

THE EFFECT OF DOMAIN GENERAL AGE-RELATED COGNITIVE CHANGES ON THE
PATTERN COMPLETION BIAS AND EPISODIC MEMORY

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ABSTRACT

Chris Michael Foster: The effect of domain general age-related cognitive changes on the pattern completion bias and episodic memory
(Under the direction of Kelly S. Giovanello)

Several prominent theories have been developed to account for changes in cognition that occur with age, and most of these theories focus upon age-related impairments in domain-general cognitive processes, such as processing speed, cognitive resources, and inhibitory functions. However, a relatively new theory has been put forth to account for age-related changes that are specific to episodic memory. The pattern completion bias (PCB) in aging theory suggests that older adults are biased to generalize a novel but similar representation (i.e., pattern complete) as opposed to creating a distinct representation (i.e., pattern separate). It has yet to be tested whether domain-general theories of cognitive aging may account for, or alter, the PCB in aging. To this end, the current dissertation project consisted of three experiments, each manipulating the study phase of the mnemonic similarity task, to assess the contribution of cognitive slowing (Experiment 1), reductions in cognitive resources (Experiment 2), and reduced inhibitory function (Experiment 3) to the age-related PCB. Regardless of the manipulation at encoding, the test phase consisted of recognition judgments regarding whether the object was a repetition of a previously seen object, a rotated version of a previously seen object, or a novel object. Successful pattern separation was measured as the ability to correctly recognize that an object was rotated at test, as compared to the orientation presented at study. The results indicate that processing speed and inhibitory function are contributors to the PCB in aging. However,

although attentional resources are critical for the formation of complex memories, there was limited evidence to support the hypothesis that attentional resources contribute to the pattern completion bias. The current set of experiments provide novel support for the notion that pattern separation processes are altered by a variety of domain-general processes that change with age. Therefore, the mnemonic similarity task, thought to specifically tax pattern separation, captures domain-general processes as well as pattern separation processes. Future research should modify the mnemonic similarity task to account for domain-general cognitive aging processes, as well as investigate the neural underpinnings of older adult improvements on the task when these accommodations are considered.

TABLE OF CONTENTS

LIST OF FIGURES	viii
LIST OF TABLES	ix
LIST OF ABBREVIATIONS.....	x
CHAPTER 1: COGNITIVE AGING	2
1.1 Introduction	2
1.2 Domain general theories of cognitive aging	5
1.2.1 Processing speed theory.....	5
1.2.2 Resource deficit	7
1.2.3 Inhibition deficit	9
1.3 The pattern completion bias in aging	10
CHAPTER 2: THE CURRENT PROPOSAL	15
2.1 The interaction of cognitive aging theories.....	15
2.2 General experimental procedures.....	16
2.2.1 Participants.	16
2.2.2 Stimuli	17
2.2.3 General Task design	19

2.2.4 Analysis plan	20
CHAPTER 3: EXPERIMENTS AND RESULTS.....	23
3.1 Experiment 1 - Processing speed and the completion bias	23
3.1.1 Results	25
3.1.1.1 Participants.....	25
3.1.1.2 Old/New Recognition and the overall lure discrimination index	25
3.1.1.3 Lure discrimination index results across all trials – Repeated measures ANOVA	26
3.1.1.4 Lure discrimination index results across all trials – Multilevel model	28
3.1.1.5 Rotation test	32
3.1.1.6 Individual differences in the lure discrimination index	32
3.1.2 Discussion.....	34
3.2 Experiment 2 - Resource deficit and the completion bias.....	37
3.2.1 Results	40
3.2.1.1 Participants.....	40
3.2.1.2 Old/New Recognition and the overall lure discrimination index	41
3.2.1.3 Lure discrimination index results across all trials – Repeated measures ANOVA	42
3.2.1.4 Lure discrimination index results across all trials – Multilevel model	43
3.2.1.5 Rotation test	44
3.2.1.6 Individual differences	45

3.2.2 Discussion.....	47
3.3 Experiment 3 - Inhibition deficit and the completion bias.....	51
3.3.1 Results	54
3.3.1.1 Participants.....	54
3.3.1.2 Old/New Recognition and the overall lure discrimination index	54
3.3.1.3 Lure discrimination index results across all trials – Repeated measures ANOVA	56
3.3.1.4 Lure discrimination index results across all trials – Multilevel Model.....	57
3.3.1.5 Rotation Test.....	58
3.3.1.6 Individual differences in the lure discrimination index	59
3.3.1.6 Discussion	60
CHAPTER 4: GENERAL DISCUSSION	65
4.1 Limitations	70
4.2 Conclusions	73
REFERENCES	95

LIST OF FIGURES

Figure 1. Results from a mnemonic similarity task showing the altered “tuning curve”	77
Figure 2. Example stimuli.....	78
Figure 3. Experiment 1 old/new recognition and overall lure discrimination performance.....	81
Figure 4. Experiment 1 lure discrimination results across all trial types.....	82
Figure 5. Experiment 1 lure discrimination across all trial types.	83
Figure 6. Model implied intercepts and slopes in Experiment 1.	84
Figure 7. Experiment 2 results from old/new recognition and overall lure discrimination.....	87
Figure 8. Experiment 2 Lure discrimination index across all trials.....	88
Figure 9. Experiment 2 Lure discrimination across all trials.....	89
Figure 10. Experiment 3 old/new recognition and overall lure discrimination index.	91
Figure 11. Experiment 3 lure discrimination index across all trials.	92
Figure 12. Experiment 3 lure discrimination index across all trials.	93

LIST OF TABLES

Table 1. Experiment 1 Demographic and Cognitive Testing Data.....	79
Table 2. Parameter Estimates from Experiment 1	80
Table 3. Experiment 2 Demographic and Cognitive Testing Data.....	85
Table 4. Parameter Estimates from Experiment 2	86
Table 5. Experiment 3 Demographic and Cognitive Testing Data.....	90
Table 6. Parameter Estimates from Experiment 3	94

LIST OF ABBREVIATIONS

PCB	Pattern completion bias
PS	Pattern separation
PC	Pattern completion
OA	Older adult
YA	Younger adult
ICC	Intra-class correlation
ANOVA	Analysis of variance

Chapter 1: Cognitive Aging

1.1 Introduction

Changes in cognition occur in all individuals as they age. These changes may take many forms; however, it is common to see impairments in perception, attention, processing speed, episodic memory, and working memory (Craik & Salthouse, 2008). While many aspects of cognition change with age, memory complaints are the most frequently reported by older adults (OAs; Newson & Kemps, 2006). Several prominent theories have been developed to account for these changes, including a change in processing speed (Salthouse, 1996a; 1996b), reductions in cognitive resources (Craik, 1983; Craik & Byrd, 1982), and impairments in inhibitory processes (Hasher & Zacks, 1988; Lustig, Hasher, & Zacks, 2007; Zacks, Hasher, & Li, 2000). These theories are domain-general explanations of cognitive aging in that a single factor explains a wide variety of cognitive changes that occur in aging. A relatively new theory of cognitive aging, hereafter referred to as the pattern completion bias (PCB), has been put forth to account for age-related episodic memory deficits. This theory posits that OAs, due to anatomical and functional changes within a medial temporal lobe brain structure called the hippocampus, are biased to pattern complete (PC; i.e., retrieve a pre-existing representation when exposed to a novel but similar representation) as opposed to pattern separate (PS; i.e., create a distinct representation even if it is similar to a stored representation). The PCB reflects an increase in the likelihood that OAs will indicate that a similar, but novel, representation is identical to a representation stored in memory (Toner, Pirogovsky, Kirwan, & Gilbert, 2009; Yassa & Stark, 2011; Yassa et al.,

2011a). The current set of experiments tested a key tenet of the PCB theory of cognitive aging, namely, that the PCB in aging cannot be accounted for by manipulating features of the task (e.g., decision making time, strategy, etc.) that may differentially impact OA's memory performance (Stark, Stevenson, Wu, Rutledge, & Stark, 2015). Despite this claim, very little research has been conducted that specifically addresses how domain-general theories of cognitive aging might moderate the PCB. I hypothesized that if age-related changes in domain-general processes are accounted for in an experimental design, then the PCB in aging will be reduced. Similarly, I hypothesized that young adults (YAs), when placed under certain experimental conditions, would also show a PCB.

The domain-general theories of cognitive aging suggest that a primary reason for poorer memory performance in OAs is a reduction in the fidelity of the encoded memory representation. For example, the processing speed theory suggests that OAs either need more *time* to create a robust representation, or are unable to build the same quality of representation due to degradation of previously processed information over time (Salthouse, 1996). The resource deficit theory posits that OAs are less able to deploy an efficient strategy to encode a representation (Craik, 1983). The inhibition deficit suggests that OAs are less able to maintain a clean mental workspace and, therefore, are more likely to encode (or be distracted by) irrelevant information, thereby reducing the quality of the goal relevant representation (Zacks et al., 2000). I hypothesized that domain-general aspects of aging would contribute to the PCB observed in OAs.

Prior research investigating the PCB has focused primarily on the neural mechanisms that account for age-related changes in episodic memory. However, only one study has examined whether aspects of the memory task design may be able to moderate the PCB in OAs (Stark et

al., 2015). Stark et al. (2015) manipulated several aspects of the memory task (e.g., incidental versus intentional encoding, time at decision making, types of response options) and found that none of these task design changes ameliorated the PCB in aging. As such, Stark and colleagues (2015) conclude that, “these data support the notion that underlying changes in the brain circuitry, specifically within the hippocampus, cannot be overcome to improve performance on this task” (p. 14).

To investigate whether domain-general aspects of cognitive aging may moderate the PCB, three experiments were conducted. Each experiment manipulated the study phase of an image-based memory task in order to assess the contribution of cognitive slowing (Experiment 1), reductions in cognitive resources (Experiment 2), and reduced inhibitory function (Experiment 3) to the age-related PCB. Regardless of the manipulation at encoding, the test phase consisted of recognition judgments regarding whether the object was a repetition of a previously seen object, a rotated version of a previously seen object, or a novel object. Pattern separation and PC processes were measured as the ability to identify rotated objects at test. Each experiment manipulated one variable to assess its’ impact on the PCB observed in aging. If the PCB in aging can be reduced by any of the experimental manipulations, it would offer novel evidence that PS and PC processes are moderated by domain general cognitive processes. The current set of experiments provide an important step in building a more comprehensive understanding of the mechanisms that give rise to age-related alterations in episodic memory function. To begin, the prominent theories of cognitive aging are discussed, followed by a summary of episodic memory deficits as they relate to the PCB. Next, a description of each experiment is provided, including rationale, methods, and results. This dissertation concludes with a discussion of the broad implications of the findings.

1.2 Domain general theories of cognitive aging

1.2.1 Processing speed theory

One of the most pervasive and influential theories of cognitive aging is the processing speed theory (e.g., Salthouse, 1996a). This theory suggests that the rate at which information is processed slows as we age (proposed to be mediated by alterations in white matter integrity), and that this slowing of processing speed has downstream effects on essentially all aspects of cognition (Craik & Salthouse, 2008; Persson et al., 2006; Salthouse, 1996b). Importantly, such slowing is thought to be a general mechanism of age-related cognitive change since a variety of speed measures share significant variance with age, and the relationships are not moderated by health factors, experience, or practice (Salthouse, 1996a; 2000). Further, changes in a wide variety of cognitive processes including memory, reasoning, and spatial abilities are significantly mediated by measures of processing speed (Salthouse, 1996a). For example, Salthouse (1996b) investigated the relation between memory performance, age, and a general factor of processing speed. A significant amount of variance in recall memory performance was accounted for by age (.289 – variance in recall performance accounted for by age); however, after accounting for a general processing speed measure derived from a large number of tests proposed to measure processing speed, the variance in memory performance accounted for by age was dramatically reduced and no longer significant (.016 – variance in recall performance accounted for by age controlling for processing speed). Thus, while processing speed accounts for many changes in cognition that occur with age, it may specifically account for many of the age-related changes in episodic memory.

Such age-related processing speed changes have been linked to white-matter health across the brain. For example, measures of white matter hyperintensities (i.e., a general measure

of white matter health) are correlated with motor speed (Soderlund et al., 2003). Fractional anisotropy (a measure of white matter integrity) has been shown to correlate with reaction times in a visual detection task (Madden et al., 2004) as well as other measures of processing speed (O'Sullivan, Jones, Summers, Morris, Williams, & Markus, 2001; Persson et al., 2006; Stebbins et al., 2001).

The processing speed theory of aging is proposed to affect cognition primarily through two mechanisms, the *limited time mechanism* and the *simultaneity mechanism* (Salthouse, 1996a). The limited time mechanism suggests that, due to OA's slower processing speed, when a task has time constraints, OAs are not be able to complete all relevant cognitive operations required by the task, or at least not to the same extent as YAs. This could lead to a host of problems, but in the case of memory, it is likely that the encoded representation is not of the same strength or quality as YAs due to fewer features of the event being processed. The simultaneity mechanism suggests that the products of earlier operations are lost or degraded in OAs because of the extended time needed to complete each step of the cognitive process. Therefore, if a cognitive operation requires the combination of previously distinct processes (e.g., a multi-staged math problem where the product from an early operation in the problem needs to be held in mind and combined with the product from a later operation) then this combination would not occur as efficiently or, potentially, not at all. Again, in relation to memory phenomena, if an association is to be formed either within or between stimuli, it is likely that the to-be-encoded stimuli are not bound as efficiently in an integrated memory trace since the parts of the stimuli that are attended to early on may not be as robust when these features need to be bound to later attended aspects of the stimulus or event.

1.2.2 Resource deficit

Another prominent theory of cognitive aging is the resource deficit theory (e.g., Craik, 1983, 1986; Craik & Byrd, 1982). In essence, this theory suggests that OAs have diminished processing resources in the form of reduced attentional or working memory capacity. Processing capacity refers to the idea that the mind has a finite pool of resources. As we engage in attention demanding tasks, that pool of resources is reduced, leaving fewer resources available to deploy to other information and cognitive tasks. Thus, if OAs' have an overall reduction in the available pool of resources, all tasks will necessarily use a greater proportion of the available resources. A decrease in resources is thought to arise from a reduction in frontal lobe functioning (Craik, 1983). Reduced resources impose restrictions on the ability to accomplish resource demanding tasks, including self-initiated encoding processes, generation of novel connections, and the use of strategic process that may improve encoding or retrieval (Zacks, Hasher, Li, 2000). If OAs use the same amount of resources as YAs during *strategic processing*, then there are fewer resources available to deploy to the *to-be-encoded information*. If, however, OAs use the same amount of resources as YAs to process the *to-be-encoded information*, then OAs have fewer resources available for strategic processes that may aid in the efficient encoding and retrieval of that representation. Essentially, if OAs have a reduction in available resources, all cognitively demanding tasks will necessarily be more difficult for OAs (Anderson, Craik, Naveh-Benjamin, 1998). In the case of memory, OAs reduced resources lead to an impairment in the strength or quality of the encoded stimulus, or a reduced ability to strategically encode that stimulus, leading to worse memory performance overall.

Evidence for this theory comes from a wide variety of paradigms, each of which implement some measure of divided attention (e.g., Anderson et al., 1998; Craik & McDowd,

1987; Jennings & Jacoby, 1993; Kim & Giovanello, 2011; Naveh-Benjamin, Craik, Guez, & Kreuger, 2005). For example, Anderson et al. (1998) required a group of YAs and OAs to encode words with no secondary task (i.e., during full attention) or while performing a secondary continuous reaction time task (i.e., divided attention). Again, the resource deficit theory posits that OAs have fewer resources than YAs, and thus, if YAs are engaged in a divided attention task, their performance on the primary task should mimic that of OAs (since there are fewer resources to devote to the primary task). Anderson et al.'s results showed that YAs exhibit a reduction in memory during divided attention that closely mimics that of OAs under full attention. Similarly, Naveh-Benjamin et al. (2005) asked participants to constantly track a stimulus presented on a screen with a computer mouse. Young adults in this study exhibited memory impairments when their attention was divided at encoding, as compared to the full attention condition; however, not to the extent of OAs. These results provide some evidence that the memory changes associated with aging reflect a reduction in the available attentional resources in OAs.

Craik and McDowd (1987) also showed that OAs have a greater cost on secondary task performance during recall tasks, suggesting that OAs have fewer resources available when performing cognitive operations that support memory retrieval; however, secondary task costs are minimal during recognition as compared to free recall. In combination, these studies suggest that the reduction of attentional resources occurs during all stages of memory (e.g., encoding and retrieval) and that the reduction of attentional resources can account for many of the episodic memory changes associated with age.

1.2.3 Inhibition deficit

The inhibitory control deficit in aging primarily concerns the ability to manage the contents of working memory (Hasher & Zacks, 1988) and is thought to arise from reduced inhibitory control mechanisms supported by frontal lobe functioning (Jonides, Marshuetz, Smith, Reuter-Lorenz, Koeppe, & Hartley, 2000). Hasher and her colleagues have proposed three mechanisms by which the contents of working memory are controlled: Access, deletion, and restraint (Lustig, Hasher, & Zacks, 2007). Access refers to the ability to control what enters working memory. Access deficits in aging have been demonstrated in studies in which words are displayed on top of line drawings. Participants are told to ignore the words and identify the drawings. Older adults, relative to YAs, show later priming for the superimposed words, suggesting that OAs are less able to ignore the words (or at least prevent access of the words into working memory) during encoding (Rowe, Valderrama, Hasher, & Lenartwoicz, 2006; Kim, Hasher, & Zacks, 2007).

Deletion refers to the ability to remove irrelevant information from working memory. Deleting information from working memory should occur if that information is no longer useful, if it accidentally entered working memory, or if it is interfering with other ongoing operations. Evidence for age-related alterations in the deletion function may be observed in working memory span studies and directed forgetting investigations. Typically, measures of working memory span increase in difficulty in a linear fashion when to-be-remembered lists get longer and longer with each trial. When these typical span measures are reversed, aging deficits are greatly reduced, suggesting that OAs have difficulty with proactive interference or deleting irrelevant information (Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999; Rowe, Hasher, & Turcotte, 2008). The deletion function has also been shown to be important for long

term memory. Directed forgetting experiments, experiments in which certain studied stimuli are directed to be remembered and other studied stimuli are directed to be forgotten, indicate that YAs are better able than OAs at suppressing previously encountered representations to aid in the efficient memory of the current, to-be-remembered representations (Zacks, Radvansky, & Hasher, 1996).

Restraint refers to the ability to prevent pre-potent responses or representations from entering working memory when these processes are not goal relevant. May and Hasher (1998) provided evidence for impairments in the restraint mechanism by instructing participants to stop responding intermittently on a category verification task (e.g., respond “yes” when an exemplar was part of the category word and “no” when it was not). Older adults were just as accurate during the response portion of the task, but much more likely to make errors when they, as compared to YAs, were supposed to withhold a response. In sum, OAs are less capable of controlling what enters the contents of, and stays within, working memory. The aforementioned inhibitory mechanisms are important for preventing “mental clutter”, such that the information that is maintained in mind during a task is related only to the goals of the current task.

1.3 The pattern completion bias in aging

The cognitive aging theories discussed thus far are domain-general theories, in that they account for age-related changes in a wide array of cognitive domains with a single process. As described above, these global changes in cognition have a clear and measurable impact on memory; however, this impact arises from upstream effects on what is processed and, therefore, remembered. For example, if processing speed is reduced, time constraints will impact what aspects of the environment are processed. This could affect the deployment of attention, the

quality of processing that occurs during encoding, the type of processes that can be executed at decision making, or the rate at which prior knowledge can be accessed and used strategically.

Despite the variety of global changes in cognition that occur with age, OAs report episodic memory changes, memories of the past that contain details of an event and its surrounding context, as their primary complaint (Newson & Kemps, 2006; Tulving, 1972). While several theoretical distinctions in the memory literature have been created to explain the phenomenological aspects of episodic memories, as compared to memories that have no contextual details or are only expressed through behavior (e.g., declarative/non-declarative, implicit/explicit, recollection/familiarity), it is generally agreed upon that episodic memories require the hippocampus to be encoded and retrieved. The hippocampus is proposed to support episodic memory by aiding in the creation of an orthogonalized neural code, even when the to-be-encoded representation is similar to one encountered in the past. The ability to create a novel code in the face of similarity is referred to as PS, while the ability to generalize degraded or partial information into a previously stored code is referred to as PC. Pattern separation and PC are critical for storing and retrieving episodic memories, as these processes prevent catastrophic interference from similar episodes (Yassa & Stark, 2011). Importantly, PS should not be thought of as encoding and PC should not be thought of as retrieval. Both PS and PC operate on a single stream of neural input. Therefore, both PS and PC contribute to a process of mnemonic discrimination such that the neural input is either made more distinct, or made more similar to previously encountered mnemonic representations.

Recently, the notion has been put forth that age-related episodic memory deficits reflect a bias to PC, also known as *representational rigidity* (Yassa & Stark, 2011). In other words, when two events have overlapping details, OAs are biased to encode the similar, but new event, as the

same as a previously encountered (old) event. To this end, YAs would be more likely to encode a similar event as a new episode, while OAs would not. Further, the PCB in aging relies almost solely on functional and anatomical changes in the hippocampus to support the theory and its predictions. For example, OAs experience a significant reduction of input from the entorhinal cortex to the dentate gyrus/cornu amonis 3, a significant reduction in dentate gyrus volume, and an overall reduction in inhibitory interneurons throughout the hippocampus (Brickman et al., 2011; Wilson, Gallagher, Eichenbaum, & Tanila, 2006).

While the PCB in aging is mediated by age-related changes in the hippocampus, there is also a preponderance of behavioral evidence using the mnemonic similarity task (Kirwan & Stark, 2007) that support the PCB theory of cognitive aging (e.g., Holden, & Gilbert, 2012; Ly, Murray, & Yassa, 2013; Pidgeon, & Morcom, 2014; Yassa et al., 2011b; Yassa, & Stark, 2010; Reagh et al., 2014; Stark et al., 2013; Stark et al., 2015; Toner et al., 2009). The mnemonic similarity task is thought to tax PS processes due to the inclusion of repeated items, similar lures, and novel foils presented during the recognition portion of the experiment. Critically, the similar lures are crafted to create a range of similarity in which some lures are extremely similar to previously studied items and others are related, but dissimilar to previously studied items. Across this range of similarity, experimenters can assess how much novelty is needed before participants are able to recognize that an item is “similar”, but “new”.

The mnemonic similarity task has consistently supported the idea that OAs require more novelty to store a similar episode as new. Toner et al. (2009) showed that OAs are more likely to indicate that a “similar” item is “old” as compared to YAs. Thus, OAs experience greater interference when distinguishing similar from old (repeated) trials. When looking across levels of similarity, Yassa et al. (2011b) showed that YAs perform similarly to OAs when the stimuli

are the most similar; however, as stimuli become less similar, YAs exhibit a more rapid improvement in the ability to say a “similar” trial is “similar” as compared to OAs. The fact that YAs ability to indicate a “similar” trial is “similar” improves more rapidly than OAs, confirms the prediction that OAs experience a bias to PC.

Older adults’ PCB is also exemplified graphically by an altered “tuning curve” (see Figure 1A; Stark et al., 2013). The reduction in the initial steepness of the curve, as compared to YAs, shows that OAs require more novelty to indicate an object is “similar”. Importantly, the anchor points of the curve, the ability to indicate that an exact repeat is “old” and a new item is “new”, are typically around the same performance level (e.g., Toner et al., 2009; Stark et al., 2013; Yassa et al., 2011b), though they are not always exactly the same (see Figure 1B; Stark et al., 2013). Concluding that OAs, or any group, have impairments in PS relies on differences in performance across the curve. Even if there are small deviations in the anchor (as can be seen in Figure 1B) the critical differences lay in how performance changes as similarity decreases. The PCB has been tested across several types of processing engaged during learning and memory, including spatial memory (Reagh et al., 2014; Stark, Yassa, & Stark, 2010), as well as perceptual and conceptual memory using both pictures (Pidgeon & Morcom, 2014) and words (Ly, Murray, Yassa, 2013). The range of memory tasks that have yielded similar results suggests that PS and PC processes are fundamental memory functions, and that the alteration of these processes with age underlies episodic memory functions, regardless of the type of processing or modality.

Not only has the PCB in aging been assessed across several domains of learning and memory, several aspects of the mnemonic similarity task have been manipulated to determine whether the task design may contribute to the PCB in aging (Stark et al., 2015). Stark and colleagues (2015) manipulated the time given to make the memory judgement, intentionality of

encoding, as well as several other features of the task. They manipulated the time allowed for decision making under the assumption that processing speed changes at decision may bias OAs to choose old responses more so than YAs. Intentionality of encoding was also manipulated to assess whether part of the PCB in aging is the result of OAs and YAs differentially deploying attentional resources during incidental encoding. Regardless of the manipulation, OAs were consistently found to show impairments on the mnemonic similarity task and these impairments were not improved when taking into account the aforementioned aspects of the task design.

The crux of the current proposal relies on a key feature of the PCB in aging. Namely, the PCB theory suggests that the episodic memory deficits that occur in aging reflect a mechanistic property of the hippocampus, such that the balance between PS and PC is altered by age via impaired functioning of the hippocampus. Based on a series of experiments that manipulated certain features of the mnemonic similarity task, Stark et al. (2015) conclude that OAs' performance on the mnemonic similarity task cannot be improved; however, this study primarily focused on aspects of the task that may impact the decision making process. Further, the only manipulation implemented at encoding (intentional vs. incidental encoding) was used to assess whether OAs could improve their performance. Thus, there is an open question as to what manipulations at encoding, if any, may alter the PCB in aging. The Stark et al. (2015) study also leaves open the question of what manipulations would be necessary to cause YAs to perform like OAs.

Chapter 2: The current proposal

2.1 The interaction of cognitive aging theories

Given the limited evidence to support the conclusion that OAs' performance on the mnemonic similarity task cannot be improved, the current proposal tested the hypothesis that the PCB in aging can be moderated when experimentally controlling for domain-general processes that also change with age. Specifically, Experiment 1 manipulated time at encoding to assess the role of processing speed on the PCB. Experiment 2 implemented a divided attention task to assess the impact of attentional resources on the PCB, and Experiment 3 implemented a directed forgetting paradigm to assess the role of inhibition in the PCB. If the PCB in aging can be moderated by domain-general processes it would provide evidence that the mnemonic similarity task captures more aspects of cognitive aging than simply mnemonic changes. Further, if the PCB in aging can be moderated by domain-general processes, it would provide novel evidence that impairments to memory caused by hippocampal changes are exacerbated by cognitive processes thought to occur outside of the hippocampus. These results would offer new strategies by which OA memory impairments may be reduced, and open new avenues of research to understand the mechanisms that cause age related memory changes. In the following pages, the general procedures that are common to all experiments are outlined first, followed by a description of each experimental design, the results, and a discussion of the findings. The dissertation ends with a discussion of the broader implications of the findings.

2.2 General experimental procedures

2.2.1 Participants.

Each experiment used a within subjects design and included approximately 50 subjects (25 YAs and 25 OAs). Young adults ranged in age from 18 – 27 years and were recruited from either the Psychology and Neuroscience 101 research participant pool at UNC Chapel Hill or through flyers displayed throughout the campus and surrounding areas. Older adults ranged in age from 60 – 86 years and were recruited through a participant database established within the Cognitive Neuroscience of Memory Laboratory, emails sent throughout the campus, flyers posted around campus, and flyers posted in the local community, including retirement communities and senior centers. All participants were screened for cognitive impairments using the Mini Mental State Exam (MMSE) and were required to score a 27 or higher to be included in the study (Folstein, Folstein, & McHugh, 1975). None of the participants recruited for the reported experiments met these exclusionary criteria.

Participants were also given several cognitive tests to obtain standardized measures of cognition. All participants completed the digit span forward and backward, both of which are subtests of the Wechsler Adult Intelligence Scale and thought to measure working memory capacity and functioning (Wechsler, 2008). Digit span forward requires that participants repeat back a list of numbers, and the number of digits increases in length. Digit span backwards requires participants to hold a list of numbers in mind and repeat them in backwards order (from the order in which they are presented). Following the digit span tasks, participants completed Trails A and B. Trails A is purely a test of processing speed and it was chosen because it does not require a memory component like other processing speed tests (e.g., Digit-Symbol Coding). Trails B is thought to also tap executive function since it requires task switching. For Trails A,

participants connect a series of 25 dots in numerical order. For Trails B, participants connect a series of dots filled with either numbers or letters by alternating between numbers and letters. Finally, conditions 1 through 3 of the color-word interference subtest of the Delis-Kaplan Executive Function System were administered (D-KEFS; Delis, Kaplan, & Kramer, 2001). The color-word interference test is primarily a measure of inhibition. In condition 1, participants must say the color of squares on a page as quickly as possible. In condition 2, participants must read words (e.g., red, blue, and green) as quickly as possible. In condition 3, participants are instructed to name the color of the ink that the word is printed in, while doing their best to ignore the fact that the word itself is a different color than the color of the ink. Participants were then administered the encoding and recognition portions of the mnemonic similarity task. After this portion of the experiment, all participants completed a mental rotation test. For this test, participants were shown an image for 2.5 sec followed by a delay of 2.5 sec. After the delay, they were shown the same image and asked to indicate whether or not it was in the same orientation. If it was in the same orientation, participants pressed “1” on the number keypad to indicate the object was “old”. If it was rotated, participants were instructed to press a number from “2” to “5”. These response options corresponded to the four possible degrees of rotation (i.e., 15° – 55°). Young adults recruited through the Psychology and Neuroscience 101 participant pool received course credit for participation. Any participant not recruited through the psychology 101 participant pool was paid \$10/hour for their time.

2.2.2 Stimuli

Typically, studies using the mnemonic similarity task employ pictures of common objects (e.g., a ping pong paddle, pumpkin, wagon, saxophone, etc.; Yassa et al., 2011a). These common objects also have similar, but different counterparts that vary to some degree from the originally

studied version of the item. The level of similarity was determined by asking participants not involved in the experiment to rate similarity on a likert scale of 1 – 7 (Kirwan & Stark, 2007). These stimuli allow for the measurement of PS/PC processes as similarity decreases; however, this procedure requires the use of subjective ratings of similarity, as opposed to systematically controlling for the level of similarity. Several other designs have been implemented to assess PS abilities, including spatial PS (Reagh et al., 2014), the effects of learning abstract representations on PS (Mattfeld & Stark, 2015), and the effect of repetition on PS (Reagh & Yassa, 2014). However, to my knowledge, only one study has used object stimuli that were systematically varied in lure similarity (Motley & Kirwan, 2012).

Motley & Kirwan (2012) utilized common objects obtained from the Amsterdam Library of Object Images (Geusebroek et al., 2005). Importantly, these objects vary based on the angle at which the picture was taken. Each object was photographed 72 times, once at every 5° of rotation. The assumption in using these stimuli is that the greater the rotation, the less similar the object should be to the previously stored representation, and further, that this manipulation gives experimental control to similarity, as opposed to relying on subjective responses from participants not involved in the experiment itself. Thus, the present set of experiments uses this approach. In keeping with the original study, lure similarity in the current study was operationalized according to four degrees of rotation from the original presentation (rotated 15°, rotated 25°, rotated 35°, and rotated 55°). At test, there were 6 categories of stimuli; the four rotated trial types, as well as new stimuli and exact repeats (see Figure 2). A random angle was chosen for each object presented at study, and this angle was used as 0°, or as the repeat, at test. The amount of rotation was semi-randomly chosen, with the restriction that an even number of

stimuli were present in each of the rotation categories. Further, the rotation off 0° was randomly chosen to be either to the left or right.

2.2.3 General Task design

With a few exceptions, much of the experimental design used for all three experiments was modeled after Reagh & Yassa (2014) who also employed a within-subjects manipulation. One exception is the intentionality of encoding. Prior studies using this paradigm are mixed as to whether or not the researchers used intentional or incidental encoding instructions; however, a study comparing the type of instructions on performance found no main effect of instruction type and no interaction with age and instruction type (Stark et al., 2015). Therefore, I employed intentional instructions under the assumption that this would not have an impact on performance between the age groups.

After informed consent and the completion of the cognitive tests mentioned previously, participants were told about the nature of the memory task. Specifically, before the encoding session, participants were informed about the memory task, including the fact that they would be tested with exact repeats of previously encountered items (to which they should indicate “old”), new items (to which they should indicate “new”), and rotated items (to which they should indicate “rotated”). Participants were given a practice session of both the study and test portions of the memory task before beginning the experiment. During encoding, participants made “toy” or “not toy” judgments. There was no correct answer. The semantic judgment was used to ensure attention was given to each stimulus.

At study, participants were shown a series of 192 common objects, one at a time, for 2.5 sec each with a 0.5 sec inter-stimulus interval (unless otherwise noted). At test, participants were presented with 288 objects, 96 were repeated, 96 were rotated lures, and 96 were novel foils (see

Figure 2). Half of the repeats and lures were taken from the within subjects manipulations described below. This left 12 trials for each level of rotation. Presentation at test was always self-paced. Participants made one of three possible judgments for each object presented at test, either “old”, “rotated”, or “new”.

Finally, to assess whether there were group differences in the ability to discern rotation, all participants were given a brief assessment that investigated their skill at noticing rotation. Participants were shown a series of 25 objects taken from the same library of object images. Five images were presented at each degree of rotation including five from the repeat category. An image was shown for 2.5 sec, covered by a color noise mask (i.e., a patch of randomly colored pixels that completely covered the portion of the screen where the image was presented) for 2.5 sec and then the same image was shown again as either an exact repeat or a rotated version of itself. Participants were given as much time as needed to make the judgment about whether the object was rotated or not. For this task, the response options were “old”, “15°”, “25°”, “35°”, “55°”. All stimuli were presented with E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

2.2.4 Analysis plan

Studies using the mnemonic similarity task have taken several approaches to analyze PS/PC effects; however, these studies tend to use a particular measure to account for response bias for similar trials in the recognition data (Stark et al., 2015). First, simple old/new recognition for repeat items is calculated as the difference between the numbers of “old” responses to repeated stimuli minus “old” responses to foils (i.e., new stimuli that were not encountered at study). The purpose of this correction is to account for individual participant’s bias to generally respond old as compared to correctly responding old. The ability to discriminate

between similar lures is measured using the lure discrimination index. This metric is calculated as the number of “similar” responses given to lure trials minus the number of “similar” responses given to foils. Again, this bias correction is used to correct for the overall tendency to say “similar” versus correctly indicating a stimulus is similar. These two indices, as the dependent variable in the model, are then entered into a 2 (Group: YA vs. OA) X 2 (Memory type: lure discrimination index vs. recognition) x 2 (manipulation type) repeated measures analysis of variance (ANOVA) to assess the effect of age and manipulation on the different assessments of memory. This measure collapses across all levels of similarity and indicates whether OAs experience a deficit in lure discrimination, as well as whether they have an overall impairment in both old/new recognition and lure discrimination.

A more fine grained analysis involves the utilization of a metric that can be investigated across all trial types. The lure discrimination index can also be calculated using “old” responses to correct for bias. In this way, the lure discrimination index is calculated as 1 minus the probability of “Old” responses for each trial type (i.e., the more likely you are to say “Old” the lower the score). Regardless of how the lure discrimination index is calculated, investigating behavioral changes along variations of similarity has been referred to as the behavioral tuning curve (see Figure 1; Stark et al., 2013). In the current study, the tuning curve was analyzed in two ways. In the first analysis strategy, the results were analyzed with a 2 (Group: YA vs. OA) x 2 (experimental manipulation) x 5 (trial type) repeated measures ANOVA. For the second strategy, a linear multilevel model using random intercepts and slopes was used to model the curve directly. Using a linear multilevel model has the added benefit of modeling the curve itself, as well as measuring within person change across the curve.

Regardless of how lure discrimination is measured, it is important to know if the manipulations affected memory overall (e.g., old/new recognition, as well as lure discrimination) or if they affected the lure discrimination to a greater extent than old/new recognition. If old/new recognition and lure discrimination are affected equally, this would suggest that the manipulation did not impact the bias to PS or PC *per se*, but affected the quality of the representation as a whole. If the lure discrimination index is affected to a greater extent than that of old/new recognition, this would suggest that the PC bias in aging is not only caused by altered mnemonic processes supported by hippocampal function, but is caused by a combination of changes in several domains that combine and lead to a PC bias. Thus the operational definition of reducing or increasing the PC bias involves two metrics, 1) the lure discrimination index showing a greater effect than old/new recognition, and 2) that the improvements in performance across levels of similarity is delayed, such that more novelty is needed to PS. It is likely that both metrics will provide complementary information; however, both of the metrics outlined provide somewhat different information as to how the manipulations effect the PCB in aging. Therefore, inferences based on the results of the experiments will be guided by both strategies.

Chapter 3: Experiments and results

3.1 Experiment 1 - Processing speed and the completion bias

According to the limited time mechanism of the processing speed theory, as we age, processing speed declines such that a greater amount of time is needed to complete the same amount of processing as a YA (Salthouse, 1996a). Importantly, there is evidence that when OAs are given a greater amount of time to make recognition judgments during the mnemonic similarity task, the behavioral deficits are attenuated (Allen, Morris, Stark, Fortin, & Stark, 2015; although see Stark et al., 2015 for an opposing finding). As indicated previously, Allen et al. (2015) and Stark et al. (2015) manipulated time at *decision making*, leaving open the question as to whether or not differential time at *encoding* allows OAs to compensate for their slower processing speed and to encode representations that are similar to that of YAs.

Most studies in this line of research have provided both OAs and YAs with two to three seconds to study the to-be-encoded materials (e.g., Stark et al., 2015; Toner et al., 2009; Yassa et al., 2011a). Specifically, related to the type of encoding processes that might support the creation of robust mental representations, it has been shown that not only do OAs tend to have slower processing speed in general, but they also have slower ability to narrow their focus of attention, requiring twice as long as YAs to selectively focus their attention (Jefferies et al., 2015). Therefore, if OAs and YAs are given the same amount of time to encode a complex representation, it is highly unlikely that OAs are able to attend to as many features as YAs, leading OAs to form a more gist-based representation.

To assess whether or not the strength of the encoded representation is impacted by the rate of presentation at encoding, two different rates of presentation were given as a within subjects manipulation to both YAs and OAs. For YAs, half of the stimuli were presented at a rate of 1.25 sec and half were presented at a rate of 2.5 sec. For OAs, half of the stimuli were presented at a rate of 2.5 sec and half were presented at a rate of 5 sec. For both groups, the rate of presentation changed every 8 objects. Participants were also presented with a screen during the regular fixation period indicating whether the next 8 objects would be presented at the fast or slow rate. The rate of presentation that started the study trials was counterbalanced across subjects.

If the PCB occurs because OAs are not able to complete the same type of processing in a limited amount of time given, then two results should be observed. First, YAs, under conditions that employ a 1.25 sec presentation rate for stimulus presentation, should show a bias toward PC, as compared to a condition in which stimuli are presented 2.5 sec. Thus, an interaction between rate of presentation, memory, and age would be found. This data pattern should emerge due to the limited amount of processing that YAs are able to accomplish in the 1.25 sec condition, mimicking the limited time mechanism that occurs in aging. Second, OAs, under conditions that employ a 5 sec rate for stimulus presentation, should show a reduced PCB, as compared to a condition in which stimuli are presented for 2.5 sec. Again, this pattern should be observed because OAs should be able to accomplish a similar amount of processing as YAs when given additional encoding time. In the analysis of old/new recognition and the overall lure discrimination index, OAs should show a reduced lure discrimination index in the 5 sec condition, while YAs in the 1.25 sec condition should show a lure discrimination deficit. In the analysis of the lure discrimination index across all trials, OAs should exhibit a more rapid

improvement in performance across degrees of rotation in the 5 sec condition while YAs in the 1.25 sec condition should exhibit a delay in the improvement of performance across degrees of rotation.

3.1.1 Results

3.1.1.1 Participants

Twenty-five YAs and 25 OAs completed the experiment. We retained all participants' data because no participant performed at chance for old/new recognition during either presentation rates. Our OAs were significantly more educated, $t(48) = -9.47, p < .001$. As expected, our OAs were also slower to perform Trails A, $t(48) = -4.17, p < .001$, Trails B, $t(48) = -2.80, p = .007$, color naming time, $t(48) = -4.01, p < .001$, word reading time, $t(48) = -2.19, p = .033$, and color-word interference time, $t(48) = -5.21, p < .001$. As a more direct measure of inhibition we subtracted the color naming time from the color-word interference time as is recommended in the DKEFS scoring manual (Delis, Kaplan, & Kramer, 2001). This measure was also significantly different between OAs and YAs, $t(48) = -4.14, p < .001$, suggesting that OAs in our sample had reduced processing speed and reduced inhibitory processes. There were no other group differences. See Table 1 for means and standard errors of all the cognitive measures collected.

3.1.1.2 Old/New Recognition and the overall lure discrimination index

Recognition and lure discrimination index scores were calculated for each group and within each speed condition and were analyzed with a 2(Group: YA vs. OA) x 2(rate of presentation: standard (2.5 sec) vs. non-standard (1.25 or 5 sec)) x 2(Memory type: old/new recognition vs. lure discrimination index) repeated-measures ANOVA (see Figure 3). There was a main effect of memory type, $F(1,48) = 384.62, p < .001, \eta_p^2 = .89$, such that old/new

recognition was significantly better than lure discrimination. There was no main effect of group, $F(1,48) = 1.98, p = .166, \eta_p^2 = .04$, and no main effect of rate of presentation, $F(1,48) = 2.59, p = .114, \eta_p^2 = .05$. These effects were qualified by significant interactions between memory type and group, $F(1,48) = 6.97, p = .011, \eta_p^2 = .13$, as well as rate of presentation and group, $F(1,48) = 32.73, p < .001, \eta_p^2 = .41$. No other effects were significant. To better understand the memory type by group interaction we conducted a t-test on the old/new recognition data averaged across the rate of presentation. There was no significant difference between old/new recognition between OAs and YAs, $t(48) = -.26, p = .800$, indicating the interaction resulted from a deficit in OAs lure discrimination as compared to YAs. The results replicate prior findings from Stark and colleagues (2013) and support the idea that OAs perform worse on lure discrimination as compared to YAs, despite maintaining similar performance for old/new recognition. The rate of presentation by group interaction analysis also provided evidence that the rate of presentation altered memory performance. When YAs were given a faster rate of presentation ($M = .43, SD = .09$) their overall memory performance declined, as compared to the regular presentation rate ($M = .47, SD = .13$), whereas when OAs were given a slower rate of presentation ($M = .44, SD = .11$), their overall memory performance improved, as compared to the regular presentation rate ($M = .37, SD = .13$).

3.1.1.3 Lure discrimination index results across all trials – repeated measures ANOVA

Analyzing data between two age groups often requires that differences in response biases be accounted for in the data. In this study, I opted to use a previously established bias correction of one minus the probability of indicating “old” to each trial type. This metric places all 3 trial types (i.e., old, rotated, and new) on the same dependent variable, and assumes that the only difference between old trials and rotated trials is the rate at which participants improve in their

ability to indicate that a stimulus has been rotated. To ensure that this bias metric was appropriate for this data set, I calculated rates of “new” responses both to new trials, and separately, averaged across old and similar trials. T-tests revealed no significant differences between YAs ($M = 80.48$, $SD = 9.54$) and OAs ($M = 78.16$, $SD = 10.61$) in rates of responding “new” to new trials, $t(48) = 0.81$, $p = .420$, and no significant differences in YAs ($M = 3.34$, $SD = 1.69$) and OAs ($M = 2.91$, $SD = 1.5$) rates of responding “new” to old or similar trials, $t(48) = 0.94$, $p = .354$. I also examined the rates of “new” only to old trials and rates of “new” only to lure trials. No significant differences were found, all p 's $> .18$. Therefore, changes in the groups' performance across the lure discrimination index was not influenced by a difference in the ability to recognize an object as previously seen.

The lure discrimination index across all trials was analyzed using one minus the probability of old as the dependent variable and a 2(Group: YA vs. OA) x 2(rate of presentation: standard (2.5 sec) vs. non-standard (1.25 or 5 sec)) x 5(degree of rotation: repeat - 55°) repeated measures ANOVA. Rate of presentation and degree of rotation were within subjects factor and group was a between subjects factor (see Figure 4). Results revealed a significant main effect of degree of rotation, $F(4,192) = 121.93$, $p < .001$, $\eta_p^2 = .72$, such that performance improved significantly across the increasing degrees of rotation. There was no main effect of rate of presentation, $F(1,48) = .23$, $p = .633$, $\eta_p^2 = .01$, but there was a significant main effect of group, $F(1,48) = 6.74$, $p = .012$, $\eta_p^2 = .12$, indicating that YAs performed better than OAs overall. There were no significant interactions between rate of presentation and group, $F(1,48) = 2.13$, $p = .151$, $\eta_p^2 = .04$, degree of rotation and group, $F(4,192) = 1.62$, $p = .170$, $\eta_p^2 = .03$, and rate of presentation and degree of rotation, $F(4,192) = .15$, $p = .964$, $\eta_p^2 < .01$. However, there was a significant three-way interaction between degree of rotation, rate of presentation, and group,

$F(4,192) = 4.06, p = .004, \eta_p^2 = .08$. I conducted a repeated measures ANOVA independently at each degree of rotation to probe the three way interaction with a between subjects factor of group and a within subjects factor of rate of presentation. The only significant effect of group occurred at 25° of rotation, $F(1,48) = 10.30, p = .002, \eta_p^2 = .18$, and at 55° of rotation, $F(1,48) = 7.73, p = .008, \eta_p^2 = .14$. There were, however, significant (or marginally significant) interactions between group and rate of presentation at 15° and 55°, p 's < .066, but no significant interaction between group and rate of presentation when objects were rotated 25° and 35°, p 's > .715. In general, YAs outperformed OAs across all degrees of rotation, except for when the objects are exact repeats. Further, in the exact repeat condition, OAs in the 2.5 sec condition ($M = .34, SD = .16$) and YAs in the 1.25 sec condition ($M = .35, SD = .11$) performed nearly identically, whereas, both groups performed better when they were given more time to encode the materials (OAs 5 sec: $M = .26, SD = .13$; YAs 2.5 sec: $M = .30, SD = .12$). In sum, in the exact repeat condition, both groups performed better during their respective slower rate of presentation. Further, in the 55° rotation condition, both groups performed better in the slower conditions (see Figure 4). These results provide evidence that both OAs' and YAs' mnemonic performance was improved when they were given more time to study the objects, suggesting that the rate of presentation affects pattern separation processes, and that processing speed is an important factor in efficient PS in both OAs and YAs.

3.1.1.4 Lure discrimination index results across all trials – Multilevel model

The advantage of a repeated measures ANOVA in this context is the comparison of mean differences in performance at each level of the task. A complementary way to look at the data is to investigate how YAs' and OAs' performance changes across the different degrees of rotation, instead of whether performance is different at each level of rotation. To investigate this question,

I implemented a multi-level model since such models properly account for nesting, in this case degrees of rotation within people, and account for the correlated residuals within the data set. In support of this choice, I calculated an intra-class correlation (ICC) by running a model with no predictors and a random intercept. An ICC provides a measure of how much variance in the model comes from within subjects as compared to between subjects. The ICC for the current model was .14, indicating that 14% of the variance came from between subjects. Of note, a repeated measures ANOVA would make the assumption that this value is zero. Another advantage of a multi-level model is that it allows for the measurement of within-person change over degrees of rotation, rather than measuring group mean change over degrees of rotation. This procedure affords the opportunity to better understand how the individual's memory performance changes across rotation.

To build an appropriate model for the data set, I tested to ensure a linear model was the best fit, as compared to a model with a quadratic term. Including a quadratic term caused a marginally significant improvement in model fit, $\chi^2(4) = 8.3, p = .081$. The quadratic term was significant in this model, $t(448) = -2.00, p = .046$, however, the estimate of the fixed effect was $-.007$ indicating that the slope curved less than a percent at each degree of rotation. Since there was mixed support for including a quadratic term I did not include it in the final model. Also, the added complexity of a model with a quadratic term is not warranted given the small estimate of the fixed effect. I also tested the model to see if allowing for unequal variance between groups improved model fit and, again, it did not, $\chi^2(4) = 4.0, p = .406$. The final model investigating the lure discrimination index, as calculated using one minus the probability of old, was a linear model with random intercepts (i.e., performance on trials that were exact repeats) and random slopes (i.e., the rate at which performance improved). The model included a between-subjects

effect of group, a within subjects effect of degree of rotation and rate of presentation, and used YAs in the 2.5 sec condition as the reference group.

The analysis indicated there was no effect of group on the ability to indicate that an exact repeat was old, $t(48) = .90, p = .372$, suggesting that when the rate of presentation was the same between the two groups, the rate of endorsing repeated items as “old” was the same for both age groups. The rate of presentation manipulation did have an effect on the ability to indicate an exact repeat was “old” for both groups. An effect of rate of presentation on repeated objects indicated YAs’ performance was significantly worse when they were given a faster rate of presentation, $t(444) = 2.41, p = .016$, and an interaction between group and rate of presentation on intercepts indicated OAs’ performance was significantly better when they were given a slower rate of presentation, $t(444) = -3.94, p < .001$. Therefore, OAs in both rate of presentation conditions were not significantly different in their ability to indicate a repeated object was “old” as compared to YAs in the 2.5 sec rate of presentation condition. Young Adults, however, performed worse during the 1.25 sec rate of presentation condition, as compared to the 2.5 sec condition *and* OAs in the 5 sec rate of presentation condition. OAs in the 5000ms rate of presentation condition performed better than YAs in the 1.25 sec rate of presentation condition *and* OAs in the 2.5 sec rate of presentation condition (see Figure 5).

There was a significant effect of degree of rotation, $t(444) = 12.71, p < .001$, indicating that YAs’ performance in the 2.5 sec rate of presentation condition improved with greater rotation of the object. The rate of improvement was significantly worse for OAs in the 2.5 sec condition, compared to YAs in the 2.5 sec condition, as indicated by a significant interaction between rotation and group, $t(444) = -3.55, p < .001$. The rate of improvement for YAs in the 1.25 sec condition was also significantly worse than YAs in the 2.5 sec condition as indicated by

a significant interaction between rotation and rate of presentation, $t(444) = -2.48, p = .014$.

Finally, OAs in the 5 sec condition's rate of improvement was significantly better than OAs in the 2.5 sec condition as indicated by a significant three way interaction, $t(444) = 3.82, p < .001$.

See Table 2 for parameter estimates.

To better understand the pattern of the results, I calculated simple effects for intercepts and slopes (see model implied results in Figure 6). The pattern of results indicates that OAs, regardless of the rate of presentation manipulation, were not significantly different in their ability to indicate a repeated object is “old” as compared to YAs in the 2.5 sec condition. Further, OAs' performance in the 5 sec conditions improved (slope = .106) in a similar manner to that of YAs' performance in the 2.5 sec rate of presentation condition (slope = .117). Older adults in the 2.5 sec condition also exhibited similar rates of improvement (slope = .072), as YAs in the 1.25 sec condition (slope = .088). Finally, to determine whether the rate of presentation manipulation matched the performance between OAs and YAs, I conducted two t-tests on slopes (i.e., rate of improvement across degrees of rotation). Despite the improvement in slopes for OAs in the 5 sec condition, these participants still had a significantly lower slope than YAs in the 2.5 sec condition, $t(48) = 3.63, p = .001$. Similarly, YAs in the 1.25 sec condition had a steeper slope than OAs in the 2.5 sec condition, $t(48) = 5.31, p < .001$. Therefore, a slower rate of presentation significantly improved OAs slopes; however, it did not completely attenuate the deficit in memory. A faster rate of presentation significantly decreased YAs slopes. However, they still improved across trials more rapidly than OAs in the 2.5 sec condition. Processing speed differences, as manipulated by presentation rate, appear to be a contributor to the PCB in aging.

3.1.1.5 Rotation test

Participants were generally quite poor at indicating the exact degree of rotation during the rotation test. Therefore, I collapsed all estimates of degree of rotation into a single metric of correctly indicating whether an object was rotated or not. There was a significant difference in YAs and OAs ability to discern whether an object was rotated or not as revealed by the rotation test. This difference was significant for accurately indicating an object was an exact repeat, $t(48) = 2.22, p = .031$, indicating an object was rotated, $t(48) = 3.15, p = .003$, and for overall performance on the rotation test, $t(48) = 3.69, p = .001$, with YAs ($M = .90, SD = .06$) outperforming OAs ($M = .83, SD = .08$) overall. Since there was a group difference in the ability to discern whether an object was rotated outside the long term memory aspects of the regular task, I performed follow up analyses controlling for overall rotation test performance for both the repeated measures ANOVA and the multilevel model that investigated the lure discrimination index across all trials. Importantly, the three-way interaction between group, rate of presentation, and rotation remained significant in the repeated measures ANOVA analysis. Further, the pattern of results in the multilevel model remained unchanged after controlling for performance on the rotation test. In combination, these follow up analyses indicate that group differences in the ability to assess rotation in short term memory is not the primary factor for group differences in the ability to notice small changes in long term mnemonic representations.

3.1.1.6 Individual differences in the lure discrimination index

Experiment 1 manipulated processing speed to assess whether there is a significant impact of duration at encoding on measures of pattern separation. While the evidence suggests that processing speed does significantly moderate the PCB in aging, it is also important to understand what individual characteristics of cognition may further contribute to the PCB in

aging. Prior research has investigated individual differences associated with pattern separation (e.g., Toner et al., 2009; Stark et al., 2010). However, both studies had much smaller sample sizes, collected cognitive measures only in OAs, and rarely found significant effects. This leaves open the question as to what types of non-mnemonic cognitive processes, may support efficient PS. It is likely that the lack of significant correlations has contributed to the general notion that PS and PC processes in some ways operate in a vacuum.

As an exploratory analysis, I extracted each individuals' intercept (i.e., model implied performance on old trials), slope (i.e., rate of improvement across the degrees of rotation) and lure trial performance, and correlated that number to their scores on digit span forward and backward, trails A and B, and the measure of inhibition derived from subtracting the color naming time from the color-word interference time. First, I combined both OAs and YAs in the 2.5 sec condition into a single group ($n = 50$). In this condition, both groups were exposed to the same task, and therefore, it is appropriate to assume that the scores in both groups represent the same basic effect. Second, I ran the same correlations with YAs in the 1.25 sec condition as a single group ($n = 25$) and OAs in the 5 sec condition as a single group ($n = 25$). Across all exploratory analyses I performed 45 correlations. A Bonferroni corrected alpha value (i.e., $.05/45$) is .001; however, all significant correlations below an alpha of .05 are reported for completeness.

Correlations derived from the 2.5 sec condition revealed that measures of processing speed and inhibition were found to be significantly correlated with both intercepts and slopes. Participants intercepts were significantly positively correlated with time on Trails B, $r(47) = .34$, $p = .016$. Since Trails B is thought to measure processing speed along with executive function, this correlation suggests that as executive function declines, so does the ability to encode a

representation that supports simple recognition of repeat items. This was the only significant correlation with intercepts. Participants slopes were significantly negatively correlated with time on Trails A, $r(48) = -.51, p < .001$, Trails B, $r(47) = -.48, p < .001$, and the measure of inhibition, $r(48) = -.53, p < .001$. The same pattern of results was found when using lure trial performance such that a significant correlation was found between lure trial performance and time on Trails A, $r(48) = -.41, p = .003$, Trails B, $r(47) = -.38, p = .007$, and the measure of inhibition, $r(48) = -.33, p = .019$. All of the correlations with slopes and lure trial performance suggest that processing speed, executive function, and inhibition correlate strongly the ability to PS. As processing speed, executive function, and inhibition decline, so does the ability to efficiently PS. Therefore, the PCB in aging is likely due to a myriad of cognitive changes that occur with age, as opposed to a deficit in a single domain of cognition (i.e., memory). When looking within groups at the different rate of presentations, only time on Trails B for OAs in the 5 sec condition was found to be significantly correlated, $r(22) = -.43, p = .037$. In sum, processing speed and inhibition have strong relationships with participant's performance, both on their ability to recognize an object as old, and to notice that an object has been rotated.

3.1.2 Discussion

The results of this experiment support the hypothesis that age-related processing speed deficits contribute to the PCB in aging. The analysis of old/new recognition and the overall lure discrimination index replicate a wide body of literature showing that OAs experience a decline in lure discrimination, despite maintaining similar performance on old/new recognition (e.g., Stark et al., 2015; Toner et al., 2009). This result was true regardless of the rate of presentation manipulation, suggesting that giving OAs more time does not improve the memory changes associated with the PCB. Importantly, when using a lure discrimination index that calculates

performance changes across degrees of rotation, a complementary, but slightly different result was found. The core result, that OAs show impairments in lure discrimination, was observed. When YAs and OAs were given the typical rate of presentation (i.e., 2.5 sec) they exhibited similar rates of saying “old” to trials that were exact repeats, yet OAs exhibited a decline in their ability to make fine grain discriminations between previously encountered stimuli and stimuli that were rotated.

The results also revealed that OAs’ and YAs’ ability to efficiently pattern separate was significantly impacted by the amount of time given to study a stimulus. This finding would not be surprising if the manipulation only affected participant’s ability to discriminate between old and new trials. The fact that providing OAs more study time uniquely improved their ability to make fine grain discriminations between previously studied images and the rotated versions presented at test, suggests that the PCB can be modulated by processing speed changes that occur with age. Further, when YAs’ were given less study time, their performance was highly similar to OAs. Not only can OA’s performance be improved to mirror YA’s, YA’s performance can be modulated to mirror that of OA’s. These results are at direct odds with the notion that the PCB in aging cannot be “overcome” (Stark et al., 2015). The hypothesized change of performance based on study time provides compelling evidence that the PCB in aging is not solely based on mnemonic changes associated with age. The sensitivity of pattern separation to rate of presentation indicates a much more complex picture of how mnemonic representations are formed, retrieved, and how aging impacts these processes.

In the context of cognitive aging theories, this experiment adds to a body of literature suggesting that age-related memory changes share variance with measures of processing speed (Salthouse, 2000). More specifically, the results of the current experiment showed correlations

between measures of processing speed (i.e., Trails A and B) and participants' pattern separation performance. While this result fits well within the processing speed literature, it is at odds with some of the findings in the pattern separation literature. Toner et al. (2009) conducted an object pattern separation task and also collected several measures of cognition in OAs. Their results revealed only one significant correlation between performance on lure trials and letter sequencing (i.e., a task similar to Trails A, but using letters). No significant correlations were found between other measures of processing speed that were collected. These results suggest that processing speed shares a minimal relationship with PS abilities, yet the results from the current experiment suggests that processing speed is intimately related to PS. First, there are many differences in the way the correlations were calculated. Whereas the current study used slopes, or the change in performance across as well as average lure trial performance, Toner et al. (2009) used average performance across all lure trials. While correlations were observed with lure trial performance, these relationships were weaker than the correlations with slope. Second, Toner et al. (2009) collected these measures on only 20 older adults and, therefore, likely had significantly less power to find the effect. Despite these issues, even the non-significant correlations were in the same direction. Therefore, the correlations found in this experiment between processing speed measures and performance on the mnemonic similarity task adds to our understanding of what may mediate age-related changes in pattern separation.

The current experiment also adds to the pattern separation literature by providing empirical evidence that memory processes required to support highly detailed discriminations are significantly influenced by processing speed changes. While memory declines with age, this experiment shows that the declines in memory as evidenced by the mnemonic similarity task are not simply the byproduct of inefficient PS processes, but also a byproduct of reduced processing

speed that occurs with age. It also suggests that even in YAs, pattern separation processes require time to form strong mnemonic representations. The importance of this point should not be understated, as understanding how time interacts with pattern separation processes will be a critical next step in building knowledge on the PCB in aging, as well as memory functions in general. It is possible that given even greater study periods (e.g., 7.5 sec), OAs may fully recover mnemonic discrimination performance. If this is found, then it would suggest that PS processes are not the cause of memory changes in mnemonic discrimination and that the PCB in aging is simply a byproduct of age related slowing. This result would fundamentally alter the memory related theories associated with aging. However, this result is unlikely. While greater time at encoding improves mnemonic discrimination on this task, there is ample evidence to support the notion that aging causes neural changes in mnemonic processes that support episodic memory function, and thus, impairments are likely to be found even if encoding times longer than five seconds are used.

3.2 Experiment 2 - Resource deficit and the completion bias

The resource deficit theory proposes that as we age, we experience a decline in the resources that are available to engage in effortful processing (e.g., Craik, 1983, 1986; Craik & Byrd, 1982). Reduced resources impose restrictions on the ability to accomplish cognitively demanding tasks including self-initiated encoding processes, generation of novel connections, and the use of strategic processes that may improve encoding or retrieval (Zacks, Hasher, Li, 2000). One way to assess the role of resources in cognition is to reduce the resources available to engage in a primary task, by having participants simultaneously engage in a secondary task (e.g., Anderson et al., 1998; Craik & McDowd, 1987; Jennings & Jacoby, 1993; Kim & Giovanello, 2011; Naveh-Benjamin, Craik, Guez, & Kreuger, 2005). Performance decrements in the primary

task are caused by a reduction in available resources which are used by the secondary task. In support of the idea that cognitive changes that occur with age are caused by a reduction in available resources, when YA's attention is divided, deficits in performance often mirror that of OAs under full attention conditions (e.g., Anderson et al., 1998; Kim & Giovanello, 2011; Naveh-Benjamin, Craik, Guez, & Kreuger, 2005).

To examine the impact of resources, or a reduction in resources due to age, on PS processes, a divided attention manipulation was used that specifically taxes relational attention (Kim & Giovanello, 2011). Relational attention refers to the idea that attending to relationships within or between stimuli requires a pool of attentional resources that supports relational memory processes. Kim & Giovanello (2011) provided evidence that dividing attention with relational processing produced relational memory deficits in YAs' that mimicked the relational memory deficit seen in OAs under full attention conditions. More specifically, participants intentionally encoded word pairs while also making judgments about which of two numbers, presented simultaneously with the word pairs, was numerically larger. Encoding word pairs and judging the relative numerical size of two numbers requires relational attention. Kim & Giovanello (2011) found that YAs under divided relational attention conditions exhibited relational memory deficits that precisely mirrored that of OAs under full attention. Therefore, a reduction in the pool of relational attention resources may also contribute to the PCB in aging.

While the paradigm employed in this study was not a typical relational memory design (e.g., encoding two words, names with faces, a picture in a certain location, etc.), successfully encoding the stimuli for later distinction between the studied item and similar items required the binding of the stimulus with all of its specific features. For example, when presented with a picture of a "house" at encoding, a typical item memory study would simply show a series of

images and instruct participants to indicate whether or not the “house” was seen previously, without showing other similar houses. Therefore, to successfully indicate that the “house” was in fact seen previously, one simply needs to remember that *a* house was presented at study, not necessarily that specific “house” with all of its unique features. For the current paradigm, participants must remember more about the “house” stimulus than its presence. Participants also need to retrieve the angle at which the “house” was presented by remembering what specific features of the house were visible at encoding. Since successful memory is supported by the encoding of within item features, this paradigm taxes relational memory processes. Therefore, a divided attention manipulation that taxes relational attention was used (Kim & Giovanello, 2011).

Experiment 2 employed the same task design as Experiment 1. However, all stimuli were presented for 2.5sec followed by a fixation for .5sec. During the encoding of the object, participants made one of two judgments, either (1) which of two numbers presented at the bottom of the screen was numerically larger (i.e., the divided attention condition), or (2) whether the object was a toy or not a toy (i.e., the full attention condition). Participants made one number comparison per study image. To reduce the difficulty of task switching, participants were given small blocks (8 images) of divided attention and full attention conditions. Between each transition to the number judgment and toy judgment, a word (i.e., either Toy or Number) was presented during the fixation period to prepare the participant for the type of judgment that would accompany the next 8 objects. The blocks of full attention and divided attention switched back and forth between the two types of decisions until all of the objects were presented. The decision that started the study trials was counterbalanced across subjects such that some participants started with the toy judgment and others started with the number judgment.

If the hypothesis that a reduction in attentional resources contributes to the PCB in aging is supported, OAs in the full attention condition should perform similarly to YAs in the divided attention condition. Therefore, an interaction between age, attention, and memory should be found. In the analysis of old/new recognition and the overall lure discrimination index, OAs in the full attention condition and YAs in the divided attention should show a lure discrimination deficit as compared to YAs in the full attention condition. In the analysis of lure discrimination across all trials, OAs in the full attention condition and YAs in the divided attention condition should show a similar delay in improvement in performance across degrees of rotation as compared to YAs in the full attention condition.

3.2.1 Results

3.2.1.1 Participants

Twenty-five YAs and 19 OAs completed the experiment. One OA participant's data was not recorded due to a technical error. Our OAs were significantly more educated, $t(42) = -6.08, p < .001$. As expected, our OAs were also slower to perform Trails A, $t(42) = -5.60, p < .001$, Trails B, $t(42) = -4.06, p < .001$, color naming time, $t(42) = -4.31, p < .001$, word reading time, $t(42) = -3.07, p < .001$, and color-word interference time, $t(42) = -5.15, p < .001$. Therefore, our sample of OAs exhibited a decrement in processing speed. Again, as a more direct measure of inhibition we subtracted the color naming time from the color-word interference time. This measure was also significantly different between OAs and YAs, $t(42) = -3.73, p = .001$, suggesting that OAs in our sample had reduced inhibitory processes. There were no other group differences. See Table 3 for means and standard errors of all the cognitive measures collected.

3.2.1.2 Old/New Recognition and the overall lure discrimination index

To investigate the effect of age and the attention manipulation on old/new recognition and the overall lure discrimination index, a 2(Group: YA vs. OA) x 2(Attention: Full vs. Divided) x 2(Memory type: Old/new vs. Lure Discrimination) repeated measures ANOVA with group as a between-subjects factor and attention and memory type as a within-subjects factors was conducted. The analysis revealed a significant main effect of the attention manipulation, $F(1,41) = 88.91, p < .001, \eta_p^2 = .68$, such that performance overall was worse during divided attention than during full attention. There was also a significant main effect of memory type, $F(1,41) = 238.31, p < .001, \eta_p^2 = .85$, indicating worse performance for lure trials as compared to old/new recognition. Additionally, a significant main effect of group, $F(1,41) = 19.62, p < .001, \eta_p^2 = .32$, was observed, indicating that overall OAs performed significantly worse than YAs. There was also a significant interaction between the attention manipulation and memory type, $F(1,41) = 26.35, p < .001, \eta_p^2 = .39$, such that the mean difference between memory types was significantly greater in the full attention condition ($M = .38, SD = .16$) than the divided attention condition ($M = .27, SD = .15$). No other effects were significant, all p 's $> .17$.

In sum, OAs' overall performance was significantly worse than YAs' overall performance. However, the divided attention manipulation had a stronger impact on performance than predicted for both OAs and YAs, producing large effects on old/new recognition (see Figure 7). While old/new recognition rates do not need to be precisely the same between groups and conditions, the divided attention task appears to have rendered encoding too weak to support simple old/new recognition in YAs. Further, OAs' performance in the full attention condition was much lower than YAs' in the full attention condition, suggesting that for OAs, the difficulty of the divided attention task carried over into the full attention condition. The effect of divided

attention on old/new performance renders an interpretation about the specific role of PS in this task not possible.

3.2.1.3 Lure discrimination index results across all trials – Repeated measures ANOVA

Since lure discrimination index across all trials relies on similar rates of “new” responses across old and rotated trials, I conducted several group comparisons on “new” response rates. Interestingly, there was a significant difference in rates of “new” responses to trials that were not encountered in the study portion of the task, $t(41) = 3.43, p = .001$, where YAs ($M = 81.16, SD = 11.25$) were significantly more accurate than OAs ($M = 70.78, SD = 10.34$). OAs ($M = 3.90, SD = 3.00$) were significantly more likely than YAs ($M = 2.21, SD = 1.44$) to indicate an old or rotated trial was “new” in the full attention condition, $t(41) = -2.47, p = .018$; however, there was no significant difference between OAs ($M = 6.74, SD = 3.60$) and YAs ($M = 5.67, SD = 1.92$) in rates of responding “new” in the divided attention condition, $t(41) = -1.27, p = .213$. These results confirm the idea that the divided attention manipulation prevented adequate engagement with the to-be-remembered objects such that even a memory strong enough to support simple old/new recognition was impaired.

A 2(Group: YA vs. OA) x 2(Attention: Full vs. Divided) x 5(Rotation: repeat – 55°) repeated measures ANOVA with group as a between-subjects factor and the attention manipulation and degree of rotation as within-subjects factors was used to analyze lure discrimination using one minus the probability of old as the dependent variable. There was a main effect of attention, $F(1,41) = 71.03, p < .001, \eta_p^2 = .63$, such that performance was significantly worse in the divided attention condition, as compared to the full attention condition. There was also a significant main effect of rotation, $F(4,164) = 65.32, p < .001, \eta_p^2 = .61$, indicating that performance improved as the degree of rotation increased. There was no

significant main effect of group, $F(1,41) = .69, p = .410, \eta_p^2 = .02$. There was no significant interaction between the attention manipulation and group, $F(1,41) = 1.74, p = .194, \eta_p^2 = .04$, indicating that overall, the difference in performance between full and divided attention was equal between the two groups. There was, however, a significant interaction between degree of rotation and group, $F(4,164) = 6.74, p < .001, \eta_p^2 = .14$, indicating that OAs' performed significantly worse across the degrees of rotation, and degree of rotation and the attention manipulation, $F(4,164) = 3.31, p = .012, \eta_p^2 = .08$, indicating that there was less improvement in performance across degrees of rotation in the divided attention condition. There was no three way interaction between degree of rotation, group, and the attention manipulation, $F(4,164) = 1.18, p = .321, \eta_p^2 = .028$. In summary, OAs' performance increases across degrees of rotation were less than that of YAs, and when attention was divided, performance was equivalently reduced in both groups (see Figure 8).

3.2.1.4 Lure discrimination index results across all trials – Multilevel model

The ICC for this data set was .19, which indicates that 19% of the variance comes from between subjects as opposed to within subjects. I tested the model to ensure that a linear model was appropriate and found no significant improvement in fit when the model included a quadratic term, $\chi^2(4) = 5.3, p = .258$. I also tested the model to ensure that a single variance estimate for both groups was best fit. There was a marginally significant improvement in fit when including separate variance estimates for YAs and OAs, $\chi^2(4) = 9.3, p = .054$. However, I opted to not include this in the final model for parsimony. I also ran the model with and without the separate variance components and the pattern of results remained the same.

The final model was a 2(Group: YA vs. OA) x 2(Attention: Full vs. Divided) x 5(Rotation: repeat – 55°) linear model with random intercepts and slopes. The results indicated a

significant effect of group on intercepts, $t(41) = 2.28, p = .028$, where OAs in the full attention condition were slightly worse at indicating a repeated object was “old” as compared to YAs. There was a significant effect of dividing attention on repeated object performance for YAs, $t(381) = 7.51, p < .001$, and a significant interaction between group and divided attention on repeated object performance, $t(381) = -2.05, p = .041$. Young adults, therefore, were significantly worse at indicating an old object was old during the divided attention task and so were OAs who performed at almost the same rate as YAs. There was a significant effect of rotation on performance, $t(381) = 12.91, p < .001$, indicating that performance improved with greater object rotation. There was also a significant interaction between degree of rotation and group, $t(381) = -4.27, p < .001$, indicating that OAs improved less across degrees of rotation as compared to YAs, and a significant interaction between degree of rotation and divided attention, $t(381) = -3.70, p < .001$, indicating that the divided attention manipulation caused both groups to improve less across degrees of rotation. There was no significant three way interaction between degree of rotation, group, and divided attention, $t(381) = 1.55, p = .122$. See Table 4 for parameter estimates of the effects. Taken together these results indicate that YAs’ performance across degrees of rotation improved most rapidly in the full attention condition. Rate of improvement for all other groups and conditions was significantly worse. Young adults in the divided attention condition, OAs in the full attention, and OAs in the divided attention condition improved across degrees of rotation at similar rates (see Figure 9).

3.2.1.5 Rotation test

As in the prior experiment, I collapsed all estimates of degree of rotation into a single metric of correctly indicating whether an object was rotated or not. The results of the rotation test revealed a significant difference in YAs and OAs ability to discern whether an object was rotated

or not. This difference was significant for accurately indicating an object was an exact repeat, $t(41) = 2.94, p = .005$, indicating an object was rotated, $t(41) = 2.34, p = .024$, and for overall performance on the rotation test, $t(41) = 3.70, p = .001$, with YAs ($M = .90, SD = .06$) outperforming OAs ($M = .81, SD = .08$) overall. I conducted follow up analyses controlling for overall rotation test performance for both the repeated measures ANOVA and the multilevel model that investigated the lure discrimination index across all trials. Importantly, the pattern of results in the repeated measures ANOVA and the multilevel model remained unchanged after controlling for performance on the rotation test. In combination, these follow up analyses indicate that group differences in the ability to assess rotation in short term memory is not the driving factor in group differences in the ability to notice small changes in long term mnemonic representations.

3.2.1.6 Individual differences

In Experiment 2, I manipulated attention to assess the role of attentional resources on PS. Since performance was impacted to a greater extent than predicted, no conclusions can be drawn about the specific role of attentional resources in the process of PS; however, this does not preclude the ability to investigate the types of cognition that support PS. It is possible that the difficulty associated with the divided attention task could cause the relationships between the various measures of cognition to weaken. This could reflect the fact that the measures of memory performance were altered to the point that they no longer represented memory function. Alternatively, it is possible that the increased task difficulty may actually strengthen the relationships and aid in elucidating the domain general cognitive processes that support PS.

Each individuals' intercept (i.e., model implied performance on old trials), slope (i.e., rate of improvement across the degrees of rotation), and lure trial performance were extracted. These

numbers were then correlated with their scores on digit span forward and backward, trails A and B, and the measure of inhibition derived from subtracting the color naming time from the color-word interference time. Correlations between all participants intercepts, slopes, and lure trial performance in the full and divided attention conditions were examined ($n = 43$ in both conditions). Thirty exploratory correlations were run. A Bonferroni corrected p-value (.05/30) in this case is .002, but again, all correlations below .05 will be reported for completeness.

Correlations derived from the full attention condition revealed that measures of processing speed and inhibition were significantly correlated with both intercepts, slopes, and lure trial performance. Participants intercepts were significantly positively correlated with time on Trails A, $r(41) = .51, p < .001$, and Trails B, $r(41) = .34, p = .024$. Trails A is thought to measure processing speed while Trails B is thought to measure processing speed along with executive function. Therefore these correlations suggests that as processing speed and executive function declines, so does the ability to encode a representation that supports simple recognition of repeat items. No significant correlation was found between the measure of inhibition and intercepts. Participants slopes were significantly negatively correlated with time on Trails A, $r(41) = -.67, p < .001$, Trails B, $r(41) = -.61, p < .001$, and the measure of inhibition, $r(41) = -.49, p < .001$. The same pattern of results was found when using lure trial performance such that a significant correlation was found between lure trial performance and time on Trails A, $r(41) = -.33, p = .03$, Trails B, $r(41) = -.43, p = .004$, and the measure of inhibition, $r(41) = -.43, p = .004$. These correlations with slopes and lure trial performance suggest that processing speed, executive function, and inhibition correlate strongly the ability to PS. As processing speed, executive function, and inhibition decline, so does the ability to efficiently PS.

A similar pattern of results was found for intercepts, slopes, and lure trial performance in the divided attention condition. Participants intercepts were significantly positively correlated with time on Trails A, $r(41) = .30, p = .049$, but not on Trails B or the measure of inhibition, p 's $> .322$. The significant relationship between Trails A and intercepts aids in explaining why memory performance was significantly worse in this condition. Performance in the divided attention task heavily relied upon the ability to quickly make a judgment about two numbers and then try to remember the object, therefore, as processing speed increases, so does one's ability to make the judgment and engage with the object long enough to form a memory that supports old/new recognition. Participants slopes were significantly negatively correlated with time on Trails A, $r(41) = -.61, p < .001$, Trails B, $r(41) = -.56, p < .001$, and the measure of inhibition, $r(41) = -.46, p = .002$. When using overall lure trial performance, a significant negative correlation was found between overall lure trial performance and time on Trails A, $r(41) = -.43, p = .004$, Trails B, $r(41) = -.33, p = .033$, but not the measure of inhibition, $r(41) = -.25, p = .100$. Significant relationships were still found in the divided attention portion of the task; however, they were noticeably weaker than the correlations found in the full attention condition. This suggests that while memory processes were still able to operate to some extent under divided attention, the divided attention condition impaired the ability to sufficiently engage with the materials and form mnemonic representations.

3.2.2 Discussion

Reductions in cognitive resources occur as individuals age (Craik, 1983). A reduction in the amount of attentional or working memory resources may cause a bottleneck in the engagement of simultaneous processes. Encoding complex stimuli, such as remembering all of the features of a stimulus, requires the deployment of cognitive resources, both for generating

novel connections that are specific to that particular object (e.g., this particular house is blue, has a door on the left side of the house, and has a bay window on the right side), as well as deploying a particular strategy that will aid in the memory of that object (e.g., this house is blue and I can only see a little bit of a window on the left side of the house). The latter strategy would be particularly helpful given that the current task required the discernment of rotation. However, the former approach would also help to build a highly detailed memory of the object. If fewer resources are available to operate on a stimulus, then the ability to engage in both processes would be impaired, and on average, a weaker representation would be stored leading to deficits in memory later on. Based on these ideas and the results of a substantial amount of research (e.g., Craik & McDowd, 1987; Kim & Givoanello, 2012), it was hypothesized that reducing the availability of resources in YAs, through a relational divided attention task, would cause memory performance to mirror that of OAs.

The current experiment elicited results supporting the notion that a reduction in attentional resources impacts pattern separation processes. The slope across degrees of rotation, as revealed by the multilevel model, shows that YAs' performance improved at a similar rate under divided attention conditions, as OAs' under full attention conditions. This finding, however, should be interpreted with caution. Despite the fact that YAs under divided attention improved at similar rates to OAs under full attention, it is quite possible that this reduction in the rate of improvement arose from increased intercepts. Since YAs under divided attention are about 20% worse at indicating an object is an exact repeat, the possible rate of increase across degrees of rotation is severely limited. Support for this idea is found in a marginally significant relationship between intercepts and slopes, $z = -1.72$, $p = .086$. The relationship suggest that as intercepts increase, slopes decrease. This, in combination with the significantly impaired

performance under the divided attention condition, provides evidence that the similar slopes are due to different underlying mechanisms.

One argument against this interpretation is that OAs' rate of improvement was even worse in the divided attention manipulation, as compared to YAs' in the divided attention condition. This result suggests that the decrease in YAs' rate of improvement under divided attention may reflect a similar underlying process as OAs, such as alterations in PS. If this possibility were the primary underlying factor, then we could conclude that PS processes are impacted by the ability to deploy an efficient strategy to encode materials, or by the ability to deploy resources in the generation of connections within a stimulus, or both. This conclusion would be significant in the pattern separation literature as researchers often, in an attempt to more closely mirror the tasks used in the rodent literature, investigate pattern separation using incidental encoding paradigms (e.g., Lacy, Yassa, Stark, Muftuler, & Stark, 2011; Motley & Kirwan, 2012; Reagh & Yassa, 2014). If the deployment and availability of attentional resources can impact the PCB in aging, then this would suggest that intentional and effortful encoding operations have a measurable impact on PS. While this would be a novel and important finding for the PS literature, it cannot be known with certainty as to whether the decrease in the rate of improvement is mediated by the same processes that reduces OAs' rate of improvement, or, whether there is simply a ceiling effect on the rate of improvement.

The divided attention manipulation does, however, highlight the critical nature of attentional resources during the encoding of complex pictorial stimuli. Performance overall was dramatically worse for both YA and OA participants when they encoded the objects while making a number judgment, and this change in performance was greater than anticipated. The attentional manipulation used in the current study has been employed in prior research, and, in

that study, had the effect of matching performance between YAs in the divided attention condition and OAs in the full attention condition (Kim & Giovanello, 2011). However, the prior study used word pairs rather than complex color photographs. It is possible that when a participant need only to encode words, the relatively simple nature of the stimuli can be stored in working memory and operated on even while engaging in the secondary task. For the current study, it appears that the primary task required more resources than were allowed by the simultaneous secondary task, and therefore, a mnemonic representation strong enough to support fine detailed memory discrimination was not formed. The results do indicate, however, that the formation of a strong episodic memory relies on the ability to deploy attentional resources to the to-be-remembered object, which is not a novel finding.

Future studies that investigate the role of attention on the PCB in aging should implement a divided attention task that taxes attention in a different way. One way to alter the divided attention task would be to make it easier. This might involve an odd/even number discrimination such that participants do not have to look at two locations on the screen, or it may involve a tone counting task so participants never have to move their eyes away from the to-be-encoded object. These options would make the divided attention task easier, yet they would not tax relational attention in the way that is hypothesized in the current study. Therefore, a divided attention task in which participants compared two tones by indicating which is higher would allow for the taxing of relational attention, while also not requiring participants to move their eyes. In this scenario, it is possible that support for the role of attentional resources as they relate to the PCB in aging would be found.

3.3 Experiment 3 - Inhibition deficit and the completion bias

A deficiency in inhibitory processing has not been explored directly as an explanation for age-related changes in PS abilities. Toner et al. (2009), however, assessed whether there were correlations between cognitive measures of inhibition (e.g., the inhibition and inhibition/switching subtests from a standardized neuropsychological instrument, tasks much like the Stroop task) and OA performance for correctly identifying lure trials. The only relationship found was a marginally significant relationship between inhibition and lure trial performance, $r = -.39, p = .09$. Further, Stark et al. (2010) presented both OAs and YAs with a spatial PS task, but presented 10 study/test lists with only 10 items in each study session. Interestingly, OAs as a group exhibited no deficit in spatial PS as compared to YAs, despite the fact that impairments have been found in other spatial PS tasks using larger sets of to-be remembered items (Reagh et al., 2014). Not surprisingly, YAs show no significant changes in performance when the set size being tested is altered; however, this specific manipulation has not been tested in OAs (Stark et al., 2015). These results suggest that part of the PCB in aging may come from the inability to inhibit previously learned information while encoding information encountered later.

For the purposes of the current study, I focus on the possibility that OAs are less able to clear the contents of working memory and, therefore, experience greater proactive interference than YAs. Zacks et al. (2000) refer to this mechanism as *deletion*, or the ability to remove prior representations from memory to efficiently focus on the current goals. The inability to clear old representations from working memory during encoding leads to “mental clutter” and impairs the ability to focus on the particular goal at hand. Zacks, Radvansky, & Hasher (1996) studied this mechanism with a directed forgetting paradigm. In this study, participants were presented with words. After the presentation of a word, participants were told to either forget the word or

remember the word for a later test. Across several experiments it was shown that OAs have an impaired ability to suppress or delete information that they were told to forget, demonstrating less of a difference between to-be-remembered versus to-be-forgotten words at test as compared to YAs (Zacks et al., 1996).

To test this prediction, the current experiment adopted methods from the directed forgetting paradigm used by Zacks et al. (1996). Participants were given specific instructions about the nature of the study episode. They were told that they should study each object, but that after the presentation of each object, a letter would appear on the screen, either an “R” or an “F”. If they saw an “R” they were to remember that object for the later test. If they saw an “F” they were to forget that object. They were also told that forgetting the to-be-forgotten objects would aid in their memory for the to-be-remembered objects. These instructions were used as a way to additionally motivate their forgetting. The letter that indicated whether they were to remember or forget an object was displayed for 1.5 sec after the presentation of the object and followed by a 0.5 sec inter-stimulus interval. The directed forgetting manipulation was used on an item-by-item basis, was split evenly between the studied stimuli, and was implemented randomly so that participants would not be able to predict which objects would go on to be remembered versus forgotten. Therefore, participants were forced to attend to each object equally before the remember or forget instructions appeared.

An item-by-item directed forgetting paradigm was specifically chosen because the paradigm implemented in this experiment required the use of a recognition test. List-wide directed forgetting paradigms tend to only find effects on recall and not recognition (Geiselman, Bjork, & Fishman, 1983), while item directed forgetting paradigms tend to elicit impairments in both recall and recognition (Basden, Basden, & Gargano, 1993; Zacks et al., 1996). This

difference is thought to occur because list-wide directed forgetting impairs processes that support memory retrieval, whereas item directed forgetting alters processing occurring at encoding. List-wide directed forgetting impairs retrieval, specifically recall, due to retrieval inhibition or through a mental context shift (Sahakyan & Kelley, 2002), but leaves recognition intact because the same operations that support recognition occur for both the to-be-forgotten list and the to-be-remembered list. Item directed forgetting impairs recognition either through the suppression of rehearsal or through the suppression of elaboration on the item, both processes that occur at encoding (Basden et al., 1993). Importantly, this experiment attempted to isolate cognitive operations occurring at encoding (e.g., the inability of OAs to efficiently delete the contents of working memory), and thus, directed forgetting at the item level was chosen.

Zacks et al. (1996), using an item method directed forgetting paradigm, found that words in the to-be-forgotten condition were recognized to the same extent for both OAs and YAs, while items in the to-be-remembered condition were recognized significantly more by YAs. This finding suggests that OAs are less able to efficiently clear the contents of working memory to support later episodic memory. Interestingly, prior research using an item method directed forgetting paradigm has shown that the difference between recognition rates, while still significant, is greatly reduced when using pictures (Hauswald & Kissler, 2008). This observation is interpreted as an advantage for the current study given that altering the tuning curve (yet leaving the anchors largely intact) will improve the interpretability of the results. Large decrements in old/new recognition bring into question whether the differences in performance for rotated trials is due to PS or due to impairments in the formation of a memory in general. Based on these studies and the general theory of the inhibitory deficit, it was predicted that there would be an interaction between age, instructions, and similarity, both in the old/new recognition

vs. lure discrimination index and in the tuning curve analysis. As such, OAs' performance across the different degrees of rotation would be similar despite the instructions to forget or remember stimuli. Young adults, however, were predicted to show a bias to PC for the objects that were to-be-forgotten and maintain their ability to efficiently notice small changes in stimuli for to-be-remembered objects, or pattern separate.

3.3.1 Results

3.3.1.1 Participants

Twenty-five YAs and 25 OAs completed the experiment. One YA was removed from the analysis due to chance level performance. The OA participants were significantly more educated, $t(47) = -10.84, p < .001$. Again, the OAs were also slower to perform Trails A, $t(47) = -4.76, p < .001$, Trails B, $t(47) = -3.89, p < .001$, color naming time, $t(47) = -3.86, p < .001$, word reading time, $t(47) = -4.57, p < .001$, and color-word interference time, $t(47) = -5.79, p < .001$. As a more direct measure of inhibition, we subtracted the color naming time from the color-word interference time. This measure was also significantly different between OAs and YAs, $t(47) = -5.49, p < .001$, suggesting that OAs in the current sample had reduced inhibitory processes. There were no other group differences. See Table 5 for means and standard errors of all the cognitive measures collected.

3.3.1.2 Old/New Recognition and the overall lure discrimination index

Recognition and overall lure discrimination index scores were calculated for each group and within each directed forgetting condition. These scores were analyzed with a 2(Group: Younger vs. Older) x 2(directed forgetting: remember vs. forget) x 2(Memory type: old/new recognition vs. lure discrimination index) repeated-measures ANOVA. There was a main effect of memory type, $F(1,47) = 267.87, p < .001, \eta_p^2 = .85$, such that old/new recognition was

significantly better than lure discrimination. There was no main effect of group, $F(1,47) = 1.14$, $p = .291$, $\eta_p^2 = .02$, and no main effect of the directed forgetting manipulation, $F(1,47) = 1.52$, $p = .224$, $\eta_p^2 = .03$. These effects were qualified by a significant interaction between the directed forgetting manipulation and group, $F(1,47) = 7.46$, $p = .009$, $\eta_p^2 = .14$, indicating that YAs exhibited better memory in the remember condition ($M = .50$, $SD = .13$) as compared to the forget condition ($M = .46$, $SD = .12$), whereas OAs showed essentially no difference in performance between the remember ($M = .44$, $SD = .10$) and forget conditions ($M = .45$, $SD = .09$). Interestingly, there was no effect of memory type and group, $F(1,47) = 2.17$, $p = .147$, $\eta_p^2 = .04$, and no significant three-way interaction between directed forgetting, memory type, and group, $F(1,47) = 2.31$, $p = .135$, $\eta_p^2 = .05$, although both trended toward significance.

Since this result fails to replicate an OA impairment in lure discrimination, I examined the pattern of behavior within each directed forgetting condition between groups. For the remember trials only, there was a marginally significant interaction between memory type and group, $F(1,47) = 3.66$, $p = .062$, $\eta_p^2 = .07$, indicating that OAs exhibited the typical impairment in lure discrimination as compared to YAs. For the forgotten trials there was no significant interaction between memory type and group, $F(1,47) = .62$, $p = .434$, $\eta_p^2 = .01$, indicating that the difference between old/new recognition and lure discrimination was similar between the two groups. To understand whether the lack of a significant three-way interaction in the full model was due to a power issue, a post-hoc power analysis was run. The observed power for the interaction between group, directed forgetting, and memory type was $\beta = .319$. While the three-way interaction was not significant in the full model, the combination of a marginally significant interaction between group and memory type in the remember condition, the lack of a significant interaction between group and memory type in the forget condition, and the low power observed

in the full model, suggests that OAs do exhibit a decline in lure discrimination and that YAs do successfully inhibit memory encoding in the forget condition (see Figure 10).

3.3.1.3 Lure discrimination index results across all trials – repeated measures ANOVA

Before running the analyses, I checked to ensure that the rates of responding “new” were similar between the two groups. No significant differences were found in rates of “new” responses to trials that were not encountered at study, nor to old or rotated trials, all p 's > .357. A 2(Group: YA vs. OA) x 2(Directed forgetting: remember vs. forget) x 5(Degree of rotation: repeat - 55°) repeated measures ANOVA with group as a between subjects factor and directed forgetting and degree of rotation as within subjects factor was used to analyze performance across the degrees of rotation. There was a significant main effect of rotation, $F(1,47) = 109.91$, $p < .001$, $\eta_p^2 = .70$, indicating that performance improved as the degree of rotation increased. There was no significant main effect of directed forgetting, $F(1,47) = 1.01$, $p = .320$, $\eta_p^2 = .02$, and no significant main effect of group, $F(1,47) = 2.27$, $p = .138$, $\eta_p^2 = .05$. There was a marginally significant interaction between directed forgetting and group, $F(1,47) = 2.88$, $p = .096$, $\eta_p^2 = .06$, such that OAs exhibited a small benefit for forget trials and YAs exhibited a small benefit for remember trials, and a significant three-way interaction between group, directed forgetting, and degree of rotation, $F(4,188) = 2.79$, $p = .028$, $\eta_p^2 = .06$. No other effects were significant, all p 's > .395 (see Figure 11). A repeated measures ANOVA was conducted independently at each degree of rotation to better understand the factor mediating the three-way interaction. A significant group by directed forgetting interaction was found at 25° of rotation, $F(1,47) = 5.47$, $p = .024$, $\eta_p^2 = .10$, such that YAs in the remember condition outperformed OAs in the remember condition, while performance was equivalent in the forget condition. A marginally significant effect of group was found at 35° of rotation, $F(1,47) = 3.33$, $p = .074$, η_p^2

= .07, and at 55° of rotation, $F(1,47) = 3.96$, $p = .052$, $\eta_p^2 = .08$, in favor of YAs. The general pattern across the data was that YAs tended to exhibit a benefit in their mnemonic performance on remember vs forgotten trials, whereas OAs exhibited little difference between remembered and forgotten trials (see Figure 12).

3.3.1.4 Lure discrimination index results across all trials – Multilevel Model

A multilevel model was used to analyze the lure discrimination index across all trials. The final model was built through likelihood ratio tests. The ICC for this experiment was .15, thus 15% of the variance came from between-subjects as opposed to within subjects. A likelihood ratio test between a model without a quadratic term and a model with a quadratic term revealed a significant improvement in fit when adding a quadratic effect $\chi^2(4) = 15.7$, $p = .003$. The quadratic effect was also significant $t(439) = -2.86$, $p = .005$; however, the estimate of the effect was -.0098. This indicates that the linear effect decreased in steepness about 1% for each increased degree in rotation. In light of this finding, I opted to leave the quadratic term out of the final model for consistency across experiments, as well as for parsimony in the model. For completeness, however, I ran all of the final models with and without a quadratic effect and the pattern of results was unchanged. I also tested to determine if a different variance estimate for each group improved model fit and found a non-significant improvement in fit, $\chi^2(4) = 5.3$, $p = .258$. The final model reported is a linear model with random intercepts and random slopes with a between subjects effect of group and within subjects effects of degree of rotation and directed forgetting.

The model revealed no significant effect of group, $t(47) = -.33$, $p = .742$, no significant effect of directed forgetting, $t(435) = .33$, $p = .740$, and no significant interaction between group and directed forgetting, $t(435) = .22$, $p = .824$. Therefore, neither the directed forgetting

manipulation nor age, had an effect on the ability to respond “old” to trials that were exact repeats. There was a significant effect of rotation, $t(435) = 10.64, p < .001$, however it did not interact with any other factors, all p 's $> .117$. See Table 6 for parameter estimates of the effects. The result of the multilevel model suggests that both groups in both conditions performed similarly across degrees of rotation.

3.3.1.5 Rotation Test

For this experiment I again ran three comparisons between YAs and OAs ability to discriminate between rotated and non-rotated objects. Younger adults and OAs were not significantly different in their ability to indicate an object that was an exact repeat was “old”, $t(47) = .43, p = .669$. Younger adults and OAs were also not significantly different in their ability to indicate a rotated object was “rotated”, $t(47) = .49, p = .630$, and not significantly different in their overall performance in indicating whether objects were rotated or not, $t(47) = .68, p = .501$. Overall YAs ($M = .84, SD = .06$) performance was very similar to OAs ($M = .83, SD = .07$). Since there were no group differences in the ability to discriminate rotation in this experiment no follow up analyses were conducted.

It is not clear why performance on the rotation test was significantly different in the prior two experiments but not in the current experiment. Accuracy on the rotation test was consistently around the low to mid 80% for OAs in all three experiments. Younger adults, however, performed at 90% in both Experiment 1 and Experiment 2, but were only 84% accurate in the current experiment. Since the rotation test used in the current set of experiments is not a standard test, it cannot be known what performance in the population should be. Therefore, no claims may be made about whether the YAs in the first two experiments were performing abnormally high, or whether YAs in the third experiment were performing abnormally low. Despite the different

findings across experiments, the results of the mnemonic similarity task used in all three experiments were unchanged when controlling for performance on the rotation task. This suggests that the rotation task, which should tax short term memory processes, is measuring a different cognitive process than the ones taxed by the mnemonic similarity task. Moreover, differences in the rotation task in Experiment 1 and 2 were found for rotated and repeat trials, while repeat trial performance in the mnemonic similarity task was consistently found to be the same. Again, this suggests that differences in rotation task performance between OAs and YAs were caused by a different underlying process.

3.3.1.6 Individual differences in the lure discrimination index

For this experiment I ran correlations between lure trial performance, as indexed by the average lure trial performance, as well as the model implied intercepts in slopes in both the remember and forget trials. All participants were included in all correlations. The only significant correlation was between the measure of inhibition and the slopes in the remember trials, $r(47) = -.35, p = .012$. It is possible that the lack of correlations between performance and processing speed measures that were found in Experiment 1 and 2 were caused by the use of a different strategy to encode the materials in Experiment 3. Successful performance in Experiment 1 and 2 relied on quickly and efficiently forming a strong mnemonic representation. Because successful performance in the forgotten trials relies on not forming a strong mental representation until after the image is off the screen, one strategy would involve forming a gist representation while encoding the object, and then expanding on it only if you are told to remember the object. In this scenario, a faster processing speed would not necessarily benefit performance.

3.3.1.6 Discussion

It was hypothesized in this experiment that OAs, due to impaired inhibitory process, would show no effect of the directed forgetting manipulation, while YAs would show reduced memory when instructed to forget objects. Based on the results, I conclude that the directed forgetting manipulation had measurable impacts only on YAs performance, and therefore, that reduced inhibitory processes do impact pattern separation processes; however, it should be noted that the results are not consistent across all analysis strategies.

The most compelling evidence that YAs are able to inhibit what has just been encountered, and therefore reduce the strength of the encoded representation, comes from the lure discrimination index across all degrees of rotation that was analyzed with a repeated measures ANOVA. In this analysis the critical three way interaction was found. After investigating the differences in performance within each rotation type, and as can be seen in Figure 12, YAs tend to exhibit an increase in performance, relative to themselves, in the remember condition, whereas OAs show no benefit for remember trials. In the analysis of old/new performance, versus the overall lure trial index, a trend toward a three-way interaction was found. Follow up analyses indicated that all of the results were in the hypothesized direction (i.e., impairments in performance for OAs in the remember trials as compared to YAs, and a reduction in YA performance in the forgotten trials that mimics the performance of OAs); however, there was not enough power in the data set to fully support the finding. Lastly, the multilevel approach found no significant changes in performance either between groups or between the directed forgetting manipulation. However, caution is warranted in drawing strong conclusions from the multilevel approach because of the non-linearity within this particular data set. There was a significant quadratic effect, although the results were unchanged when

implementing a quadratic term, which provides evidence the data are not well represented by a straight line. To follow up on this idea I ran a model with a cubic term to see if that improved model fit and found a marginally significant improvement in model fit, $\chi^2(5) = 9.4$, $p = .094$, again suggesting the data is simply not appropriate for a model that assumes consistent changes across trials. In sum, a repeated measures ANOVA is the most appropriate way to analyze this data set due to the fact that it makes no assumptions about how the change across degree of rotation should occur. The repeated measures ANOVA also provided consistent evidence that YAs were able to engage cognitive processes that suppressed memory formation when they were told to forget, whereas OAs were not able to do so. Thus, despite the limitations discussed above, there is sufficient evidence to support the idea that inhibitory processes are critical for efficient PS processes to take place.

Encoding memories not only requires the focus of attention on the to-be-remembered object, it also requires the ability to keep a clean mental workspace such that the to-be-remembered object is not cluttered by irrelevant information. Mental clutter during encoding could occur because the object itself triggers irrelevant memories, or because previously encountered information is not efficiently cleared from the mental workspace. The latter mechanism is referred to as a deletion mechanism (Zacks et al., 2000). One line of inquiry suggests that OAs tend to have reduced digit span because they experience more proactive interference. When OAs are given the digit span not in order of increasing length they often perform at equivalent rates to YAs due to the fact that they have reductions in the deletion mechanism (e.g., Zacks et al., 2000). I hypothesized that, due to an impairment in the deletion mechanism, OAs would show no reductions in performance for trials they were instructed to forget, while YAs would show reductions in forgotten trials. The difference in performance

between trials that were to-be-remembered and trials that were to-be-forgotten lies in the ability to efficiently delete the contents of working memory when instructed to do so. Since YAs are better at clearing out the contents of working memory, they are better able to suppress encoding mechanisms and therefore see a reduction in memory when they are instructed to forget.

Evidence from this experiment extends the prior literature on the inhibitory deficit by providing evidence that the deletion mechanism is critical not only for simple recall and recognition, but also critically important for encoding a highly detailed representation. When investigating the old/new recognition and the overall lure discrimination index, YAs perform better for lure trials in the remember, versus forget, condition, whereas OAs' performance was equivalent regardless of the instruction. Similarly, when investigating performance across lure trials with a repeated measures ANOVA, YAs tended to show better memory in the remember versus forgotten condition, whereas OAs did not. These differences were observed, despite the fact that old/new recognition was the same across both groups. Therefore, impairments in inhibitory processes, and specifically in the deletion mechanism, contribute to reductions in the fidelity of a mnemonic trace, even when the trace itself can support old/new recognition.

This result is important for the inhibition literature because prior research tends not to find reductions in recognition memory during list wide directed forgetting (Geiselman, Bjork, & Fishman, 1983), while item directed forgetting leads to impairments in both recall and recognition (Basden, Basden, & Gargano, 1993; Zacks et al., 1996). List-wide directed forgetting effects recall, but not recognition, since list-wide directed forgetting impacts retrieval inhibition, a process that occurs at retrieval and not at encoding. The theory suggests that all the operations that take place at encoding are the same between the two lists (i.e., the to-be-forgotten list and to-be-remembered list), it is simply what happens to the lists after encoding has taken place that

affects memory. Item directed forgetting tends to also disrupt recognition due to changes in rehearsal or elaboration mechanisms. While retrieval inhibition or a context shift may be the primary mechanisms behind recall deficits in list-wide directed forgetting, it is also possible that these mechanisms impact recognition when the decision process can only be guided by the fine details of the mnemonic trace. Retrieval inhibition, or a sudden context shift, may also serve to disrupt consolidation mechanisms that take place after an entire list is learned through rehearsal and elaboration suppression. Therefore, an unexplored possibility is that list-wide directed forgetting does impair recognition rates, however, it only impairs recognition processes that tax pattern separation.

The results of the current experiment also extend the PS literature. Efficient PS relies on mechanisms that orthogonalize a neural code such that it can be encoded as novel, even when it overlaps with a previously encountered representation. However, the current results suggest that efficient PS is also reliant on the ability to maintain a clean mental workspace. In relation to the current experiment, if the previous trial's trace could not be cleared from the contents of working memory, the current trial was likely to be an amalgam of two representations, leading to a weaker memory trace for the current trial and impaired PS. A clean mental workspace may therefore be a prerequisite to efficient PS processes. Evidence for this notion also comes from the correlation between the measure of inhibition and the individual slopes estimated from the remember trials. As the efficiency of inhibitory processes increase, so does PS as revealed by the mnemonic similarity task. Put another way, PS processes are the most effective in persons who can maintain a clean mental workspace by efficiently suppressing irrelevant information. Although we do not have direct evidence of this in OAs, OAs impairments in inhibitory

processes related to deleting irrelevant information are likely a major contributor to the PCB in aging.

Chapter 4: General Discussion

The primary goal of this study was to investigate how domain general cognitive processes altered by age influence the PCB. It has been argued by Stark and colleagues (2015) that the PCB in aging is caused solely by functional and anatomical changes in the hippocampus and, “cannot be overcome to improve performance on this task” (p. 14). The set of experiments tested this notion by manipulating different features of the typical mnemonic similarity task to assess whether or not domain general theories of cognitive aging may account for the PCB in aging.

My hypothesis for each study centered on the idea that domain general aspects of cognitive aging may contribute to the PCB in aging. Across the three experiments, the results primarily showed that the PCB in aging does not operate in a vacuum, but rather, it may be modulated by other factors. More specifically, processing speed and inhibitory processes contribute to the PCB in aging. As we get older, the rate at which information is processed throughout the brain slows. As processing speed slows, so does the time it takes to form strong mnemonic representations. The results from Experiment 1 suggest that much of the memory function in OAs is retained, and that after accounting for the longer time needed to create a strong memory trace, memory performance is significantly improved. This is likely due to the limited time mechanism (Salthouse, 1996a). The limited time mechanism suggests that OAs’ reduced processing speed causes a reduction in the cognitive operations that can be performed when a task has a time constraint. In relation to the mnemonic similarity task, when OAs and YAs are given the same amount of time to form a robust, highly detailed memory of an object,

reductions in OAs' processing speed causes a reduction in the ability to quickly interact with all the different features of the object, and therefore, they form a weaker, more gist based representation of the object. Also, based on the results of Experiment 1, the PCB in aging is not likely to be caused by the simultaneity mechanism. In this case, products of earlier cognitive operations are degraded by the time they are needed for later operations. If the simultaneity mechanism were a contributor to the PCB in aging, then the manipulation used in Experiment 1 (i.e., giving OAs longer time to encode materials) would have exacerbated the PCB. Similarly, giving YAs less time may have also improved performance, whereas YAs in Experiment 1 performed much more like OAs under a traditional speed condition. Therefore, more time, not less, improves memory performance for both OAs and YAs, providing evidence that PS relies on participants having sufficient time to form a robust mnemonic representation.

Reductions in processing speed are directly related to the ability to efficiently pattern separate, a process supported by hippocampal function. It is likely that processing in the occipital cortex – a part of the brain that processes visual information - is improved when OAs are given more time to encode the stimulus. The improved processing in occipital cortex then sends a more complete representation to the hippocampus where pattern separation processes efficiently encode the representation. This is one possibility, yet it is also possible that visual processing remains largely unchanged, and that the improvement in processing comes solely from more efficient PS in the hippocampus when the hippocampus has more time to process the representation. Alternatively it may be the case that some combination of these underlying factors. Regardless, it will be an important next step to examine how and where these manipulations alter neural processes that support memory.

An impairment in OAs' inhibitory processing also contributes to the PCB. Inhibitory processes are theorized to consist of a deletion mechanism, an access mechanism, and a restraint mechanism (Lustig, Hasher, & Zacks, 2007). Experiment 3 focused on OAs' and YAs' ability to delete previously encountered representations from the mental workspace by asking participants to forget some of the encountered objects. Efficient deletion of previously encountered material aids in keeping a clean mental workspace. The results of Experiment 3 suggest that PS acts on the representation being held in mind, even if that representation is an amalgam of two events. Therefore, it is likely that PS acts in a passive way to create a mnemonic trace of the cognitive operations that are occurring in that moment. If OAs are less able to hold in mind a single event, or are less able to delete a previous event, then the ability to create a mnemonic trace of that single event will be impaired. Young adults exhibited the ability to minimize the processing of a stimulus once they were given the instruction to forget. Their performance for to-be-forgotten objects was similar to that of OAs'. Older adults exhibited no difference between to-be-remembered and to-be-forgotten objects, suggesting the ability to clear out previously encountered information is impaired, and that a cluttered mental work space contributes to the PCB in aging.

Gazzaley, Cooney, Rissman, & D'Esposito (2005) instructed participants to view scenes and faces. Participants were told to ignore faces or scenes, and focus only on the non-ignored stimuli. Results showed that OAs were less able to inhibit activity in a part of the brain that selectively processes faces when they were told to ignore faces. The same result occurred for OAs who were told to ignore scenes. Future studies investigating the neural processes supporting deletion could use the mnemonic similarity task, but use scenes and faces. In this scenario, it would be possible to investigate how the forget instructions impact processing both outside and

within the hippocampus. If activity during the processing of to-be-remembered and to-be-forgotten faces is similar for OAs, it would support the idea that OAs are less able to stop, or delete, a prior event from the processing stream. A similar result may also occur in the hippocampus, such that hippocampal activity is not reduced in the to-be-forgotten trials, suggesting that OAs are not able to inhibit the mechanisms that support memory, even when given the instruction to do so. Therefore, part of the PCB in aging would be mediated by a cluttered mental workspace, leading the hippocampus to process no longer relevant information and impair PS processes.

It will also be important for future studies to investigate the role of access and restraint in the PCB. Similar to deletion, impairments in OAs' ability to prevent irrelevant information from entering the mental workspace may also be a contributor to the PCB. It is possible that as OAs and YAs encode objects, that OAs incidentally engage in mnemonic retrieval. For example, if an OA sees a picture of a tinker toy, they may be more likely to retrieve a memory of playing with a tinker toy as a child. While this may actually benefit simple old/new recognition through a generation or elaboration mechanism, it will likely impair memory for that specific object. The current to-be-encoded representation will necessarily compete with the retrieved memory of a similar object, and again, lead to a weaker trace of the current event.

There is no clear evidence that attentional resources, as measured and manipulated in Experiment 2, contribute to the PCB in the way it was hypothesized. The results show that attention is critical in the formation of memories in general, however the pattern of impairments in YAs does not match that of OAs under full attention. While this particular hypothesis needs more study, it is possible that the reduction of resources is not a significant contributor to the PCB in aging. I have discussed attentional resources in this study as the ability to generate

connections within the stimuli or to use strategic processing to guide memory encoding. The critical bottleneck in the formation of memories, however, is more likely what you are able to do with the resources, as opposed to the total amount of resources. The constraint may not be limited resources, but limitations on the processes one is able to execute on what is being held by these resources. Despite these possibilities, prior research has shown that impairments in attentional resources match memory performance remarkably well, and therefore, it is more likely that the task itself requires a great deal of our available resources and the divided attention task is too distracting. It will be important for future research to implement different strategies for dividing YAs' attention such that performance on the primary task remains similar to performance under non-divided attention conditions.

It is also important to note that the present set of experiments found evidence that the PCB in aging can be moderated by task design, while Stark et al. (2015) did not find this result. The inconsistency in the results likely arose for several reasons. First, while their task alterations set out to assess whether the task itself contributed to the PCB in aging, they did not specifically set out to test whether domain-general processes could moderate the PCB. For example, Stark et al. 2015 manipulated the time allowed for decision making such that there were no time constraints when participants made a mnemonic judgment. While this directly assesses the role of processing speed on decision making, it does not assess the role of processing speed on encoding of the to-be-remembered information. Therefore, processing speed does have an impact on the PCB in aging, however, this impact is greater at encoding than retrieval. Second, while Stark et al. manipulated set size in YAs, they did not implement this manipulation in OAs. The set size of a memory task has been shown to contribute to OA impairments in memory such that increasing the set size causes greater proactive interference in OAs (Zacks et al., 2000). The

present study manipulated inhibition through directed forgetting, however, another way to assess the role of inhibition in OAs would be to manipulate the set size as Stark et al. (2015) did in YAs. It is possible that Stark and colleagues would have found evidence for reductions in the PCB in aging when accounting for inhibition if they had included OAs in this experiment. In sum, it is likely that Stark et al. 2015 did not find that task design manipulations moderated the PCB in aging because they did not test a sufficient number of task parameters.

Finally, it is important to note that even though accounting for domain-general aspects of aging may improve memory performance in OAs and impair memory performance in YAs, the PCB in aging was still found in each experiment. Therefore, the conclusions of the present set of experiments should be stated clearly. As we age, PS processes that support episodic memory are altered such that OAs are more likely to pattern complete a similar, but novel episode.

Processing speed and inhibitory processes that also change with age contribute to the PCB in aging and when taken into account, allow OAs to strengthen the memory formation process and reduce the PCB.

4.1 Limitations

There are several limitations that warrant discussion. First, the study of inhibition found mixed evidence to support the claim that inhibition is a contributor to the PCB in aging. The mixed evidence primarily came from a limitation in the power to find effects, but it also came from mixed results across analysis strategies. While I believe there is sufficient evidence despite these shortcomings to conclude that inhibition does contribute to the PCB, it will be important to replicate the key findings. One strategy would be to shorten the list of study materials and only use the overall lure discrimination index to try and strengthen the finding. This strategy alone

may ameliorate the power issues. Anecdotally, participants seemed to find this particular experiment more taxing than the others which may contribute to the weaker effect.

Additionally, I adopted a within-subjects manipulation. There are many strengths to within-subjects designs, yet it would be important to know, for example, whether more time on study without the contrasting shorter study periods, would still improve memory function. It is possible that participants hone in on the increased study time and more effectively use the longer study periods. If they do not have exposure to shorter study periods, they may not use this extra time effectively and thus see a limited benefit. This would be important to know if you wanted to translate this into strategies OAs could adopt to aid in their memory performance.

Another limitation to the current set of studies is the fact that I did not find a traditional “tuning” curve. This likely results from two things. First, I was not able to include any new trials in the actual analysis due to the fact that the new trials were not part of the within subjects design which eliminated one anchor of the curve. This is likely the primary cause to not consistently finding a non-linear effect due to the fact that the curve typically bows up or below the straight line between old and new trials. Second, in Experiment 3, non-linear and non-quadratic effects were found. Again this likely stems more from the somewhat more difficult nature of the third Experiment which may have contributed to the increased variability across degrees of rotation. Despite this, all studies use the difference between YAs and OAs as the measure of more or less PS and PC instead of the absolute bow of the line, and therefore, the interpretations would not change (e.g., Stark et al., 2010; Stark et al., 2015).

Relatedly, some of the “old” anchor points were impacted by the different manipulations adopted in this study. These changes in the old anchor point were consistently small except for in Experiment 2. It is likely that the small changes in Experiment 1 and 3 come from pulling

performance off of floor. All studies that have investigated the PCB in aging have used around 120 objects at study whereas I used around 190. This additional load on memory appears to have brought performance on the old trials up to around 30% where many studies find performance closer to 20% (e.g., Stark et al., 2010; Toner et al., 2009; Yassa et al., 2011a). In the current experiments performance on old trials was never better than 20% and, therefore, likely represents floor performance. Since performance on the standard task was slightly off floor, it left room for small improvements to appear at the old anchor. I do not believe that the small, but significant changes have an impact on the final conclusions drawn for the study. As can be seen in Experiment 2, performance on old trials can get much worse, so the small improvements seen in some conditions are not the cause of an increase rate of improvement.

Lastly, the materials used in the current set of experiments were common objects in which the memory test centered on the ability to discriminate whether an object was rotated or not. While there is ample evidence that mental rotation abilities, as assessed with complex 3D objects and rotations along more than one axis, change with age (e.g., Jansen & Heil, 2010; Vandenberg & Kruse, 1978), there is also evidence to support the idea that simple objects and less complex changes in rotation (Cerella, Poon, & Fozard, 1981), as well as reduced time pressures when using complex 3D objects (Sharps & Gollin, 1987), eliminate age-related impairments in mental rotation. In two of the three experiments, there was evidence that YAs were better at the basic task of noticing rotation as compared to OAs. This result was unexpected given the single axis of rotation and the lack of a time constraint on the decision making process. It is possible that the way in which the rotation test was administered had an adverse impact on OAs ability to correctly respond. Namely, response options were increased such that during the rotation test, participants responded by indicating if the object was rotated by judging the degree

of rotation (as opposed to simply indicating rotated). This distinction may have made the task somewhat more difficult for OAs given the increased load of response options. Moreover, error rates were increased for rotated objects as well as for objects that were exact repeats. This suggests that it was not the ability to notice rotation *per se* that was altering performance. Interestingly, old/new recognition was not impaired in the mnemonic similarity task, and when rotation test performance was used as a covariate in Experiments 1 and 2, the results remained the same. This again suggests that age differences in the rotation test were not representative of OAs' ability to successfully notice small changes between an object being presented and one stored in memory.

4.2 Conclusions

Despite these limitations, the findings from this study support the claim that memory processes do not occur in a vacuum. This claim is not new. This study, however, moves closer to specifying what domain general-cognitive processes contribute to cognitive operations (i.e., PS and PC) that support memory formation. Ultimately this research suggests that processes occurring outside the hippocampus significantly alter the ability of the hippocampus to efficiently execute its functions. Hippocampal PS and PC, therefore, rely heavily on upstream cortical processing to operate effectively. According to Stark and colleagues, the PCB in aging cannot be overcome to improve memory performance (Stark et al., 2015). The results within these experiments reveal a much more complex picture of aging. As we age, a myriad of changes occur that lead to a variety of bottlenecks in cognitive processing. Whether it is cognitive slowing or changes in inhibitory processes, altered memory is not solely caused by altered hippocampal function. Bottlenecks exist throughout the brain and these bottlenecks cause a reduction in the fidelity of the information that is sent to the hippocampus. Extra-hippocampal

bottlenecks, such as limitations on processing under time constraints, combine with impairments in PS and PC processes, and lead to the PCB in aging. While the current findings also provide evidence for the idea that the PCB in aging cannot be fully overcome, they indicate that the typical mnemonic similarity task measures more than just memory changes associated with age. Since the goal of the mnemonic similarity task is to specifically tap into PS processes, the task itself needs to be modified to accommodate other processing deficits that occur with age. These accommodations will likely be even more critical when understanding how PS processes are altered in pathological aging such as early Alzheimer's disease.

This set of experiments provides compelling evidence that the PCB in aging is a combination of complex factors that occur throughout the human brain. This set of experiments does not, however, elucidate what neural processes are altered by the manipulations. For example, when we account for processing speed by giving OAs more time to study the materials and form stronger memories, the question remains as to what neural regions support the formation of stronger memories. I have argued throughout this dissertation that the manipulations alter processing upstream to the hippocampus, however, it is also possible that the manipulations used in this study specifically alter hippocampal function. When participants are given more time to study the materials, upstream processing in the occipital cortex may be increased, creating a stronger representation that will then be sent to the hippocampus. Similarly, the ability to inhibit irrelevant information from entering the mental workspace may enhance processing through the reduction of mental clutter. An alternate possibility, however, is that hippocampal PS alone is improved such that PS is able to create a unique mnemonic trace when given more time. While it is most likely a combination of these factors, understanding how the

alterations in the PCB in aging found in this study are mediated by neural processes will be a critical next step.

Finally, the results of the present study suggest that memory changes associated with age can be moderated and that it may be possible to implement strategies in OAs to reduce memory dysfunction. This is an important finding since much of our population is aging. Cognitive training with the goal of improving domain-general cognition has recently become the focus of a great deal of research. The present findings suggest that OAs may already have the requisite cognitive abilities to improve their memory performance; however, they may need to be given appropriate strategies to realize these improvements. Based on the processing speed manipulation (Experiment 1), it is plausible that if OAs were instructed to slow down when trying to encode and simply spend more time studying the material, that they would recover much of their memory abilities. Similarly, when designing technological interfaces for the public, it is likely that the user experience for OAs would be improved if the rate of presentation was slowed to allow for a more complete processing of each bit of information. Further, given OA deficits in inhibition, one strategy that may improve memory and cognition in general, would be to instruct OAs to learn new materials in smaller chunks. For example, if an OA is attempting to remember how to operate a new program on a computer, they may be able to learn more quickly if they break the learning into small portions. Learning may be improved in this scenario through the reduction of proactive interference. Since OAs have impairments in the deletion mechanism, their ability to discriminate between similar events that occur at different times in a long sequence of events would be impaired in relation to YAs. Learning in smaller chunks would help to keep a clean mental workspace, and therefore, allow OAs to build stronger representations of each stage of the process and improve learning and memory. It will be

important for future research to investigate whether teaching OAs strategies related to overcoming domain-general cognitive changes will actually improve learning and memory.

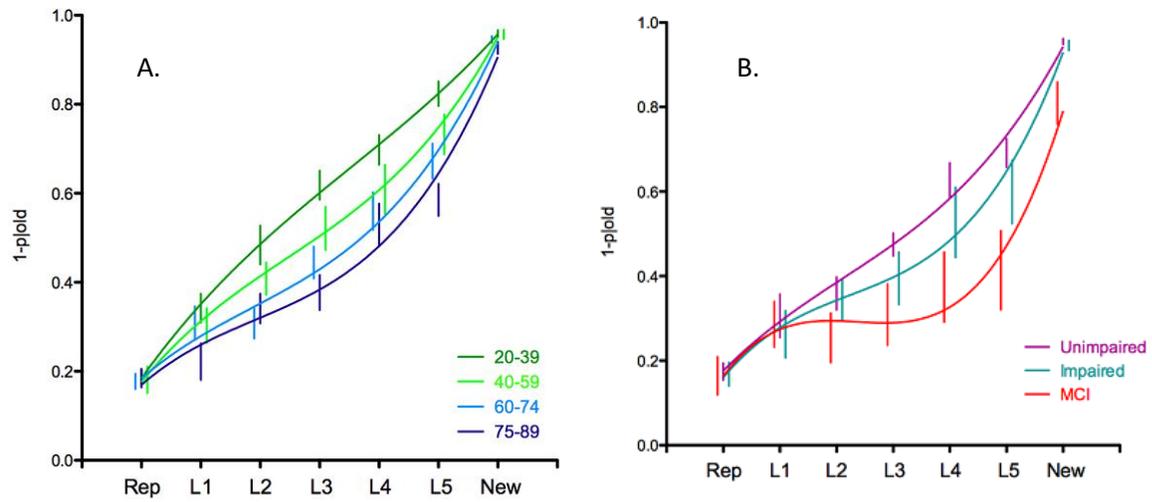


Figure 1. Results from a mnemonic similarity task showing the altered “tuning curve” that occurs in healthy aging (A) and in mild cognitive impairment (MCI, B). Note that in the anchor point for new trials is not the same across all groups (B), however the interpretation remains unchanged (Figure adapted from Stark et al., 2013)

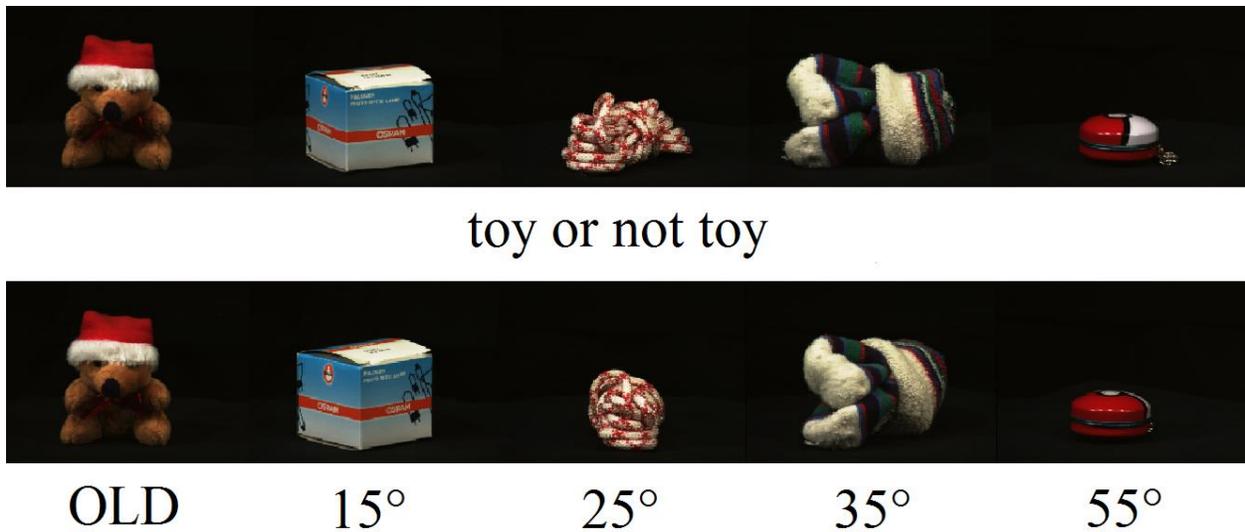


Figure 2. Example stimuli. During encoding participants will be shown a continuous stream of objects (top row). During test, participants will be shown stimuli that are either “old” (exact repeats of previously seen stimuli), “new” (objects never seen before), or “rotated” (objects that are rotated from the original presentation to varying degrees), and make “old”, “rotated”, or “new” judgments. As a note, a “new” image is not presented in the figure however, there will be an equal number of “old”, “rotated”, and “new” stimuli at test.

Table 1.

Experiment 1 Demographic and Cognitive Testing Data

	YA	OA
N	25	25
Gender	12m/13f	7m/18f
Age	19.08(.29)*	69(1.17)
Education	12.8(.22)*	17.88(1.17)
Mini Mental State Exam	29.68(.11)	29.4(.18)
Digit span - forward	11.16(.41)	10.8(.47)
Digit span - backward	7.36(.45)	7.28(.47)
Trails A (sec)	20.48(.87)*	34.36(3.21)
Trails B (sec)	49.16(3.10) *	87.80(12.11)
D-KEFS Color-Word interference test		
Color naming	24.52(.83) *	30.48(1.24)
Word reading	19.44(.75) *	22.0(.89)
Interference	41.48(1.53) *	58.8(2.95)

Note: YA = Younger adult. OA = Older adult. Asterisks indicate a significant difference between groups, $p < .05$. Numbers represent means and (standard errors).

Table 2.

Parameter Estimates (PE) from Experiment 1

Fixed Effects	One Minus the Probability of Old		
	PE	SE	<i>p</i> - value
Intercept	.307	.029	< .0001
Rotation	.117	.009	< .0001
Group	.037	.041	.3718
ROP	.068	.028	.0163
Rotation x Group	-.045	.013	.0004
Rotation x ROP	-.029	.012	.0136
Group x ROP	-.158	.040	< .0001
Rotation x Group x ROP	.063	.016	.0002
Random Effects			
Intercept	.011	.003	.0004
Intercept/Slope	-.001	.0008	.0960
Slope	.0003	.0002	.0860

Note. ROP = Rate of Presentation, SE = standard error.

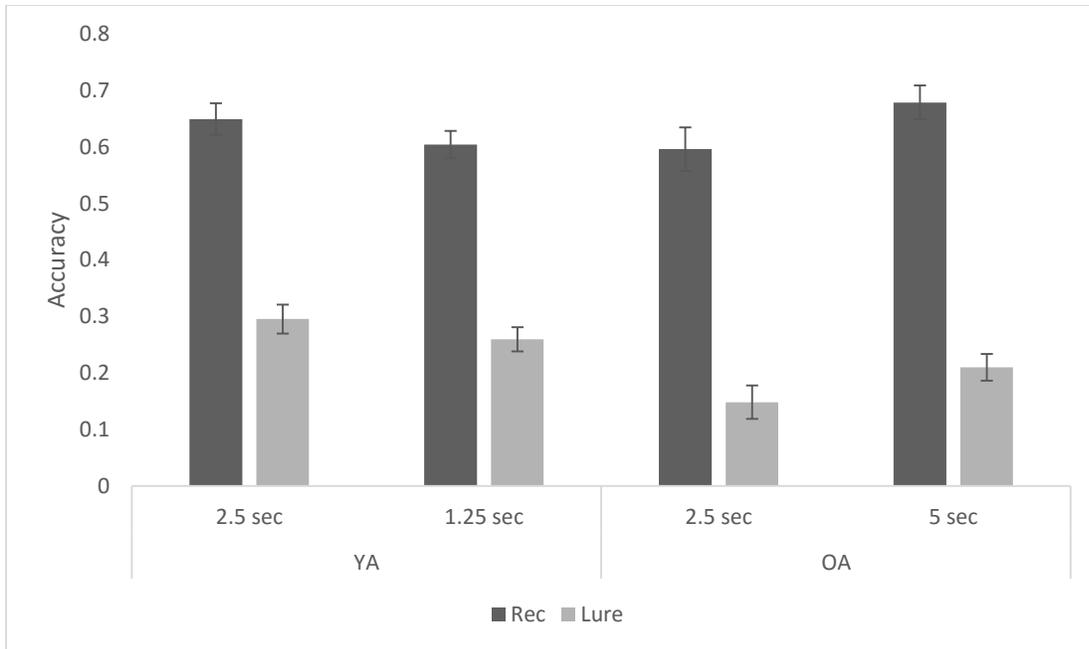


Figure 3. Experiment 1 old/new recognition and overall lure discrimination performance. YA = young adult. OA = older adult. Error bars represent standard error of the mean.

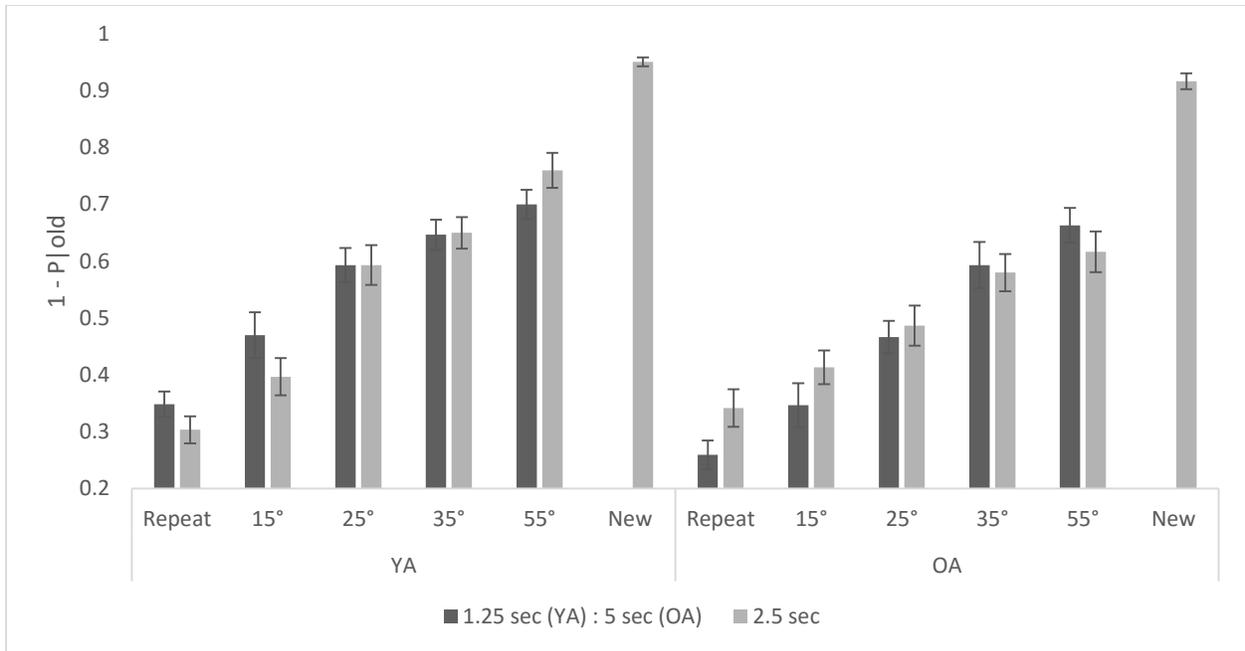


Figure 4. Experiment 1 lure discrimination results across all trial types. YA = young adult. OA = older adult. Numbers represent rate of presentation in seconds. Error bars represent standard error of the mean.

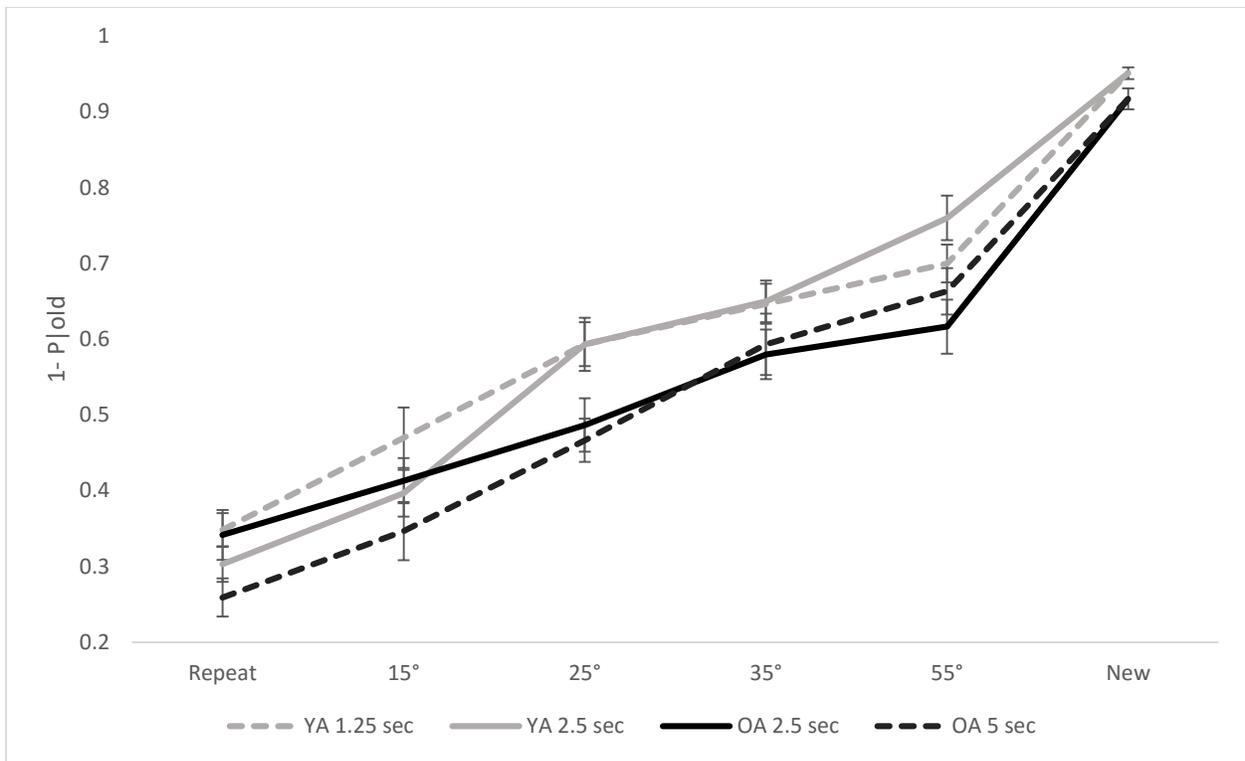


Figure 5. Experiment 1 lure discrimination across all trial types. YA = young adult. OA = older adult. Numbers represent rate of presentation in seconds. Error bars represent standard error of the mean.

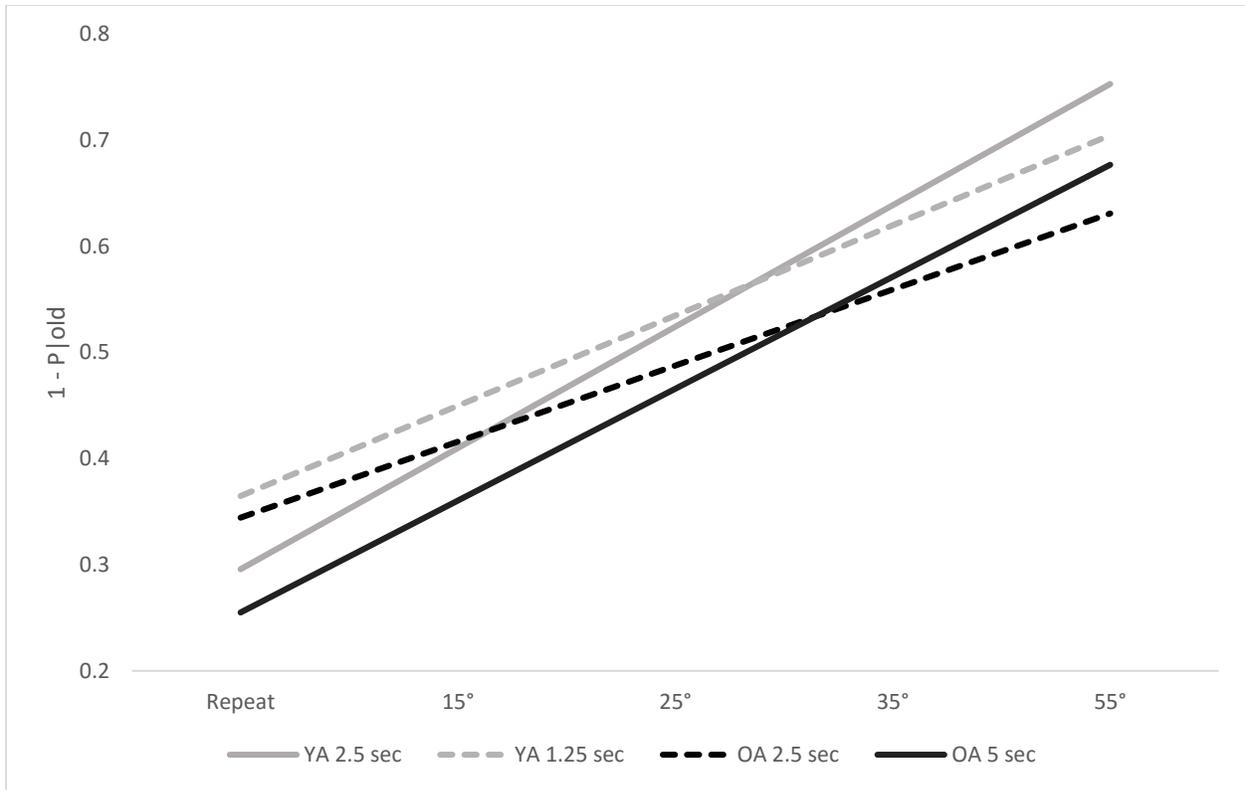


Figure 6. Model implied intercepts and slopes in Experiment 1. YA = young adult. OA = older adult. Numbers represent rate of presentation in seconds. The dotted lines indicate the model implied results in the “faster” condition for each group. The solid lines indicate the model implied results in the “slower” condition for each group.

Table 3.

Experiment 2 Demographic and Cognitive Testing Data

	YA	OA
N	25	18
Gender	10m/15f	6m/12f
Age	20.04(.53)*	73.22(1.82)
Education	13.48(.48)*	17.75(.48)
Mini Mental State Exam	29.40(.16)	29.33(.23)
Digit span - forward	10.80(.44)	10.33(.51)
Digit span - backward	7.52(.43)	7.11(.52)
Trails A (sec)	21.04(1.32)*	37.06(2.84)
Trails B (sec)	49.08(2.99)*	81.50(7.51)
D-KEFS Color-Word interference test		
Color naming	24.00(.70)*	30.94(1.74)
Word reading	18.68(.73)*	22.17(.90)
Interference	42.72(2.04)*	60.17(3.08)

Note: YA = Younger adult. OA = Older adult. Asterisks indicate a significant difference between groups, $p < .05$. Numbers represent means and (standard errors).

Table 4.

Parameter Estimates (PE) from Experiment 2

Fixed Effects	One Minus the Probability of Old		
	PE	SE	<i>p</i> - value
Intercept	.272	.032	< .0001
Rotation	.122	.009	< .0001
Group	.113	.050	.0281
DA	.212	.028	< .0001
Rotation x Group	-.062	.015	< .0001
Rotation x DA	-.043	.012	.0002
Group x DA	-.090	.044	.0407
Rotation x Group x DA	.028	.018	.1216
Random Effects			
Intercept	.016	.005	.0003
Intercept/Slope	-.002	.001	.0856
Slope	.0006	.0003	.0338

Note. DA = Divided Attention, SE = standard error.

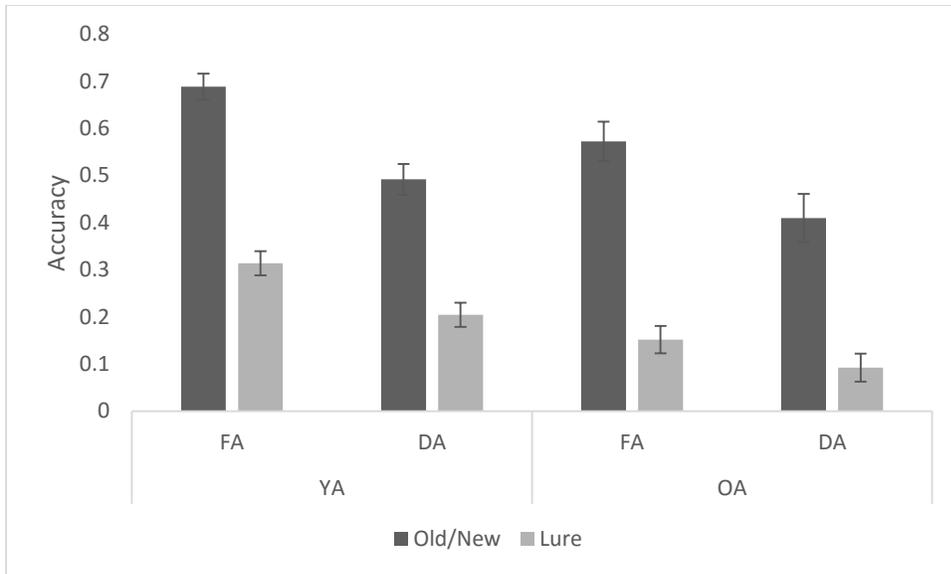


Figure 7. Experiment 2 results from old/new recognition and overall lure discrimination. FA = full attention. DA = divided attention. YA = young adult. OA = older adult. Error bars represent standard error of the mean.

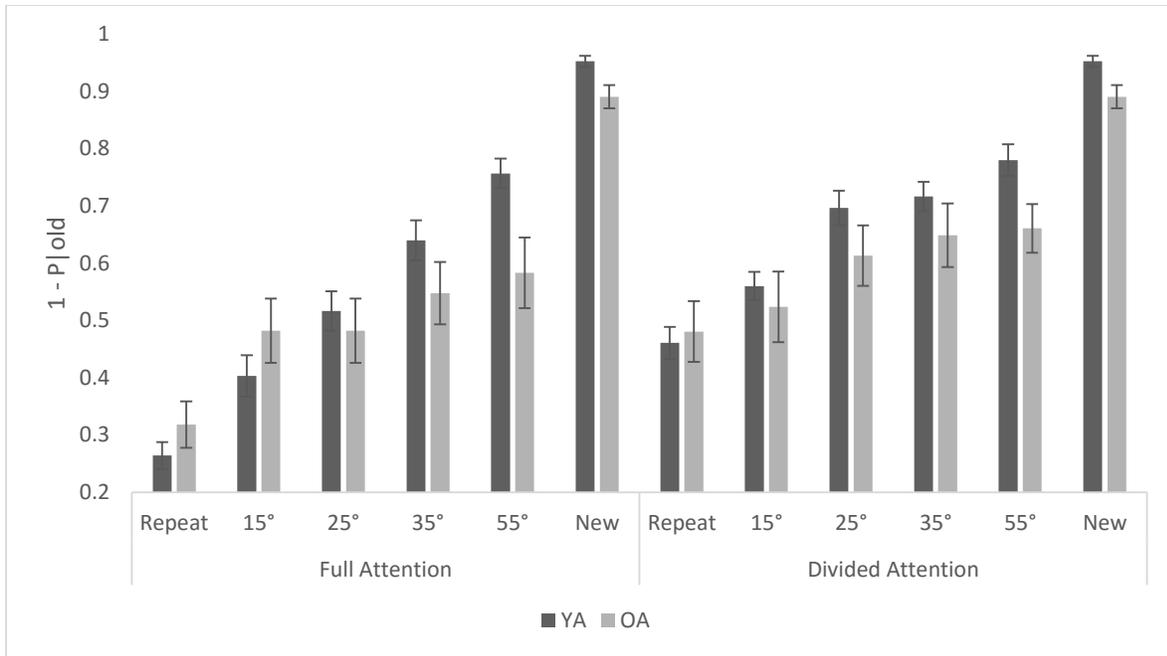


Figure 8. Experiment 2 Lure discrimination index across all trials. YA = young adult. OA = older adult. Error bars represent standard error of the mean.

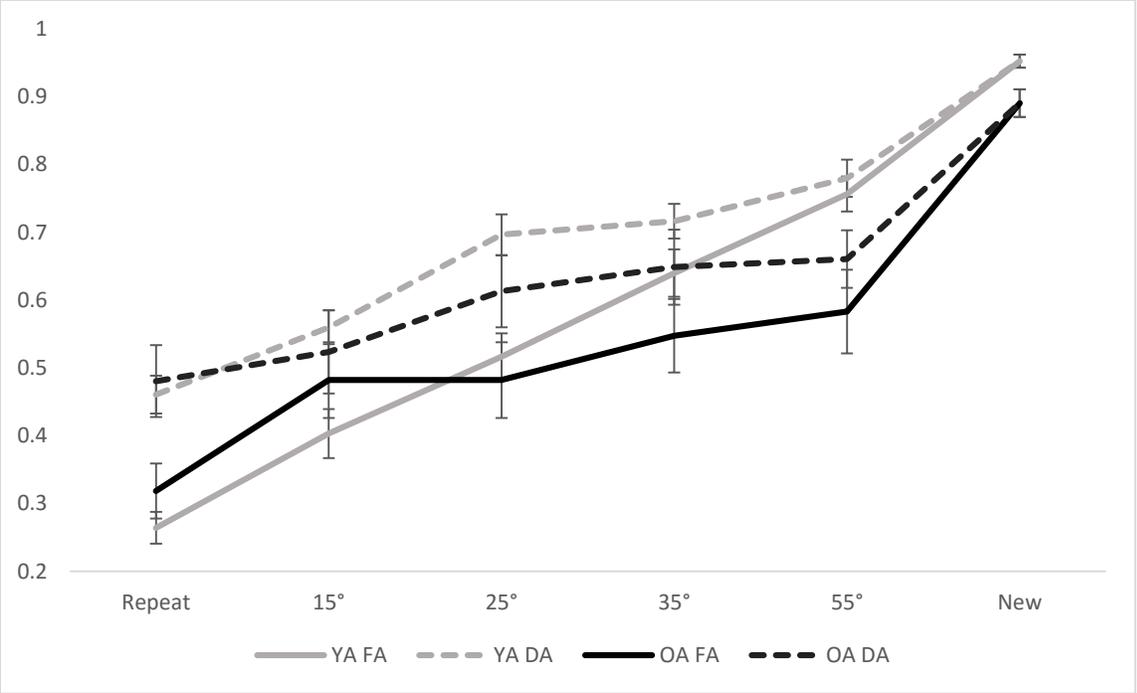


Figure 9. Experiment 2 Lure discrimination across all trials. FA = full attention. DA = divided attention. YA = young adult. OA = older adult. Error bar represent standard error of the mean.

Table 5.

Experiment 3 Demographic and Cognitive Testing Data

	YA	OA
N	24	25
Gender	7m/17f	10m/15f
Age	18.67(.17)*	69.92(1.24)
Education	12.54(.15)*	17.67(.51)
Mini Mental State Exam	29.12(.25)	29.40(.16)
Digit span - forward	11.08(.39)	10.76(.41)
Digit span - backward	7.67(.44)	7.40(.49)
Trails A (sec)	23.13(1.56)*	34.20(1.71)
Trails B (sec)	51.58(2.80)*	78.72(6.27)
D-KEFS Color-Word interference test		
Color naming	24.33(.77)*	30.72(1.44)
Word reading	18.08(.48)*	22.32(.78)
Interference	39.42(1.29)*	61.64(3.55)

Note: YA = Younger adult. OA = Older adult. sec = seconds.
 Asterisks indicate a significant difference between groups, $p < .05$. Numbers represent means and (standard errors).

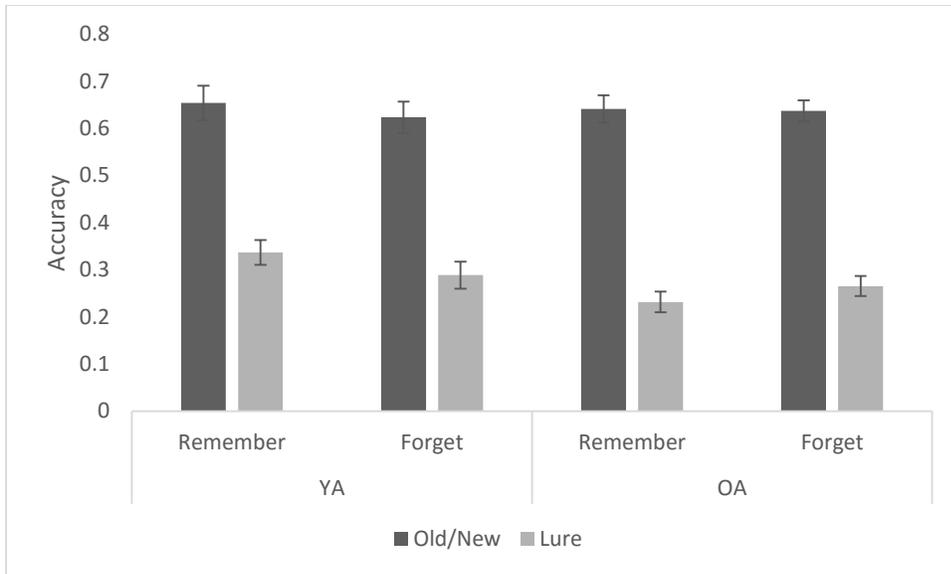


Figure 10. Experiment 3 old/new recognition and overall lure discrimination index. YA = young adult. OA = older adult. Error bars represent standard error of the mean.

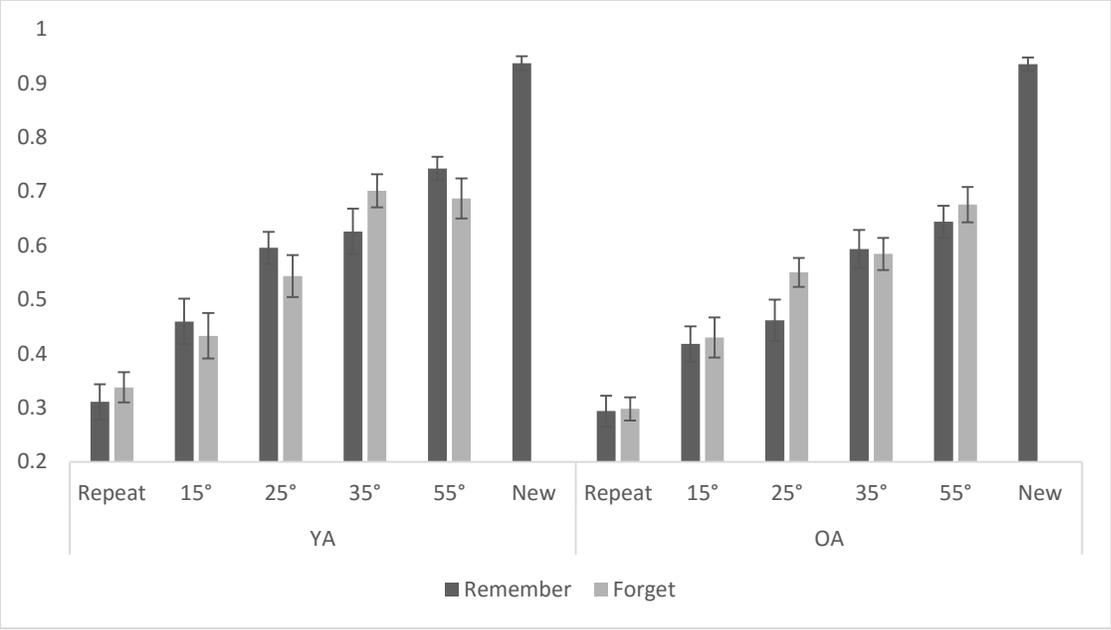


Figure 11. Experiment 3 lure discrimination index across all trials. YA = young adult. OA = older adult. Error bars represent standard error of the mean.

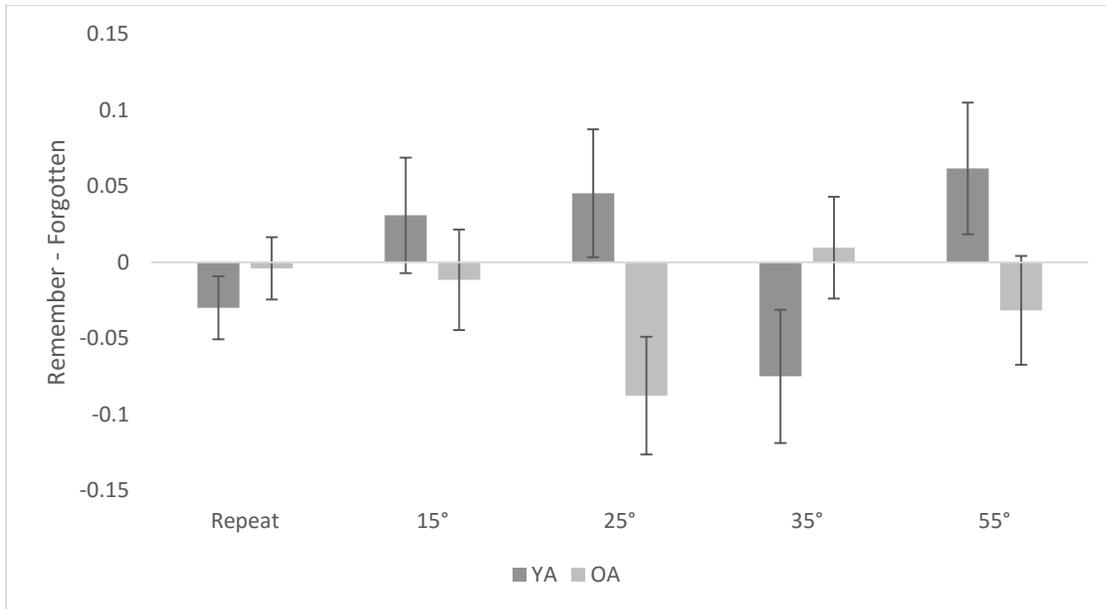


Figure 12. Experiment 3 lure discrimination index across all trials. Forgotten trials were subtracted from Remember trials. Being positive on the scale indicates greater memory for remembered versus forgotten trials. YA = young adult. OA = older adult. Error bars represent standard error of the mean.

Table 6.

Parameter Estimates (PE) from Experiment 3

Fixed Effects	One Minus the Probability of Old		
	PE	SE	<i>p</i> - value
Intercept	.322	.033	< .0001
Rotation	.110	.010	< .0001
Group	.015	.046	.7421
DF	.010	.029	.7397
Rotation x Group	-.023	.015	.1177
Rotation x DF	-.008	.012	.4943
Group x DF	.009	.040	.8244
Rotation x Group x DF	.012	.016	.4858
Random Effects			
Intercept	.016	.004	.0001
Intercept/Slope	-.003	.001	.0163
Slope	.001	.0004	.0062

Note. DF = Directed Forgetting, SE = standard error.

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