.131702

Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(27), 9673–9678. doi:10.1073/pnas.0504136102

Gainotti, G., Almonti, S., Di Betta, A. M., & Silveri, M. C. (1998). Retrograde amnesia in a patient with retrosplenial tumour. *Neurocase*, *4*(6), 519–526. doi:10.1080/13554799808410644

Galton, Francis. (1879). Psychometric Experiments. *Brain*, 149–162.

Ganis, G., Thompson, W. L., & Kosslyn, S. M. (2004). Brain areas underlying visual mental imagery and visual perception: an fMRI study. *Cognitive Brain Research*, *20*(2), 226–241. doi:10.1016/j.cogbrainres.2004.02.012

Gemar, M. C., Kapur, S., Segal, Z. V., Brown, G. M., & Houle, S. (1996). Effects of self-generated sad mood on regional cerebral activity: A PET study in normal

subjects. *Depression*, *4*(2), 81–88. doi:10.1002/(SICI)1522-7162(1996)4:2<81::AID-DEPR8>3.0.CO;2-I

Greenberg, D. L., Rice, H. J., Cooper, J. J., Cabeza, R., Rubin, D. C., & LaBar, K. S. (2005). Co-activation of the amygdala, hippocampus and inferior frontal gyrus during autobiographical memory retrieval. *Neuropsychologia*, *43*(5), 659–674. doi:10.1016/j.neuropsychologia.2004.09.002

Greenberg, D. L., & Rubin, D. C. (2003). The Neuropsychology of Autobiographical Memory. *Cortex*, *39*(4–5), 687–728. doi:10.1016/S0010-9452(08)70860-8

Gusnard, D. A., Akbudak, E., Shulman, G. L., & Raichle, M. E. (2001). Medial prefrontal cortex and self-referential mental activity: Relation to a default mode of brain function. *Proceedings of the National Academy of Sciences*, *98*(7), 4259–4264. doi:10.1073/pnas.071043098

Hamann. (2001). Cognitive and neural mechanisms of emotional memory. *Trends in Cognitive Sciences*, *5*(9), 394–400. doi:10.1016/S1364-6613(00)01707-1

Hamann, S. B., Cahill, L., & Squire, L. R. (1997). Emotional perception and memory in amnesia. *Neuropsychology*, *11*(1), 104–113. doi:10.1037/0894-4105.11.1.104

Hamann, S. B., Ely, T. D., Grafton, S. T., & Kilts, C. D. (1999). Amygdala activity related to enhanced memory for pleasant and aversive stimuli. *Nature Neuroscience*, *2*(3), 289–293.

Hoffman, K. L., & McNaughton, B. L. (2002). Coordinated Reactivation of Distributed Memory Traces in Primate Neocortex. *Science*, *297*(5589), 2070–2073. doi:10.1126/science.1073538

Hopfinger, J. B., Buonocore, M. H., & Mangun, G. R. (2000). The neural mechanisms of top-down attentional control. *Nature Neuroscience*, *3*(3), 284–291. doi:10.1038/72999

Hutchison, R. M., Womelsdorf, T., Allen, E. A., Bandettini, P. A., Calhoun, V. D., Corbetta, M., … Chang, C. (2013). Dynamic functional connectivity: Promise, issues, and interpretations. *Neuroimage*, *80*(C), 360–378. doi:10.1016/j.neuroimage.2013.05.079

Inman, C. S., James, G. A., Hamann, S., Rajendra, J. K., Pagnoni, G., & Butler, A. J. (2012). Altered resting-state effective connectivity of fronto-parietal motor control systems on the primary motor network following stroke. *Neuroimage*, *59*(1), 227–237. doi:10.1016/j.neuroimage.2011.07.083

Jacques, P. L. S., Botzung, A., Miles, A., & Rubin, D. C. (2010). Functional neuroimaging of emotionally intense autobiographical memories in post-traumatic stress disorder. *Journal of Psychiatric Research*, 1–8. doi:10.1016/j.jpsychires.2010.10.011

Jacques, P. L. S., Kragel, P. A., & Rubin, D. C. (2011). Dynamic neural networks supporting memory retrieval. *Neuroimage*, 1–9. doi:10.1016/j.neuroimage.2011.04.039

James, G. A., Kelley, M. E., Craddock, R. C., Holtzheimer, P. E., Dunlop, B. W., Nemeroff, C. B., … Hu, X. P. (2009). Exploratory structural equation modeling of resting-state fMRI: Applicability of group models to individual subjects. *Neuroimage*, *45*(3), 778–787. doi:10.1016/j.neuroimage.2008.12.049

Kamada, T., & Kawai, S. (1989). An algorithm for drawing general undirected graphs. *Information Processing Letters*, *31*(1), 7–15. doi:10.1016/0020-0190(89)90102-6

Kensinger, E. A., & Corkin, S. (2004). Two routes to emotional memory: Distinct neural processes for valence and arousal. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(9), 3310–3315. doi:10.1073/pnas.0306408101

Knight, R. T., Richard Staines, W., Swick, D., & Chao, L. L. (1999). Prefrontal cortex regulates inhibition and excitation in distributed neural networks. *Acta Psychologica*, *101*(2–3), 159–178. doi:10.1016/S0001-6918(99)00004-9

Kobayashi, Y., & Amaral, D. G. (2003). Macaque monkey retrosplenial cortex: II. Cortical afferents. *The Journal of Comparative Neurology*, *466*(1), 48–79. doi:10.1002/cne.10883

Krishnan, A., Williams, L. J., McIntosh, A. R., & Abdi, H. (2011). Partial Least Squares (PLS) methods for neuroimaging: A tutorial and review. *NeuroImage*, *56*(2), 455–475. doi:10.1016/j.neuroimage.2010.07.034

LaBar, K. S., & Cabeza, R. (2006). Cognitive neuroscience of emotional memory. *Nature Reviews Neuroscience*, *7*(1), 54–64. doi:10.1038/nrn1825

Lynall, M.-E., Bassett, D. S., Kerwin, R., McKenna, P. J., Kitzbichler, M., Muller, U., & Bullmore, E. (2010). Functional Connectivity and Brain Networks in Schizophrenia. *The Journal of Neuroscience*, *30*(28), 9477–9487. doi:10.1523/JNEUROSCI.0333-10.2010

Maguire, E. A. (2001). Neuroimaging studies of autobiographical event memory. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *356*(1413), 1441–1451. doi:10.1098/rstb.2001.0944

Maguire, E. A., Mummery, C. J., & Büchel, C. (2000). Patterns of hippocampal-cortical interaction dissociate temporal lobe memory subsystems. *Hippocampus*, *10*(4), 475–482. doi:10.1002/1098-1063(2000)10:4<475::AID-HIPO14>3.0.CO;2-X

Maguire, E. A., Vargha-Khadem, F., & Mishkin, M. (2001). The effects of bilateral hippocampal damage on fMRI regional activations and interactions during memory retrieval. *Brain*. Retrieved from http://brain.oxfordjournals.org.proxy.library.emory.edu/content/124/6/1156.short

Maldjian, J. A., Laurienti, P. J., Kraft, R. A., & Burdette, J. H. (2003). An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. *Neuroimage*, *19*(3), 1233–1239. doi:10.1016/S1053-8119(03)00169-1

Markowitsch, H. J. (1995). Which brain regions are critically involved in the retrieval of old episodic memory? *Brain Research Reviews*, *21*(2), 117–127. doi:10.1016/0165-0173(95)00007-0

Markowitsch, H. J., & Staniloiu, A. (2011). Amygdala in action: Relaying biological and social significance to autobiographical memory. *Neuropsychologia*, *49*(4), 718–733. doi:10.1016/j.neuropsychologia.2010.10.007

Markowitsch, H. J., Thiel, A., Reinkemeier, M., Kessler, J., Koyuncu, A., & Heiss, W.-D. (2000). Right Amygdalar and Temporofrontal Activation During Autobiographic,

But Not During Fictitious Memory Retrieval. *Behavioural Neurology*, *12*(4), 181–190. doi:10.1155/2000/303651

Markowitsch, H. J., Vandekerckhove, M. M. P., Lanfermann, H., & Russ, M. O. (2003). Engagement of Lateral and Medial Prefrontal Areas in the Ecphory of Sad and Happy Autobiographical Memories. *Cortex*, *39*(4–5), 643–665. doi:10.1016/S0010-9452(08)70858-X

Mazaika, P. K., Hoeft, F., Glover, G. H., & Reiss, A. L. (2009). Methods and Software for fMRI Analysis of Clinical Subjects. *NeuroImage*, *47, Supplement 1*, S58. doi:10.1016/S1053-8119(09)70238-1

Mazaika, P., Whitfield-Gabrieli, S., Reiss, A., & Glover, G. (2007). Artifact repair for fMRI data from high motion clinical subjects. In *13th Annual Meeting of the Organization for Human Brain Mapping. Chicago: IL*.

McCormick, C., St-Laurent, M., Ty, A., Valiante, T. A., & McAndrews, M. P. (2013). Functional and Effective Hippocampal-Neocortical Connectivity During Construction and Elaboration of Autobiographical Memory Retrieval. *Cerebral Cortex*. doi:10.1093/cercor/bht324

McGaugh, J. L. (2000). Memory--a Century of Consolidation. *Science*, *287*(5451), 248–251. doi:10.1126/science.287.5451.248

Mcintosh, A. R. (1999). Mapping Cognition to the Brain Through Neural Interactions. *Memory*, *7*(5-6), 523–548. doi:10.1080/096582199387733

McIntosh, A. R., Chau, W. K., & Protzner, A. B. (2004). Spatiotemporal analysis of event-related fMRI data using partial least squares. *NeuroImage*, *23*(2), 764–775. doi:10.1016/j.neuroimage.2004.05.018

McIntosh, A. R., & Lobaugh, N. J. (2004). Partial least squares analysis of neuroimaging data: applications and advances. *NeuroImage*, *23, Supplement 1*, S250–S263. doi:10.1016/j.neuroimage.2004.07.020

McIntyre, C. K., McGaugh, J. L., & Williams, C. L. (2011). Interacting brain systems modulate memory consolidation. *Neuroscience and Biobehavioral Reviews*, *36*(7), 1750–1762. doi:10.1016/j.neubiorev.2011.11.001

McKeown, M. J. (2000). Detection of Consistently Task-Related Activations in fMRI Data with Hybrid Independent Component Analysis. *NeuroImage*, *11*(1), 24–35. doi:10.1006/nimg.1999.0518

Metzler-Baddeley, C., Jones, D. K., Belaroussi, B., Aggleton, J. P., & O'Sullivan, M. J. (2011). Frontotemporal Connections in Episodic Memory and Aging: A Diffusion MRI Tractography Study. *Journal of Neuroscience*, *31*(37), 13236–13245. doi:10.1523/JNEUROSCI.2317-11.2011

Moscovitch, M. (1995). Confabulation. In *Memory distortions: How minds, brains, and societies reconstruct the past* (pp. 226–251). Cambridge, MA, US: Harvard University Press.

Moscovitch, M., & Melo, B. (1997). Strategic retrieval and the frontal lobes: Evidence from confabulation and amnesia. *Neuropsychologia*, *35*(7), 1017–1034. doi:10.1016/S0028-3932(97)00028-6

Muscatell, K. A., Addis, D. R., & Kensinger, E. A. (2010). Self-involvement modulates the effective connectivity of the autobiographical memory network. *Social Cognitive and Affective Neuroscience*, *5*(1), 68–76. doi:10.1093/scan/nsp043

Newell, A., & Simon, H. A. (1972). *Human problem solving* (Vol. xiv). Oxford, England: Prentice-Hall.

Oddo, S., Lux, S., Weiss, P. H., Schwab, A., Welzer, H., Markowitsch, H. J., & Fink, G. R. (2010). Specific role of medial prefrontal cortex in retrieving recent autobiographical memories: An fMRI study of young female subjects. *Cortex*, *46*(1), 29–39. doi:10.1016/j.cortex.2008.07.003

Parker, A., Bussey, T. J., & Wilding, E. L. (2005). *Cognitive Neuroscience of Memory: Encoding and Retrieval*. Psychology Press.

Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., & Nichols, T. E. (2011). *Statistical Parametric Mapping: The Analysis of Functional Brain Images: The Analysis of Functional Brain Images*. Academic Press.

Petrides, M. (2002). The Mid-ventrolateral Prefrontal Cortex and Active Mnemonic Retrieval. *Neurobiology of Learning and Memory*, *78*(3), 528–538. doi:10.1006/nlme.2002.4107

Poppenk, J., Evensmoen, H. R., Moscovitch, M., & Nadel, L. (2013). Long-axis specialization of the human hippocampus. *Trends in Cognitive Sciences*, 1–11. doi:10.1016/j.tics.2013.03.005

Poppenk, J., & Moscovitch, M. (2011). A Hippocampal Marker of Recollection Memory Ability among Healthy Young Adults: Contributions of Posterior and Anterior Segments. *Neuron*, *72*(6), 931–937. doi:10.1016/j.neuron.2011.10.014

Power, J. D., Cohen, A. L., Nelson, S. M., Wig, G. S., Barnes, K. A., Church, J. A., … Petersen, S. E. (2011). Functional Network Organization of the Human Brain. *Neuron*, *72*(4), 665–678. doi:10.1016/j.neuron.2011.09.006

Prince, S. E. (2005). Neural Correlates of Relational Memory: Successful Encoding and Retrieval of Semantic and Perceptual Associations. *Journal of Neuroscience*, *25*(5), 1203–1210. doi:10.1523/JNEUROSCI.2540-04.2005

Ranganath, C., & Paller, K. A. (1999). Frontal Brain Potentials during Recognition Are Modulated by Requirements to Retrieve Perceptual Detail. *Neuron*, *22*(3), 605–613. doi:10.1016/S0896-6273(00)80714-X

Ranganath, C., & Paller, K. A. (2000). Neural correlates of memory retrieval and evaluation. *Cognitive Brain Research*, *9*(2), 209–222. doi:10.1016/S0926-6410(99)00048-8

Rorden, C. (2007). *MRIcron*.

Rubin, D. C. (1982). On the retention function for autobiographical memory. *Journal of Verbal Learning and Verbal Behavior*. Retrieved from http://www.sciencedirect.com.proxy.library.emory.edu/science/article/pii/S0022537182904236

Rubin, D. C. (2005). A Basic-Systems Approach to Autobiographical Memory. *Current Directions in Psychological Science*, *14*(2), 79–83. doi:10.1111/j.0963-7214.2005.00339.x

Rubin, D. C. (2006). The Basic-Systems Model of Episodic Memory. *Perspectives on Psychological Science*, *1*(4), 277–311. doi:10.1111/j.1745-6916.2006.00017.x

Rubin, D. C., Schrauf, R. W., & Greenberg, D. L. (2003). Belief and recollection of autobiographical memories. *Memory & Cognition*, *31*(6), 887–901. doi:10.3758/BF03196443

Rubin, D. C., & Schulkind, M. D. (1997). Properties of word cues for autobiographical memory. *Psychological Reports*. Retrieved from http://www.amsciepub.com.proxy.library.emory.edu/doi/pdf/10.2466/pr0.1997.81.1.47

Rubinov, M., & Sporns, O. (2010). Complex network measures of brain connectivity: Uses and interpretations. *Neuroimage*, *52*(3), 1059–1069. doi:10.1016/j.neuroimage.2009.10.003

Rugg, M. D., & Vilberg, K. L. (2012). Brain networks underlying episodic memory retrieval. *Current Opinion in Neurobiology*, 1–6. doi:10.1016/j.conb.2012.11.005

Rugg, M. D., & Wilding, E. L. (2000). Retrieval processing and episodic memory. *Trends in Cognitive Sciences*, *4*(3), 108–115. doi:10.1016/S1364-6613(00)01445-5

Shibata, H., & Yukie, M. (2003). Differential thalamic connections of the posteroventral and dorsal posterior cingulate gyrus in the monkey. *European Journal of Neuroscience*, *18*(6), 1615–1626. doi:10.1046/j.1460-9568.2003.02868.x

Simons, J. S., & Spiers, H. J. (2003). Prefrontal and medial temporal lobe interactions in long-term memory. *Nature Reviews Neuroscience*, *4*(8), 637–648. doi:10.1038/nrn1178

Sporns, O. (2013). Network attributes for segregation and integration in the human brain. *Current Opinion in Neurobiology*, 1–10. doi:10.1016/j.conb.2012.11.015

Sporns, O., Chivalo, D., Kaiser, M., & Hilgetag, C. C. (2004). Organization, development and function of complex brain networks. *Trends in Cognitive Sciences*, *8*(9), 418–425. doi:10.1016/j.tics.2004.07.008

Spreng, R. N., & Grady, C. L. (2009). Patterns of Brain Activity Supporting Autobiographical Memory, Prospection, and Theory of Mind, and Their Relationship to the Default Mode Network. *Journal of Cognitive Neuroscience*, *22*(6), 1112–1123. doi:10.1162/jocn.2009.21282

Spreng, R. N., Mar, R. A., & Kim, A. (2009). The common neural basis of autobiographical memory, prospection, navigation, theory of mind, and the default mode: a quantitative meta-analysis. *Journal of Cognitive Neuroscience*. Retrieved from http://www.mitpressjournals.org.proxy.library.emory.edu/doi/abs/10.1162/jocn.2008.21029

Squire, L. R. (2004). Memory systems of the brain: A brief history and current perspective. *Neurobiology of Learning and Memory*, *82*(3), 171–177. doi:10.1016/j.nlm.2004.06.005

Squire, L. R., & Bayley, P. J. (2007). The neuroscience of remote memory. *Current Opinion in Neurobiology*, *17*(2), 185–196. doi:10.1016/j.conb.2007.02.006

Squire, L. R., Stark, C. E. L., & Clark, R. E. (2004). The Medial Temporal Lobe. *Annual Review of Neuroscience*, *27*(1), 279–306. doi:10.1146/annurev.neuro.27.070203.144130

Stark, C. E. L., & Squire, L. R. (2001). When zero is not zero: The problem of ambiguous baseline conditions in fMRI. *Proceedings of the National Academy of Sciences*, *98*(22), 12760–12766. doi:10.1073/pnas.221462998

St Jacques, P., Dolcos, F., & Cabeza, R. (2010). Effects of aging on functional connectivity of the amygdala during negative evaluation: A network analysis of

fMRI data. *Neurobiology of Aging*, *31*(2), 315–327. doi:10.1016/j.neurobiolaging.2008.03.012

St. Jacques, P. L., Kragel, P. A., & Rubin, D. C. (2011). Dynamic neural networks supporting memory retrieval. *NeuroImage*, *57*(2), 608–616. doi:10.1016/j.neuroimage.2011.04.039

St Jacques, P. L., Kragel, P. A., & Rubin, D. C. (2013). Neural networks supporting autobiographical memory retrieval in posttraumatic stress disorder. *Cognitive, Affective, & Behavioral Neuroscience*. doi:10.3758/s13415-013-0157-7

Svoboda, E., & Levine, B. (2009). The Effects of Rehearsal on the Functional Neuroanatomy of Episodic Autobiographical and Semantic Remembering: A Functional Magnetic Resonance Imaging Study. *Journal of Neuroscience*, *29*(10), 3073–3082. doi:10.1523/JNEUROSCI.3452-08.2009

Svoboda, E., McKinnon, M. C., & Levine, B. (2006). The functional neuroanatomy of autobiographical memory: A meta-analysis. *Neuropsychologia*, *44*(12), 2189–2208. doi:10.1016/j.neuropsychologia.2006.05.023

Tulving, E. (1983). *Elements of Episodic Memory*. Clarendon Press.

Tulving, E. (2002). Episodic Memory: From Mind to Brain. *Annual Review of Psychology*, *53*, 1–25.

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review*, *80*(5), 352–373. doi:10.1037/h0020071

Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., … Joliot, M. (2002). Automated Anatomical Labeling of Activations in SPM

Using a Macroscopic Anatomical Parcellation of the MNI MRI Single-Subject Brain. *Neuroimage*, *15*(1), 273–289. doi:10.1006/nimg.2001.0978

Valenstein, E., Bowers, D., Verfaellie, M., Heilman, K. M., Day, A., & Watson, R. T. (1987). Retrosplenial Amnesia. *Brain*, *110*(6), 1631–1646. doi:10.1093/brain/110.6.1631

Van Der Werf, Y. D., Jolles, J., Witter, M. P., & Uylings, H. B. M. (2003). Contributions of Thalamic Nuclei to Declarative Memory Functioning. *Cortex*, *39*(4–5), 1047–1062. doi:10.1016/S0010-9452(08)70877-3

Velanova, K., Jacoby, L. L., Wheeler, M. E., McAvoy, M. P., Petersen, S. E., & Buckner, R. L. (2003). Functional–Anatomic Correlates of Sustained and Transient Processing Components Engaged during Controlled Retrieval. *The Journal of Neuroscience*, *23*(24), 8460–8470.

Vincent, J. L., Kahn, I., Snyder, A. Z., Raichle, M. E., & Buckner, R. L. (2008). Evidence for a Frontoparietal Control System Revealed by Intrinsic Functional Connectivity. *Journal of Neurophysiology*, *100*(6), 3328–3342. doi:10.1152/jn.90355.2008

Vincent, J. L., Snyder, A. Z., Fox, M. D., Shannon, B. J., Andrews, J. R., Raichle, M. E., & BUCKNER, R. L. (2006). Coherent Spontaneous Activity Identifies a Hippocampal-Parietal Memory Network. *Journal of Neurophysiology*, *96*(6), 3517–3531. doi:10.1152/jn.00048.2006

Wager, T. D., & Smith, E. E. (2003). Neuroimaging studies of working memory: *Cognitive, Affective, & Behavioral Neuroscience*, *3*(4), 255–274. doi:10.3758/CABN.3.4.255

Wagner, A. D. (1998). Building Memories: Remembering and Forgetting of Verbal Experiences as Predicted by Brain Activity. *Science*, *281*(5380), 1188–1191. doi:10.1126/science.281.5380.1188

Wagner, A. D., Maril, A., Bjork, R. A., & Schacter, D. L. (2001). Prefrontal Contributions to Executive Control: fMRI Evidence for Functional Distinctions within Lateral Prefrontal Cortex. *NeuroImage*, *14*(6), 1337–1347. doi:10.1006/nimg.2001.0936

Watrous, A. J., Tandon, N., Conner, C. R., Pieters, T., & Ekstrom, A. D. (2013). Frequency-specific network connectivity increases underlie accurate spatiotemporal memory retrieval. *Nature Neuroscience*, 1–10. doi:10.1038/nn.3315

Wig, G. S., Schlaggar, B. L., & Petersen, S. E. (2011). Concepts and principles in the analysis of brain networks. *Annals of the New York Academy of Sciences*, *1224*(1), 126–146. doi:10.1111/j.1749-6632.2010.05947.x

Wixted, J. T., & Squire, L. R. (2011). The medial temporal lobe and the attributes of memory. *Trends in Cognitive Sciences*, 1–8. doi:10.1016/j.tics.2011.03.005

Xia, M., Wang, J., & He, Y. (2013). BrainNet Viewer: A Network Visualization Tool for Human Brain Connectomics. *PLoS ONE*, *8*(7), e68910. doi:10.1371/journal.pone.0068910

Appendix A

Table 1

Neutral memory cue words in Study 1.

	Set 1		Set 2		Set 3	
Order	Words	Valence	Words	Valence	Words	Valence
PRACTICE	dinner	neutral	sand	neutral	squirrel	neutral
1	teacher	neutral	money	neutral	door	neutral
2	street	neutral	friend	neutral	bread	neutral
3	paper	neutral	toothbrush	neutral	car	neutral
4	hill	neutral	sofa	neutral	bag	neutral
5	star	neutral	bird	neutral	rain	neutral
6	shoe	neutral	hair	neutral	window	neutral
7	book	neutral	gift	neutral	kitchen	neutral
8	doctor	neutral	shirt	neutral	dog	neutral
9	night	neutral	computer	neutral	flower	neutral
Extra	table	neutral	candy	neutral	bicycle	neutral
Extra	picture	neutral	key	neutral	hand	neutral
Extra	field	neutral	card	neutral	fence	neutral
Extra	tree	neutral	bridge	neutral	ball	neutral
Extra	basket	neutral	house	neutral	paint	neutral
PRACTICE	friend	unhappy	car	unhappy	paper	unhappy
10	key	unhappy	ball	unhappy	basket	unhappy
11	card	unhappy	rain	unhappy	picture	unhappy
12	hair	unhappy	kitchen	unhappy	night	unhappy
13	shirt	unhappy	fence	unhappy	tree	unhappy
PRACTICE	dog	happy	doctor	happy	bird	happy
14	window	happy	hill	happy	toothbrush	happy
15	fence	happy	teacher	happy	computer	happy
16	car	happy	paper	happy	sand	happy
17	kitchen	happy	night	happy	house	happy
18	bridge	unhappy	hand	unhappy	book	unhappy
19	gift	unhappy	flower	unhappy	shoe	unhappy
20	sofa	unhappy	dog	unhappy	dinner	unhappy
21	house	unhappy	bread	unhappy	doctor	unhappy
22	money	unhappy	bicycle	unhappy	field	unhappy
23	squirrel	happy	dinner	happy	key	happy
24	door	happy	star	happy	gift	happy
25	bicycle	happy	street	happy	hair	happy
26	bag	happy	table	happy	money	happy
27	rain	happy	picture	happy	candy	happy
Extra	sand	unhappy	squirrel	unhappy	table	unhappy

Extra	toothbrush	unhappy	paint	unhappy	street	unhappy
Extra	bird	unhappy	bag	unhappy	teacher	unhappy
Extra	computer	unhappy	door	unhappy	hill	unhappy
Extra	candy	unhappy	window	unhappy	star	unhappy
Extra	paint	happy	tree	happy	bridge	happy
Extra	bread	happy	book	happy	sofa	happy
Extra	flower	happy	basket	happy	card	happy
Extra	hand	happy	field	happy	friend	happy
Extra	ball	happy	shoe	happy	shirt	happy