RICE UNIVERSITY

Inhibitory control mechanisms and their role in task switching:

A multi-methodological approach

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

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HOUSTON, TEXAS
MAY, 2012
ABSTRACT

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Executive control allows us to ignore distraction and switch between tasks in a flexible, yet organized fashion. While a hallmark of controlled behavior, distinctions among executive control processes are not thoroughly agreed upon. The present work explored the organization of two of these executive control processes, inhibition and shifting, and their relationship to each other. There were two primary goals. The first goal was to investigate the distinction among inhibitory control processes, as “inhibition” has oftentimes been considered a unitary construct. For example, there is evidence that response-distractor inhibition, which involves resolving interference from dominant responses or distractors in the external environment, is different from resistance to proactive interference (PI), which involves overcoming interference from previously relevant representations in memory. Using aging, neuropsychology, and individual differences methodologies, I investigated the unity and diversity of inhibitory control mechanisms. The healthy aging and neuropsychological evidence supported a distinction between response-distractor inhibition and resistance to proactive interference. However, when controlling for processing speed, the individual differences work suggested a need for further specification, as only a subset of these tasks emerged in the single factor model that provided the best fit to the data. The second goal was to explore how inhibitory control processes interact with task switching, as some theoretical accounts of
task switching have suggested that switch costs result from the need to overcome interference from the previously relevant task. Inconsistent with these theories, I found little relation between inhibitory control and measures of global and local task switching, and instead, working memory served as the best predictor of these shifting measures. In contrast, inhibitory control was related to the backward inhibition abilities of older adults. These findings are discussed within a theory of working memory that accounts for the patterns of results found across the different methodologies.
ACKNOWLEDGMENTS

To start, I would like to express my gratitude to my advisor, Dr. Randi Martin. Randi has been an unending source of guidance, encouragement, and support throughout my years at Rice. She has pushed me to become a better student, writer, researcher, and leader. Additionally, she has always given me the freedom to pursue my own research interests, even if they diverge from her own. The breadth and depth of topics we have covered in the Brain and Language lab has made me very well rounded, and because of this, I am extremely excited (as opposed to nervous) about my move into a slightly new field for my postdoctoral fellowship. In short, Randi has made me the young cognitive psychologist that I am today. For these and many other contributions, including her many helpful comments on earlier versions of this dissertation, I am grateful.

I would also like to thank my committee members, Tatiana Schnur, Fred Oswald, Chandramallika Basak, and Suzanne Kemmer. My proposal meeting felt like an academic brain storming session, as each of my committee members provided thoughtful input that contributed to the success of this dissertation. Despite the fact that a large committee means balancing a lot of different schedules and opinions, I felt strongly that each committee member would provide invaluable advice. I was not mistaken.

Throughout my time as a graduate student, Tatiana Schnur has continually been an unofficial mentor, discussing everything from future positions to teaching strategies to research directions with me. I appreciate her organization and drive, and sincerely thank her for her support. Fred Oswald and Chandramallika Basak both exposed me to new research directions that played a role in various parts of this work. Fred’s Individual Differences seminar opened up this research domain to me, and I thank Fred for being so
patient and supportive in answering my questions as I learned confirmatory factor analytic theory and R programming. Similarly, Chandra’s Cognitive Interventions and Plasticity in Aging seminar also played a role in some of this (and my future) work’s direction. Thank you to Chandramallika for teaching me so much about healthy aging; this influence encouraged the development of my interest in aging as a field of study. I would also like to thank Suzanne Kemmer for providing an outside-the-department perspective. Her input has helped me think more about the importance of my research in everyday life.

I would like to acknowledge both past and present members of the Brain and Language Lab. Thanks to Dr. Bob Slevc, Dr. Kelly Biegler, Dr. Jason Crowther, Dr. Loan Vuong, Dr. Yi Guo, Yingying Tan, Azli Hassan, Heather Dial, and Hao Yan – in one way or another, each labmate has taught me something valuable. Additionally, completion of this dissertation would not have been possible without the generous and organized help of Sanam Jivani and Allen Lin. Their subject testing efforts enabled me to collect so very much of my data. To these two Research Assistants, I am forever grateful. And, of course, I must also acknowledge my generous funding sources, including my advisor Randi Martin, the Department of Psychology’s Maurin Fund, and Rice University’s Social Sciences Research Institute’s Dissertation Improvement Award.

I would also like to recognize several others outside of my research/academic life. To all of my friends, especially Lauren MacAfee and Jacquie Beitel, thank you for providing support, guidance, and encouragement. They have made all aspects of my life richer, better, and more exciting as I have pursued this graduate school adventure. Similarly, for the past several years, Kate Abad has been not only a mentor and role
model, but also a friend. She has played a very influential role in the development of my leadership skills and confidence, and I would like to thank her for teaching me so much—whether intentionally or not.

To my family, who has instilled in me a love of education, a drive to be successful, and confidence in myself. They have never hesitated to tell me how proud they are of me, and how much they love me. And, they have taught me so much more than I will ever recognize. Words cannot express my gratitude for their unconditional love and support.

Last, but certainly not least, I would like to acknowledge the love and support of my soon-to-be husband Nate Pettigrew (and the nonverbal support of Chuck and Ellie!). Nate has stood by me, patiently serving as a never-ending support system in times of happiness, sadness, goofiness, and frustration. He has been present both through this dissertation journey, as well as my time in Houston more generally. Nate made it possible for me to find and make a “home” so far away from my family.
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Inhibitory control mechanisms and their role in task switching:

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Chapter 1: Brief Introduction

Among other functions, executive control allows us to ignore irrelevant information, arguably through inhibitory processes, and to switch between tasks in a flexible, yet organized fashion. My dissertation explored the organization of two of these executive control processes, as well as their relationship with each other. Within this work, there were two primary goals. The first goal was to investigate interference resolution processes, exploring whether inhibition is best described as a single process or multiple distinct processes. The second goal was to explore how inhibitory control processes interact with task switching. I approached these questions with multiple different – yet complementary – methodologies, including aging (Chapters 4 and 5), individual differences (Chapter 6), and neuropsychology (Chapter 7).

Before getting into the theoretical background and experimental data, however, I first discuss the importance of executive control, from both a conceptual and everyday point of view. Take your current activities as an example. As you sit there, reading this dissertation, there are many other tasks you could be doing, things you could be thinking about, and distractors in the environment that you need to ignore in order to maintain focus. In other words, we are plagued by internal and external conflict, yet we nonetheless manage to focus on a single task while ignoring others. This suggests that we are generally fairly good at interference resolution, enabling us to take part in goal-directed behavior. Nonetheless, we can flexibly switch between tasks when needed – such as switching to respond to a student who walks into your office or to answer a
ringing telephone. That is, while we can effectively manage interference, we can also
determine when interfering stimuli are relevant and should be allocated attention. When
needed, we can reorient our goals in order to achieve another goal.

Let’s take the real-world example of switching between reading a manuscript (or
dissertation) and answering the phone. The switch in tasks may seem easy and seamless,
but evidence from cognitive psychology suggests that switching between tasks incurs a
cost. Individuals are slower and more error prone after a task switch, relative to a task
repetition. Additionally, inflexibility is a hallmark sign of frontal lobe damage (e.g.,
Milner, 1963, 1964), as many patients with frontal lobe damage are impaired in switching
between tasks. Furthermore, Meiran (2010) has argued that cognitive flexibility plays a
critical role in social interactions, cooperative behavior, and emotional regulation. Thus,
understanding our ability to flexibility switch between tasks is not only essential to
understanding flexible, regulated behavior, but may also have implications for treating
patients with frontal lobe damage, social interactions, and emotional regulation.

Importantly for the present work, cognitive control abilities such as interference
resolution, working memory resources, and switching flexibly between tasks are
theoretically intertwined. That is, in order to preferentially perform one task over another,
we must select that task in the face of competition from other possible tasks. Thus, the
goal of the present work is to explore the mechanisms involved in interference resolution,
as well as their interaction with cognitive flexibility.
Chapter 2: Theoretical Background

The overall goal of this work was to examine the executive control mechanisms involved in inhibition and shifting. This chapter provides an overview of relevant theories, with specific study goals being identified at the end of the chapter. Generally speaking, the studies reported herein investigated how inhibition and shifting processes can be dissociated, how they relate to each other, and executive control models that account for these relationships.

Task Switching and Switch Costs

Our ability to behave in a cognitively flexible manner is moderated by executive control. Specifically, cognitive flexibility necessitates shifting our focus of attention between different tasks, an aspect of executive function that is known as task switching (e.g., Jersild, 1927; Miyake et al., 2000; Rogers & Monsell, 1995; Spector & Biederman, 1976). Task switching behavior is typically measured in a shifting paradigm (e.g., Jersild, 1927), in which subjects change between two or more cognitive tasks in an organized, goal-oriented fashion. In standard shifting paradigms, subjects are asked to complete both single and mixed task blocks. In single task blocks, or pure blocks, subjects perform a single task throughout the duration of the block; in contrast, mixed task blocks require subjects to switch between two or more tasks. In mixed blocks, task changes can occur randomly, with changes externally cued by a word, symbol, or spatial location. Alternatively, task changes can be predictable, as with the alternating runs paradigm (Rogers & Monsell, 1995) in which the task changes after N runs (e.g., task$_1$, task$_1$, task$_2$, task$_2$); given task predictability, cues are not necessary (but are sometimes used) as subjects can keep track of the relevant task using subvocal rehearsal (e.g., Baddeley,
Regardless of cue manipulations or the manner in which tasks change, switching incurs a cost: individuals are slower and more error prone when task changes are required, relative to when continuing with a single task.

The cost of changing tasks is known as the switch cost, and researchers distinguish between several types (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995). Global switch costs are measured as the difference between mixed and pure blocks (e.g., Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976). As described above, mixed blocks require the performance of multiple tasks within a single block, while pure blocks only require performance of a single task. Such global switch costs are thought to measure the cost of updating, manipulating, and maintaining multiple tasks in working memory (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995), as multiple tasks need to be available in mixed blocks, relative to pure blocks.

Local switch costs, in contrast, are measured as the performance difference between switch and non-switch (or repeat) trials within a mixed block (Rogers & Monsell, 1995). For example, mixed blocks may be composed of multiple runs of a single task, followed by multiple runs of a different task, e.g., task\(_1\), task\(_1\), task\(_2\), task\(_2\), task\(_1\). Local switch costs are computed by subtracting mean performance on repeat trials (not underlined) from mean performance on switch trials (underlined). Given they measure the processes involved in initiating and executing a task change, local costs are hypothesized to be a purer measure of task switching (Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995). More specifically, this cost is hypothesized to reflect disengagement of the currently relevant task (e.g., Mayr & Keele, 2000) and retrieval of the task information from long-term memory (e.g., Mayr & Kliegl, 2000).
Multiple lines of evidence support the idea that global and local switch costs reflect separate processes. Aging studies have found that older adults show exaggerated switch costs on measures of global, but not local, shifting (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001; cf. Kray, Li, & Lindenberger, 2002; Mayr & Kliegl, 2000a). Kray and Lindenberger (2000), for example, used a predictable, implicitly cued switching paradigm to investigate age differences in global and local switch costs. Age differences were found in global switch costs, such that middle-aged and older adults showed greater global switch costs than young adults. In contrast, age effects were either minimal or not observed in local switch costs. Similarly, Mayr (2001) replicated these effects in an unpredictable, explicitly cued shifting paradigm. Mayr concluded that older adults have difficulty selecting among relevant tasks in mixed blocks. Further supporting the separation of global and local costs as distinct executive processes, Kray and Lindenberger found that these switch costs were better represented by two latent switching factors in a confirmatory factor analysis, as opposed to a single-factor model. Additionally, global and local switch costs are differentially affected by articulatory suppression (i.e., repeating irrelevant verbal information while performing a task to disrupt inner rehearsal; e.g., Allen, 2010; Baddeley et al., 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003; Saeki & Saito, 2004; cf. Miyake, Emerson, Padilla, & Ahn, 2004).

**Models of Task Switching**

Models of task switching assume that the intention to perform a given task is accompanied by the adoption of a “task set” (e.g., Allport, Styles, & Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976), or attentional mechanisms
that are used to guide behavior. According to Kiesel et al. (2010), task sets are “mental representations that enable the person to act in accordance to task requirements”. Task sets are thought to consist of multiple internal control templates, including the task goal, possible task-relevant responses, and stimulus-response (S-R) mappings. Task goal representations enable attention to be drawn to specific stimulus features; for example, in the context of a “shape” task, the goal would be “respond to object shape” (but not color or size). Task-relevant responses include representations of what responses can be made to particular stimuli, such as knowing that the possible shapes are square and circle. And, S-R mappings represent the motor-action plans associated with particular responses – that a square target requires one to press the left button. Critically, task sets should be instantiated at trial onset, maintained through the trial, and changed or updated whenever a new task becomes relevant; at the point of a task switch, task sets must be reconfigured.

Models of task switching propose the involvement of two distinct stages in task set reconfiguration, what Rogers and Monsell (1995) called endogenous and exogenous reconfiguration. As discussed below, endogenous reconfiguration can occur prior to target onset once one knows the task to performed, whereas exogenous reconfiguration cannot occur until after the target has been presented. However, theories differ in their assumptions about the processes that occur during these two stages.

Evidence for the processes involved in the endogenous component of task set reconfiguration comes from manipulations of preparation time, or the amount of time available to prepare for the upcoming target. In cued shifting, this is the cue-stimulus interval (CSI), the interval between cue and target onset; in predictable paradigms, this is the response-stimulus interval (RSI), the interval between the response to the previous
trial and onset of the next trial’s target. In both cases, longer preparation intervals result in significantly reduced switch costs, indicating that some form of advance preparation for the upcoming task takes place. Although accounts differ on the exact factors involved, such advance preparation is thought to involve updating the currently relevant task set into working memory (e.g., Altmann & Gray, 2008; Mayr & Kliegl, 2000, 2003; Meiran, 2000; Rubinstein, Meyer, & Evans, 2001). Whether or not retrieval of the task set occurs for both switch and repeat trials is a matter of debate. Rogers and Monsell (1995), for example, propose that endogenous reconfiguration is unique to switch trials. In contrast, Mayr and Kliegl (2000, 2003; see also Altmann & Gray, 2008) propose that task set information is retrieved on both switch and repeat trials, but that this retrieval process takes longer when a different task was performed on the previous trial. On such switch trials, the retrieval path needs to be changed (or, similarly, retrieval time is faster on non-switch trials because of having just performed the same task).

Evidence for the exogenous component of task set reconfiguration comes from “residual” switch costs. Despite the fact that switch costs can be reduced with advanced preparation, switch costs are not eliminated (e.g., Rogers & Monsell, 1995; but see Verbruggen, Liefooghe, Vandierendonck, & Demanet, 2007). That is, even when given ample time to prepare for the upcoming task, switch costs remain. As a result, task switching theories have proposed an exogenous component to task set reconfiguration that cannot be implemented until target onset. Again, theories differ in their exact specifications of exogenous reconfiguration; however, two general classes of theories emerge. The first class emphasizes response processes such as activating or loading S-R rules into WM and applying these rules to the target (Mayr & Kliegl, 2003; Meiran,
2000; Rubinstein et al., 2001). The second class emphasizes the need to overcome interference from previously executed tasks (e.g., Allport et al., 1994; Mayr & Keele, 2000; but see De Jong, 2000, for an alternative to both of these accounts). Of course, both could play a role with the interference arising when attempting to replace prior S-R mappings with the ones relevant to the current task. Given the relevance of interference accounts to the goals of the present body of work, the interference accounts will be reviewed in more detail, followed by a brief discussion of other evidence indicating a role for interference resolution in task switching.

**Interference-Based Accounts of Switch Costs**

One of the most influential interference-based accounts of switch costs was proposed by Allport and colleagues (1994; Allport & Wylie, 1999), and attributes switch costs to “task set inertia”. Allport and colleagues proposed that switch costs result from proactive interference from recently activated task sets. This account assumes a combination of continued priming from the previously, highly activated task, and prior suppression of the currently relevant task – that is, a combination of positive and negative priming. They hypothesize that previously relevant tasks receive a high level of activation in order to allow selection for action; shifting, however, requires that the cognitive system overcome that high activation in order to instantiate the newly relevant task set. To this end, inhibition is called upon as a mechanism for suppressing the previously relevant task set, allowing the new task set to take over. Switch costs, then, result from task set inertia – the continued activation of previously relevant task sets, which needs to be overcome in task switch situations.
Empirical evidence for the contribution of proactive interference to switch costs comes from findings of asymmetrical switch costs, found when one task is more dominant than another (Allport et al., 1994; see Meuter & Allport, 1999, for similar findings in language switching). Allport and colleagues imbedded a Stroop task (Stroop, 1935) in their shifting paradigm; subjects had to switch between color naming (while ignoring the written word) and word naming (while ignoring the stimulus’ ink color). Because word reading is a more automatic process, word reading is the easier, more dominant task with a stronger baseline activation. In contrast, color naming is the more difficult task, arguably with a weaker baseline activation. When switching between these tasks, switch costs were larger when switching to the dominant task of word reading, relative to switching to the less dominant (more difficult) task of color naming. Allport and colleagues explained these asymmetrical switch costs by proposing that persisting activation (of the no longer relevant task) needs to be suppressed. Because the baseline activation of the dominant (word reading) task is higher, more inhibition needs to be applied to this task in order to successfully activate the color naming task. In order to switch back to the dominant word reading task, one needs to overcome the inhibition they had previously applied to this task; and, this need to overcome persisting inhibition is a time consuming process. Switch costs, then, result in part from the temporal persistence of this strong inhibition. In contrast, the lower baseline activation of the less dominant task means less inhibition is required for overriding it. Because less inhibition is needed to suppress this task, there is less persisting inhibition to be overcome when switching back to this task in future trials (i.e., smaller switch costs).
To summarize, Allport and others (1994; Meuter & Allport, 1999) have explained asymmetrical switch costs in terms of the need for inhibition in overcoming interference from previously relevant tasks, and differing levels of persisting inhibition. However, as Koch et al. (2010) explain, explanations of asymmetrical switch costs do not unequivocally require inhibition, as asymmetrical switch costs can be explained by positive priming alone (Yeung & Monsell, 2003; see Koch et al., 2010 for a discussion). Specifically, positive priming accounts maintain that weaker tasks require “stronger control biases” (Yeung & Monsell, 2003, p. 468), or larger boosts in activation to overcome the greater baseline activation of the more dominant task. In contrast, because more dominant tasks have higher baseline activation levels, less priming is needed. This proportionally stronger priming for weaker tasks makes it more difficult to overcome this task’s activation when switching back to the strong task, resulting in asymmetrical switch costs. Thus, while asymmetrical switch costs support the need for interference resolution in task switching, they cannot conclusively confirm a role for inhibition. According to Healey, Campbell, Hasher, and Ossher (2010), “one way to adjudicate between inhibitory and noninhibitory accounts…is to search for convincing evidence from different paradigms” (p. 5).

Using a modified shifting paradigm, Mayr and Keele (2000) have found a compelling marker of inhibition in task switching. Mayr and Keele use a shifting paradigm with three tasks (tasks A, B, and C), as opposed to the more traditional method of using two tasks (tasks A and B only). The logic is as follows: if task sets are inhibited once abandoned, it should be more difficult to switch back to a recently inhibited task (ABA, N-2 repetition), as opposed to a less recently inhibited task (CBA; N-2 switch). In
the previous example, the underlined task represents the trial of interest. In both conditions, subjects are switching back to task A; however, what varies is the recency with which task A was previously performed. Mayr and Keele found significant N-2 repetition costs across a variety of experiments, providing support for the notion that inhibition is involved in shifting away from a recently abandoned task set (see also Gade & Koch, 2005, 2007; Schuch & Koch, 2003; Schneider & Verbruggen, 2008). N-2 repetition costs are evidence of a process that has been called both “backward inhibition” and “task-set inhibition”.

To gain a more thorough understanding of this backward inhibition effect, we will take a detailed look at the logic (e.g., Mayr & Keele, 2000). Below, I use $A_1$ to refer to the first instance of task A and $A_2$ to refer to the second instance of task A within the ABA sequence. In the ABA task sequence, performance of task $A_1$ requires activation of the relevant task set. Subsequent successful performance of task B requires that this task gain a higher level of activation than task $A_1$. As previously discussed, one mechanism for overcoming the previous task’s activation is inhibition, with a switch from task $A_1$ to task B resulting in inhibition of task $A_1$ (so called backward inhibition). Similarly, a switch from task B to task $A_2$ requires not only that task B be inhibited, but also that the cognitive system overcome the inhibition that was previously applied to task $A_1$. In the CBA sequence, in contrast, task C must be inhibited to allow for successful performance of task B, and task B must be inhibited to allow for the successful performance of task A. However, because task A was less recently inhibited (i.e., at some point prior to Task C), there is less inhibition to overcome when switching to this task. Importantly, this N-2 repetition cost is incompatible with activation-only (Mayr & Keele, 2000) or episodic
retrieval (Mayr, 2002) theories of task repetition, as both of these theories would predict facilitation of the N-2 repetition condition, relative to the N-2 switch. As a consequence, Mayr and Keele have suggested that backward inhibition allows for selection among competing task sets, functioning to reduce the activation of the now-irrelevant task and therefore facilitate selection of the newly-relevant task. However, a side effect of this interference resolution mechanism is the need to overcome inhibition persistence when the inhibited task becomes once again relevant, thus resulting in at least part of the residual switch cost.

Bringing this discussion back to models of task switching, the above evidence suggests that at least some component of exogenous reconfiguration – or equivalently, some component of residual switch costs – is the need to overcome interference from previously executed tasks via backward inhibition. Such an explanation clearly implicates a role for inhibitory processes in task switching. Before discussing the nature of these inhibitory mechanisms, we will first review other evidence of interference in task switching, as a large body of work supports the notion that switching involves resolving interference between tasks.

**Other Evidence for Interference in Task Switching**

Other effects also implicate a need for interference resolution in task switching. Switch costs are only found when task sets overlap. For example, Jersild (1927; see also Spector & Biederman, 1976) found that switch costs were reversed or eliminated when task stimuli unambiguously indicated which task should be performed on a given trial (e.g., Jersild, 1927; Spector & Biederman, 1976); in other words, switch costs are only present when two tasks must be performed on the same stimulus set. When subjects
alternated between adding and subtracting 3 from a list of numbers, switch costs were found. In contrast, no switch costs were found when subjects alternated between number and word stimuli, on which subjects subtracted three from the numbers and produced an antonym to the words (Jersild, 1927; Spector & Biederman, 1976; see also Allport et al., 1994). This difference has been taken as evidence that targets can serve as an unintentional retrieval cue for the irrelevant task set (Spector & Biederman, 1976).

Additional interference effects in task switching were illustrated in a set of elegant experiments by Rogers and Monsell (1995). First, subjects performed better on congruent trials, where the relevant and irrelevant target features (shape, size) were mapped to the same button (i.e., both are mapped to the left button), relative to incongruent trials where the relevant and irrelevant target features were mapped to different buttons. According to Kiesel and colleagues (2010), these findings suggest that bivalent targets activate responses for both currently relevant and currently irrelevant tasks. Second, subjects performed better when the irrelevant target attribute had no associated S-R mapping (a neutral, or univalent target). That is, performance was worse in response to bivalent targets, relative to univalent targets. Given univalent stimuli do not allow for the activation of an irrelevant S-R mapping, this effect suggests interference from irrelevant tasks, regardless of overlapping S-R mappings. That is, the difference in performance between these stimulus conditions was accounted for by the competition afforded by the bivalent stimuli: bivalent stimuli are associated with both the relevant and the competing (irrelevant) task, resulting in interference. Third, subjects performed better on neutral trials, relative to congruent trials. This suggests that the presence of any irrelevant target feature that has an irrelevant task S-R mapping (whether congruent or incongruent)
affects performance; as in the bivalent condition, the irrelevant stimulus attribute is assumed to activate the irrelevant task set, causing interference with stimulus processing. Rogers and Monsell discussed these effects in terms of exogenous task cueing effects, representing the “degree to which an irrelevant attribute associated with a now-inappropriate task makes that task harder to suppress, irrespective of its particular response value” (p. 212). As noted by Rogers and Monsell, these effects interact with, but do not fully account for, switch costs.

Additionally, mixing costs (e.g., Rubin & Meiran, 2005) can also be taken as evidence for task interference. Specifically, mixing costs are measured by the difference between repeat trials (in mixed blocks) and pure block performance. These two trial types are theoretically similar insofar as only one task must be performed. However, these two trial types are not statistically equivalent, as performance is worse on repeat trials. The additional time needed on repeat trials in mixed blocks (relative to pure task trials in pure blocks), has been attributed to the need to manage the competition between multiple task sets (Rubin & Meiran, 2005). While a review of mixing costs is beyond the scope of the present research, as the present work does not address this measure of shifting, mixing costs can be taken as evidence that interference plays a strong role in task switching ability.

**Nature of the Inhibitory Mechanisms in Task Switching**

While Mayr and Keele’s (2000) three-task shifting paradigm presented conclusive evidence for the role of inhibition in task switching (via N-2 repetition costs, or backward inhibition), a large question remained: what, exactly, is being inhibited, and how are interference resolution processes implemented in task switching? While a plethora of
experimental research has explored the first question, much less experimental work has explored the second question. These two issues will be reviewed in turn.

**Backward inhibition: What is being inhibited?** To answer the question of what is being inhibited by backward inhibition, researchers have used creative variants of the three-task shifting paradigm. All in all, results tend converge on the idea that inhibition is applied when internal conflict arises; while most have suggested this occurs at the level of response selection (e.g., Gade & Koch, 2005, 2007; Schuch & Koch, 2003; Schneider & Verbruggen, 2008), others have proposed a more flexible mechanism that depends on task design (Houghton, Pritchard, & Grange, 2009).

Gade and Koch (2007) used a shifting paradigm with four tasks. Three of these tasks were standard switching tasks, using multivalent (M) stimuli with overlapping response sets. The fourth task, however, was a neutral, univalent (U) task with a unique stimulus (i.e., the stimulus was in no way similar to the stimuli for the other three tasks); critically, the univalent task’s degree of response set overlap with the multivalent stimuli was manipulated across experiments. Their logic was as follows: if inhibition of the previously relevant task set (N-1) occurs as a function of competition at the response level on the current trial (N), removing trial N’s response-level competition should eliminate the need for inhibition. For example, if subjects perform three consecutive multivalent tasks (M_A1 M_B M_A2), successful selection and implementation of task M_B requires inhibition of M_A1 (as discussed above), and returning to task M_A2 requires overcoming this persisting inhibition, resulting in the N-2 repetition cost. In contrast, if there were no competition when switching to task M_B, inhibition would not be required. This condition was tested using a multivalent-univalent-multivalent triplet (M_A1 U M_A2).
In this triplet, the univalent task does not cause interference between tasks N-2 and N-1 because there is no response set overlap, thus no need to inhibit task $M_{A1}$—as a result, there should also be no N-2 repetition cost. Gade and Koch found significant N-2 repetition costs when three consecutive multivalent tasks followed each other ($M_{A1}M_{B}M_{A2}$), but no N-2 repetition cost when the same multivalent task was separated by the univalent task ($M_{A1}UM_{A2}$). The authors concluded that backward inhibition resolves competition produced by response set overlap.

To further test their hypothesis that response set overlap is critical to the triggering of backward inhibition, Gade and Koch (2007) manipulated the univalent task’s degree of response set overlap. In Experiment 3, the univalent task’s stimulus remained unique, but the response set overlapped with the response sets of the multivalent tasks. Contrary to the first experiment, when the univalent task had a unique response set, the overlapping response set in Experiment 3 produced significant N-2 repetition costs, even in the multivalent-univalent-multivalent triplet ($M_{A1}UM_{A2}$). These results suggest that overlapping response sets trigger backward inhibition in shifting paradigms, as illustrated by the occurrence of N-2 repetition costs; however, given the neutral nature of the univalent stimulus, it should be noted that this is the only place in which task set competition occurs (i.e., there are no overlapping target features), and therefore this account cannot rule out the possibility that backward inhibition would be applied to other task set representations at the point at which conflict arises (e.g., Houghton et al., 2009).

Schuch and Koch (2003) further supported a role for response level processes in the triggering of backward inhibition in task switching. Schuch and Koch combined a
shifting task with the go/no-go paradigm to explore the role of response selection in the N-2 repetition cost. No-go trials were unpredictably imbedded as relatively rare events in the shifting paradigm, with the no-go signal occurring simultaneously with target onset. Because subjects did not know in advance if a trial would be go or no-go and go trials were more frequent, they assumed business as usual and prepared for the upcoming task during the CSI. However, in no-go trials, a no-go signal informed subjects that responding was unnecessary. The authors predicted that if response selection was responsible for the N-2 repetition cost through the triggering of inhibition, N-2 repetition costs should be found when response selection is required for task B of an ABA triplet (go condition), but not when response selection is not required for task B (no-go condition). The authors found exactly that: if trial N-1 was a go trial, there was a significant N-2 repetition cost; in contrast, if trial N-1 was a no-go trial, there was no N-2 repetition cost, suggesting no inhibition of task A1.

Schuch and Koch (2003) also ruled out response execution (independent of response selection) as a necessary condition for inhibition. In Experiments 3 and 4, Schuch and Koch required subjects to execute both possible responses in no-go trials (i.e., both response keys were pressed on these trials), requiring response execution independent of response selection. Similar to the previously discussed no-go trials, N-2 repetition costs were only found in the go condition, when response selection and execution were required. N-2 repetition costs were not found in the no-go condition that required only response execution. Schuch and Koch conclude that the occurrence of backward inhibition depends on response selection, more specifically, at the level of the previous category-response mappings. They propose that inhibition supports the
“recoding of the meaning of responses in overlapping S-R tasks” (p. 101). When all the
tasks use overlapping responses, task changes result in response level conflicts such that
the previously relevant response meanings (e.g., left button = circle, right button =
square) are no longer relevant, and must be abandoned in favor of the currently relevant
response meanings (left button = red, right button = blue). This abandonment of
irrelevant category-response mappings is achieved via backward inhibition.

While several lines of research have suggested that backward inhibition plays a
functional role at the level of response selection, Houghton and colleagues (2009) found
varying degrees of backward inhibition as a function of cue processing requirements.
While keeping all other task features the same, the authors manipulated the degree of
cue-to-target match in an attentional switching paradigm requiring that participants
identify visual features. Switching was measured via the reallocation of attention to a new
visual feature (as opposed to a switch in tasks per se). In their study, transparent cues
provided visual overlap between the cues and targets, allowing direct identification of
target properties and resulting in direct task set activation. For example, an angled,
unfilled rectangle served as the cue for angled targets whereas a shaded rectangle served
as the cue for shaded targets. In contrast, less transparent cues required that the cue first
be translated into a representation that was more similar to the target (see also Baddeley
et al., 2001; Bryck & Mayr, 2005 for similar logic concerning cue manipulations). For
example, an unfilled octagon served as the cue for angled targets whereas an unfilled
square served as a cue for shaded targets. In these less transparent cue conditions, cue
meanings had to be retrieved before the relevant visual features could be identified.
Houghton et al. found larger backward inhibition effects with less transparent cues,
arguing that the need to retrieve the cue’s meaning resulted in competition from the representations that were already active from the previous trial; this conflict was subsequently resolved by backward inhibition. In contrast, transparent cues allowed for the immediate identification of the target’s visual features, allowing the relevant feature to be directly instantiated into the focus of attention. As pointed out by Houghton et al., the notion that backward inhibition is more flexible (in that it can act on any representation that induces competition) is in line with Mayr and Keele’s (2000) suggestion that backward inhibition is a mechanism for clearing working memory and may play a more general role in reducing internal conflict (see also Bao, Li, Chen, & Zhang, 2006, for evidence of backward inhibition in a working memory paradigm).

In summary, then, several lines of research have suggested that backward inhibition plays a functional role at the response selection level, though others have suggested that backward inhibition is more flexible. Regardless of the representation to which this mechanism is applied, backward inhibition functions to reduce the interference of irrelevant task information in order to facilitate selection of the newly relevant task set. Thus, while backward inhibition facilitates aspects of task set selection, it also comes with a consequence, as persisting inhibition slows task performance when a task is repeated at a later time point (ABA), as opposed to when a task is not repeated (CBA) – a so-called fingerprint of inhibition (Healey et al., 2010).

**Inhibition in task switching: How is it implemented?** Above, we reviewed a large body of evidence suggesting that interference resolution mechanisms are important in task switching. The notion that inhibition is important to aspects of working memory is not new, as several theories have proposed a role for interference resolution in working
memory (e.g., Engle & Kane, 2004; Hasher & Zacks, 1988; Kane, Bleckley, Conway & Engle, 2001; Lustig, May & Hasher, 2001; May, Hasher & Kane, 1999; cf. MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). For example, Hasher and colleagues have proposed that inhibition serves a critical role in memory and attentional processes, serving three important functions: restricting access to working memory such that only relevant information is accessed; deleting no longer relevant information from the contents of working memory (conceptually similar to the above-discussed backward inhibition); and withholding strong, automatic responses until they can be evaluated (Hasher, Zacks, & May, 1999). According to Hasher, Zacks, and colleagues, these inhibition functions are directed at the contents of working memory.

This and other theoretical perspectives (e.g., Harnishfeger, 1995; Kok, 1999; Munakata et al., 2011; Nigg, 2000) suggest inhibition is not a unitary construct, but can instead by represented by separate inhibitory mechanisms. Psychometric support for the non-unitary nature of inhibitory control comes from an individual differences study. Friedman and Miyake (2004) used confirmatory factor analysis to examine three types of inhibition, similar to those identified by Hasher and colleagues. The first was preponent response inhibition, measuring the ability to inhibit dominant or automatic responses, which is similar to Hasher and Zacks’ (1988) restraining function. Second, Friedman and Miyake measured resistance to distractor interference, conceptualized as the ability to resist interference from irrelevant information in the external environment, which is similar to Hasher and Zacks’ access function. Lastly, Friedman and Miyake measured the resistance to proactive interference, or the ability to resist interference from previously
relevant information; May and colleagues (May, Hasher, & Kane, 1999) hypothesize that the deletion function of inhibition is important for resisting proactive interference.

Although three distinct inhibitory mechanisms were hypothesized, confirmatory factor analysis (CFA) results suggested only two inhibition mechanisms (cf. Hedden & Yoon, 2006). Specifically, Friedman and Miyake (2004) found a strong relation between preponent response inhibition and resistance to distractor interference and proposed this relationship resulted from the fact that they both “share the requirement to actively maintain task goals in the face of interference” (p. 126). As a result, they combined these two types of inhibition into a single construct called “response-distractor inhibition”. In contrast, resistance to proactive interference construct (which involves resisting interference from irrelevant information residing in memory rather than from the external environment) was not related response-distractor interference. Thus, Friedman and Miyake proposed a two-factor model of inhibition consisting of response-distractor inhibition and resistance to proactive interference, though they recognize there may be other types of inhibition that were not investigated in their study.

What types of inhibition might have Friedman and Miyake (2004) have failed to investigate? One possibility is a more automatic form of inhibition that is separate from cognitively controlled inhibitory mechanisms (but see Munakata et al., 2011, for an alternative perspective). Automatic inhibitory mechanisms may be implemented via lateral inhibition of neural representations as a (unintentional but functional) side effect of selective attention (e.g., Desimone & Duncan, 1995; Miller & Cohen, 2001; Munakata et al., 2011; Nigg, 2000). With this form of inhibition, selective attention acts to bias the processing of particular target or task features (conceptually similar to a task set);
however, a downstream consequence of this attentional biasing is the lateral inhibition of competing representations.

Bringing the discussion back to task switching, the issue being addressed throughout the present research project is the role for inhibition in task switching. Although a plethora of research has provided evidence for interference resolution in shifting paradigms, little work has experimentally investigated what type of inhibition is utilized. Similarly, no experimental work has investigated whether backward inhibition is functionally similar to other traditional measures of inhibition, such as response-distractor inhibition or resistance to proactive interference (though several authors have suggested that backward inhibition reflects an automatic form of inhibition such as lateral inhibition, e.g., Koch et al., 2010; Mayr & Keele, 2000; Schuch & Koch, 2003; Vandierendonck, Liefooghe & Verbruggen, 2010). Thus, while purely behavioral studies have suggested a role for interference resolution in task switching, as well as the existence of a backward inhibition mechanism (Mayr & Keele, 2000), questions remain about the nature of this interference resolution mechanism. Given this open question, the goals of the present body of work are discussed next.

**Goals of this Work**

While the struggle to gain an understanding of inhibition mechanisms is not new, the use of experimental research to answer the question of what types of inhibition are involved in task switching is. The present work will investigate the dissociation among inhibitory mechanisms and their individual roles in various aspects of task switching using several approaches. While some of the background associated with the various goals below has not yet been discussed, this background will be addressed in the chapters
that follow. The minimal details provided below are simply “teaser” descriptions to motivate the individual goals, further elaborated in Chapters 4-7.

Goal 1: Dissociations among inhibitory mechanisms. The present study sought to replicate the dissociation among inhibitory mechanisms using two approaches: the effects of aging and individual differences.

1a) Aging. With respect to aging, some authors (e.g., Hasher & Zacks, 1988) have suggested that inhibition deficits are a source of age-related cognitive decline. While a preponderance of evidence has suggested that older adults show exaggerated performance on various resistance to proactive interference tasks (e.g., Hasher, Chung, May, & Foong, 2002; Jonides, Marshuetz, Smith, Reuter-Lorenz, & Koenpe, 2000; May et al., 1999; McCabe, Robertson, & Smith, 2005; Thompson-Schill et al., 2002), evidence for age-related impairments in response-distractor inhibition is less consistent. That is, a number of studies have found exaggerated interference effects on response-distractor inhibition tasks (e.g., Comalli, Wapner, & Werner, 1962; Dempster, 1992; Spieler, Balota, & Faust, 1996; West & Baylis, 1998; see Kok, 1999 for a brief discussion), though other work and meta-analyses have failed to find differences or suggested these exaggerated interference effects are better attributed to general slowing (e.g., Fisk & Sharp, 2004; Madden, 1990; Wheatley, Scialfa, Boot, Kramer, & Alexander, 2012; Verhaeghen & Cerella, 2002; Verhaeghen & De Meersman, 1998). Critically, such an age-related impairment in resistance to proactive interference without a corresponding impairment in response-distractor inhibition supports the dissociation between these inhibitory mechanisms, suggesting that they can be selectively affected by healthy aging. The research reported in Chapter 4 examined the effects of aging on multiple tasks tapping each inhibitory
mechanism to determine whether a) consistent evidence for a response-distractor inhibition impairment could be found and b) the results of healthy aging supported dissociations among inhibitory mechanisms.

1b) Individual differences. Using an individual differences approach, this work sought to replicate the confirmatory factor analysis results of Friedman and Miyake (2004), which found separate latent variables for representing response-distractor inhibition and resistance to proactive interference. This question is addressed in Chapter 6.

Goal 2: Role for inhibitory mechanisms in task switching. The large body of work suggesting a role for interference resolution in task switching is mostly theoretical, and has not closely examined the possibility that there are multiple components to inhibition. To this end, the second goal of this work was to investigate the relationship between measures of task switching and inhibition. This goal was approached with three approaches: aging, individual differences, and neuropsychology.

Goal 2a: Aging. Given hypotheses of age-related declines in inhibition (addressed in Chapter 4), as well as findings of exaggerated switch costs with age (e.g., Kray & Lindenberger, 2000, Mayr, 2001; Mayr & Liebscher, 2001; cf. Mayr & Kliegl, 2000), Chapter 5 reports an investigation of the possibility that age-related impairments in task switching are associated with impaired inhibitory ability. In other words, the research addressed the question of whether it possible to find age-related associations between deficits in inhibition and shifting, across various measures of each executive function. Additionally, backward inhibition was examined from an aging perspective to provide a replication of the single aging experiment of Mayr (2001) in a larger sample of subjects;
this issue addressed the question of whether all aspects of inhibition are impaired with healthy aging (e.g., Hasher & Zacks, 1988).

**Goal 2b: Individual differences.** Using an individual differences approach, the research reported in Chapter 6 investigated the relationship between various task switching costs (including global switch costs, local costs, and N-2 repetition costs) and measures of inhibition – both response distractor inhibition and resistance to proactive interference (Friedman & Miyake, 2004) – to determine what type of inhibition contributes to shifting performance.

**Goal 2c: Neuropsychology.** The research in Chapter 7 investigated the relationship between inhibition and task switching from a neuropsychological perspective by comparing two patients, one with and one without inhibitory control impairments (e.g., Allen, Vuong, & Martin, 2010; Hamilton & Martin, 2005, 2007). In this respect, the logic is similar to that of Goal 2a – if there is a direct relationship between inhibitory abilities and task switching, as discussed above, we would expect the patient with inhibition deficits to show corresponding impairments on measures of task switching.

To accomplish all of these goals, this body of work used multiple tasks for measuring both response-distractor inhibition and resistance to proactive interference, and included a shifting paradigm that allowed for the calculation of various shifting performance measures (global, local, N-2 repetition costs, and congruency effects). The inclusion of multiple inhibitory control tasks allowed for the investigation of consistent patterns of dissociations in aging (Goal 1a) and neuropsychology (Goal 2c), as well as the construction of inhibition latent variables in a confirmatory factor analysis (Goal 1b). Importantly, latent variables should provide a purer measurer of the inhibitory control
mechanisms by capitalizing on the variance common to each of the individual inhibition tasks. Additionally, the latent variable constructs were used to investigate the relationship of inhibition with shifting measures, in order to gain a better understanding of the role for inhibition in task switching (Goals 2a-2c).
Chapter 3: General Method

This chapter describes the participants, materials, design, and general procedure used for the present study.

Participants

Participants were 105 young adults and 62 older adults. The young adult sample consisted of individuals between the ages of 18 and 32 ($M = 21$, $SD = 3$). Sixty-seven of the young adults were from the Rice University community. One young adult failed to return for the second session and another’s data were excluded because he was not a fluent speaker of English. The remaining 65 Rice young adults ($M$ age = 19.4; $M$ education = 13.5 years) received experiment credit towards partial fulfillment of course requirements. The other 38 young adults were recruited from the Houston community through Craig’s List; only one did not return for the second session. On average, the community young adult sample was older ($M$ age = 24; $t(45.02) = 9.90$, $p < .001$) and more educated ($M$ education = 14.9 years; $t(51.71) = 4.11$, $p = .001$) than the Rice sample.

The sample of 62 older adults consisted of members of the Houston community who had expressed prior interest in participating in Psychology experiments. For one older adult, testing was discontinued and data was excluded because of possible dementia, as indicated by a score of less than 25 on the Mini-Mental State Examination (MMSE-2; Folstein, Folstein, McHugh, & Fanjiang, 2001). Additionally, the data of another older adult was excluded due to an unwillingness to participate in the second session. The remaining 60 older adults were between the ages of 64 and 87 ($M = 71$, $SD = 5$) and had completed an average of 16 years of education ($SD = 2.8$). The older adults
were significantly more educated than the young adults ($t(84.67) = 4.87, p < .001$). All community participants (both young and old) participated in exchange for monetary compensation ($10/hour).

Additionally, two patients with aphasia and short-term memory deficits also participated in exchange for monetary compensation. Further patient details are provided in Chapter 7.

**Procedure**

All participants were individually tested on a battery of cognitive tasks over 2 separate two-hour sessions. With a few exceptions, all tasks were administered in the fixed order shown in Table 3.1; due to computer availability, some participants received the automated operation span either at the end of the second session (as opposed to at the beginning) or in a separate session. Prior to any testing, participants completed a demographic questionnaire; this was especially important in screening older adults for confounding disorders (e.g., TBI, dementia) or histories of neurological trauma or impairment that might have affected cognitive functioning. Breaks were provided between tasks. Unless otherwise indicated, all computerized tasks were administered on a Macintosh computer running PsyScope (Cohen, MacWhinney, Flatt & Provost, 1993) and responses (response times (RTs); accuracy) were collected with the PsyScope button box. As described in Chapter 7, some tasks were modified for patient testing. For patients, task order was not consistent with that listed in Table 3.1, as testing was spread over 3-4 one-hour sessions based on patient availability and some tasks were split into multiple parts.
Table 3.1. Task order and description.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Typea</th>
<th>Methodb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Session 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Informed consent and demographics questionnaire</td>
<td>Background/screening</td>
<td>P</td>
</tr>
<tr>
<td>Mini-Mental State Examination</td>
<td>Background/screening (older</td>
<td>P</td>
</tr>
<tr>
<td>adults only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vocabulary</td>
<td>Background</td>
<td>P</td>
</tr>
<tr>
<td>Task switching: three tasks</td>
<td>Shifting</td>
<td>C</td>
</tr>
<tr>
<td>Digit-symbol substitution</td>
<td>Background/processing speed</td>
<td>P</td>
</tr>
<tr>
<td>Release from PI</td>
<td>Resistance to PI</td>
<td>C</td>
</tr>
<tr>
<td>Picture-word interference</td>
<td>R-D inhibition</td>
<td>C</td>
</tr>
<tr>
<td>Recent negatives</td>
<td>Resistance to PI</td>
<td>C</td>
</tr>
<tr>
<td><strong>Session 2</strong></td>
<td></td>
<td></td>
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<tr>
<td>Automated operation span</td>
<td>Background/working memory</td>
<td>C</td>
</tr>
<tr>
<td>Backwards digit span</td>
<td>Background/working memory</td>
<td>P</td>
</tr>
<tr>
<td>Cued recall, directed forgetting</td>
<td>Resistance to PI</td>
<td>C</td>
</tr>
<tr>
<td>Flanker</td>
<td>R-D inhibition</td>
<td>C</td>
</tr>
<tr>
<td>Sternberg recognition task</td>
<td>Background/retrieval</td>
<td>C</td>
</tr>
<tr>
<td>Stroop</td>
<td>R-D inhibition</td>
<td>C</td>
</tr>
<tr>
<td>Nonverbal Stroop</td>
<td>R-D inhibition</td>
<td>C</td>
</tr>
<tr>
<td>Saccade and anti-saccade</td>
<td>Background/retrieval</td>
<td>C</td>
</tr>
<tr>
<td>Task switching: two tasks</td>
<td>Shifting</td>
<td>C</td>
</tr>
</tbody>
</table>
a Resistance to PI = resistance to proactive interference; R-D inhibition = response-distractor inhibition.

b P = paper and pencil; C = computerized.

c Time-permitting; while the majority of young adults completed the saccade ($N = 99$) and two-task shifting tasks ($N = 94$), very few older adults had time to do so ($Ns = 13$ and $20$, respectively).

Materials and Task Descriptions

Dependent variables (DV) are described below, and also in the following chapters. Generally, however, dependent variables for inhibitory control tasks were either difference scores between interference and no-interference conditions, or intrusions made during recall. For shifting tasks, DVs were difference scores between the relevant conditions (e.g., the difference between mixed and pure blocks for global switch costs). All tasks included a sufficient number of examples and/or practice trials for task familiarization and learning of stimulus-response mappings. Unless otherwise specified/restricted, task stimuli were pseudorandomized with stimulus order being fixed across subjects.

Background Measures

Background measures were included to assess the basic cognitive abilities of all non-brain damaged participants.

Mini-Mental State Examination (MMSE). The standard version of the MMSE-2 (Folstein, Folstein, & McHugh, 1975; Folstein, Folstein, McHugh, & Fanjiang, 2001) was administered to older adults in order to screen for dementia; individuals scoring less
than 25 (out of 30) were excluded from further testing. Only one adult was excluded from testing; the remaining older adults performed quite well ($M = 28.8$, $SD = 1.1$, $N = 60$).

**Vocabulary.** The WAIS-III vocabulary subtest (Weschler, 1997) was used to measure expressive vocabulary. In this subtest, participants provide definitions to words. For all participants, testing started at item 11 and was otherwise administered and scored according to standard testing instructions. Across the 33 items, definitions received 0, 1, or 2 points; the maximum score was 66 points. A research assistant scored all definitions using the scoring criteria and template provided by the WAIS.

**Symbol-digit coding.** The symbol-digit coding task from the MMSE-2 (Folstein et al., 1975, 2001) was included as a measure of processing speed. In this paper and pencil task, participants matched numbers to individual symbols, and coded them accordingly. The top of the page contained a key, indicating the symbol that corresponded to each number, and participants used this key to code as many numbers as possible (going in consecutive order) within a 30 second time period. The dependent variable was the number of numbers correctly coded.

**Working memory.** Working memory was assessed via the automated operation span and the backwards digit span. The automated operation span task (Ospan) is a measure of working memory capacity shown to have good internal consistency and test-retest reliability (Turner & Engle, 1989; Unsworth, Heitz, Schrock, & Engle, 2005). Participants first saw a math operation to verify (true/false), followed by a letter to remember. Following several math operation-letter pairs, participants saw an array of twelve letters with boxes next to them. Participants clicked boxes to indicate the serial order in which letters were previously presented. Prior to the experimental trials,
participants performed three practice blocks. In the first practice block, participants practiced letter retention and serial recall. In the second practice block, only math operations were practiced and participants responded as quickly as possible. The automated Ospan task uses this practice solution time (plus or minus 2.5 standard deviations) to calculate the time allowed for problem solving in the experimental trials; during experimental trials, participants were expected to solve the math problems within this time limit. In the third practice block, participants practiced the combined tasks of math operation and letter retention. For experimental trials, participants completed 3 trials at each set size, with set size ranging from 3-7 items. The dependent variable was the operation span, which is the “sum of all perfectly recalled sets” (Unsworth et al., 2005, p. 501). This task was presented on a Dell PC running E-Prime (Schneider, Eschman, & Zuccolotto, 2002).

In the backwards digit span from the Weschler Adult Intelligence Scale-Revised (WAIS-R; Weschler, 1981), participants heard a series of numbers presented aurally at a rate of one number/second. Following list presentation, participants recalled numbers in backwards order, starting with the most recently presented item. Participants completed two trials at each list length. All testing started at a list length of two items and continued until either errors were made on both trials at a given list length or the maximum list length (8 items) was completed. The dependent variable was the total number of trials correctly recalled.

**Retrieval tasks.** Retrieval tasks were included to measure the ability to disengage from information in the focus of attention. The Sternberg recognition task was included as a measure of memory retrieval. While the most recently presented list item is thought
to remain in the focus of attention, less recently presented items require retrieval (e.g., McElree & Dosher, 1989). In contrast, the saccade tasks were used to measure disengagement from an attentional distractor (e.g., Basak, Boot, & Kramer, 2008).

In the Sternberg recognition task (McElree & Dosher, 1989; Nee & Jonides, 2008), participants saw a list of five serially presented words, with each word being presented for 500 ms (similar to Nee & Jonides, 2008). A 300 ms mask was presented over the last word, and followed by a probe that remained on the screen for 700 ms; participants indicated whether the probe word was in the most recently presented list. Half of the trials were no trials, and half yes trials. Across the yes trials, each serial position was probed equally often. Researchers have hypothesized that the most recent item (serial position 5) remains in the focus of attention and does not require retrieval; in contrast, earlier list items (serial positions 1-4) do require retrieval (e.g., McElree & Dosher, 1989). Evidence for this distinction comes from faster RTs to probes matching the final serial position relative to RTs to probes matching items in earlier serial positions. The retrieval times of the earlier serial positions are invariant as a function of serial position, suggesting a direct access retrieval mechanism for these items (McElree & Dosher, 1989); specifically, these items are hypothesized to be in a region of direct access that is separate from the focus of attention (McElree & Dosher, 1989; Oberauer, 2002), with retrieval being used to move an item from the region of direct access into the focus of attention. The dependent variable for this task was the performance difference (RT) between trials requiring retrieval (i.e., ‘yes’ trials for which the probe matches a word in the middle serial positions) and trials requiring no retrieval (i.e., ‘yes’ trials for which the probe matches the word in the final serial position, within the focus of attention).
difference between these conditions measures the speed with which one can retrieve information outside the focus of attention.

In the saccade tasks, participants completed a pro-saccade task followed by an anti-saccade task; this task was done as time permitted, and as a consequence, was only collected on a subset of participants. In both tasks, participants saw a center fixation point. Around this fixation point were four boxes, one-inch in size and spaced approximately four inches above, below, and to the left and right of the fixation point. In the pro-saccade task, a red box flashed (duration = 175 ms) in one of the four boxes in order to attract attention to that box. Immediately following box offset, the target appeared for 150 ms, followed by a gray square mask that remained on the screen until a button was pressed. Via button press, participants indicated whether the target was a 1, 2, or 3. In the anti-saccade task, targets (and masks) appeared in the square opposite from the location of the red flash; participants had to suppress the tendency to look at the red flash, and instead look at the opposite box. The dependent variable was the RT difference between saccade and anti-saccade trials, as this difference measures the speed with which one can disengage from an attentional distractor. Despite using similar timings as previous work (Hull, Martin, Beier, Lane, and Hamilton, 2008), the first set of older adults tested found that the anti-saccade targets were too difficult (i.e., disappeared too quickly) to detect. As a result, the testing of older adults on this task was discontinued. Therefore, only a subset of young adults successfully completed this task (n = 97).

**Shifting Tasks**

All participants completed a three-task shifting task; time permitting, participants also completed a two-task shifting task. Both versions utilized cued shifting whose
targets consisted of a number (one, two; number task) of shapes (circle or diamond; shape task) of varying sizes (small (1.5”x1.5”) or large (3”x3”); size task). Trials started with a cue, indicating the relevant task for a given trial. Cues read either “Number”, “Shape”, or “Size”. The target appeared 200 ms after cue onset. The target was displayed in the center of the screen and participants responded to the target based on the relevant cued task. Both the cue and target remained on the screen until a button press was made, and the response-cue interval was fixed at 200 ms. The dimensions of circle, small, and one were mapped to the left response key, while the dimensions diamond, large, and two were mapped to the right response key.

**Three-task shifting.** In three-task shifting, participants completed six experimental blocks: a number pure block, a shape pure block, a size pure block, and three mixed blocks. The order of the pure blocks was counterbalanced across participants. In the pure task blocks, participants responded to either “Number, “Shape”, or “Size” throughout the duration of the block. Each pure block contained 42 trials, with the first two trials of each block being excluded as warm-up. In mixed blocks, the relevant task depended on the cue presented at the start of the trial, with the relevant task changing every trial; each experimental mixed block contained 99 trials, with the first three trials of the block excluded as warm-up.

Targets were selected pseudo-randomly with the constraint that no exact stimulus repetitions were allowed. Additionally, within the mixed blocks, task sequence was also constrained by the following: a) all three tasks occurred equally often, b) there were neither direct task repetitions nor direct stimulus repetitions, c) each task triad (e.g., size, shape, number; shape, size, number; etc.) appeared equally often within a block, and d)
there was an equal number of N-2 task switches (CBA) and N-2 task repetitions (ABA).

Three practice blocks (three single task blocks) preceded the experimental pure blocks, and one practice mixed block preceded the experimental mixed blocks. The design of this task allowed for the measurement of global switch costs (performance differences between mixed and pure blocks) and N-2 repetition costs (performance differences between N-2 repeat and N-2 switch trials, within the mixed block).

**Two-task shifting.** In two-task shifting, participants completed three mixed blocks, each consisting of only two relevant tasks. In the first block, the two relevant tasks were form and size; in the second block, form and number; and in the third block, size and number. Each mixed block contained 35 trials, with the first 3 trials of each block excluded as warm-up. Unlike three-task shifting, triad frequency was not calculated (as there were only two possible tasks/block) and task repetitions were allowed. The subset of young adult participants (n = 93) tested on this task completed all blocks in the same order. The design of this task allowed for the measurement of local switch costs (performance differences between switch and repeat trials).

**Response-Distractor Inhibition Tasks**

**Stroop task.** The Stroop task (Stroop, 1935) was administered in a single block consisting of incongruent, congruent, and neutral stimuli. In this task, each trial was preceded by a beep, followed by target onset. Participants named the color of the target, which was either a word (in the incongruent and congruent trials) or string of asterisks (in the neutral condition). The colors to be named included blue, yellow, orange, red, green, or purple. On incongruent trials, color words appeared in a color that was different from the written word (e.g., blue). On congruent trials, color words appeared in the same color
as the written word (e.g., red). On neutral trials, the stimulus was a string of asterisks. Trials were presented in a fixed order. A voice key recorded response times and the experimenter coded participant responses as correct, incorrect, or voice-key errors. Experimental trials (N = 154 trials) were preceded by three practice blocks: the first block was for testing and adjusting the microphone’s sensitivity, the second block tested color-naming ability by presenting all the to-be-named colors as strings of asterisks, and the third block consisted of 13 practice trials. The dependent variable is the Stroop effect, measured as the difference between incongruent and neutral trials.

**Nonverbal Stroop task.** The nonverbal Stroop task (Hamilton & Martin, 2005) was administered in a 4 blocks of 60 trials. Participants pressed a button in response to the direction an arrow was pointing (right, left), with arrows appearing on either the left side of the screen, the center of the screen, or the right side of the screen. As with the Stroop task, the nonverbal Stroop contained incongruent trials (left-pointing arrow on the right side of the screen), neutral trials (left-pointing arrow on the center of the screen), and congruent trials (left-pointing arrow on the left side of the screen). Trials were presented in a fixed order and responses were recorded with the PsyScope button box. A single practice block with 12 trials preceded the experimental blocks. The dependent variable is the Stroop effect, measured as the difference between incongruent and neutral trials.

**Flanker task.** In the Flanker task (e.g., Eriksen & Eriksen, 1974; adapted from Friedman & Miyake, 2004) participants responded to a central letter in a sting of letters (e.g., KKKHKKK) by pressing one of two buttons. If the central letter was H or K, participants pressed the left button; if the central letter was C or S, participants pressed
the right button. In the congruent condition, the flanking letters were the same as the target letter (e.g., HHHHHHH). In the neutral condition, the flanking letters were letters not mapped to a response key (e.g., OOOHOOO). In the incongruent condition, the flanking letters were mapped to opposite button as the target letter (e.g., SSSHSSS). Trials were presented in a fixed order, and the PsyScope button box recorded participant responses. A single 30-trial practice block preceded four 56-trial experimental blocks with an equal number of trials/condition. The dependent variable for the Flanker task was the difference between incongruent and neutral trials.

**Picture-word interference task (PWI).** In the picture-word interference task (e.g., Lupker, 1979; Schriefers, Meyer & Levelt, 2002), participants saw a picture with a super-imposed word; participants named the picture while ignoring the super-imposed distractor word. Each picture was seen in a semantically related condition (i.e., picture and word come from the same category; the interference condition) and in a semantically unrelated condition (i.e., picture and word come from different categories; the no interference condition). Distractor words did not overlap with items pictured for naming. Trials were presented in a fixed order, and the PsyScope button box recorded participant RTs; additionally, the experimenter coded participant responses as correct, incorrect, or voice-key errors. Prior to beginning the task, participants viewed all of the to-be-named pictures in one practice block where they saw each picture with its correct name. Practice was followed by two 90-item blocks. The semantic interference effect served as the dependent variable, measured as the difference between semantically related and semantically unrelated trials.

**Resistance to Proactive Interference Tasks**
Recent negatives task. In the recent negatives task probe task (e.g., Monsell, 1978), participants heard a list of three words followed by a probe word, and indicated whether the probe word was in the previous list by pressing yes or no. This task contains three trial types. On positive trials, the probe word was presented in the most recently presented list (list n), requiring a “yes” response. On recent negative trials, the probe word was not presented in the most recent list (list n), but it was presented in the previous trial (list n-1); this trial type required a “no” response. On non-recent negative trials, the probe word was not presented in any of the most recent lists; this trial type also required a “no” response. A 1000 ms inter-stimulus interval (ISI) separated list items, and a 2000 ms ISI separated the final list item from the probe word. The PsyScope button box recorded participant responses. Participants first received a single practice block with 10 trials; following this, they completed a single experimental block consisting of 96 trials. Half of these trials were positive (yes) trials and half were negative (no) trials; additionally, of the negative trials, half were recent and half non-recent negative trials. The dependent variable was the difference between recent and non-recent negative trials, demonstrating a participant’s susceptibility to interference from previously relevant information.

Release from proactive interference task. In the release from proactive interference (PI) task (a variant of the task used by Peterson & Peterson, 1959; similar to Friedman & Miyake, 2004), participants completed ten blocks of lists. In each block, participants read aloud four lists of eight items. The first three lists were from the same semantic category (using the category norms of Battig & Montague, 1969), and were used to build up interference; the fourth list was used as a release from PI trial. Lists were constructed of words equal to or less than 10-letters in length, and item frequency was
matched across lists within the same block. The words “!!Get Ready!!” cued participants to the start of a trial. Following this, each list item was presented individually, with each item remaining on the screen for 1750 ms; there was a 250 ms ISI between words. After the final (eighth) item of each list, participants completed a sixteen second filler task that involved counting by letter and number: participants counted up from a visually presented letter-number pair (e.g., if they saw H-39, “H-39, I-40, J-41…”). When cued with a green box and the word “Recall”, participants stopped counting and had 20 seconds to recall as many words as possible in any order. An experimenter recorded responses, including correct recall, intrusions, new words, and omissions. Participants completed two practice lists at the start of the experiment, and took a forced 15 s break between all blocks. Similar to Friedman and Miyake, the dependent variable was a measure of the buildup of PI, the difference in recall and/or intrusions on the first and second list of the same category, averaged across blocks.

**Cued recall task.** In the cued recall task (Tolan & Tehan, 1999; similar to Friedman & Miyake, 2004), participants saw a list (or lists) of four words, with each word presented one at a time for 2000 ms each. After a filler task, participants saw a category cue and were asked to recall the item from the category that was in the most recently presented list. Approximately one third of the trials (14/40) consisted of one four-item list; the remaining 26 trials consisted of two four-item lists. Of these two list trials, half were “control” (no interference) trials in which only the second list contained an item from the cued category. The other half of the two-list trials were “lure” (interference) trials; in these trials, both lists contained an item that matched the cued category (though participants only had to recall the one from the second list). In order to
induce more interference, the list-one lure was always a higher frequency category member than the list-two target. Blocks commenced with the word “Ready!,” presented for 2000 ms. Each list was preceded by a 1000 ms instruction indicating how the upcoming list should be read, either “ALOUD” or “SILENT”. At the start of a trial, participants did not know whether there would be one or two lists, and prior to recall, participants competed an eight second filler task. This filler task consisted of eight numbers, presented for 1 second each, to which participants made verbal magnitude judgments (greater or less than 50). Thus, one-block trials consisted of the “Ready!” signal, followed by a reading instruction (one-block trials were always read ALOUD), four sequentially presented words, the filler task, and a category cue. Two-block trials consisted of the “Ready!” signal, followed by a reading instruction (the first list was always ALOUD), four sequentially presented words, a second reading instruction (the second list was always SILENT), four sequentially presented words, the filler task, and a category cue. The dependent variable was a measure of interference, measured in several possible ways: a) the difference in accuracy between one-block and two-block control trials (Friedman & Miyake, 2004); b) the difference in accuracy between two-block control and two-block interference trials; and c) the proportion of list one lures recalled after two-block interference trials.

Data Processing

For all RT tasks, the following procedures are relevant to all chapters; if any additional data processing occurred (e.g., as in Chapter 6), it is described in that chapter. RTs from errors or voice key errors were removed. Additionally, all extreme outliers (RTs <250 ms and >10,000 ms) were also removed. For the shifting tasks, RTs on trials
following errors were removed, as is traditionally done in these paradigms. Log-transformations were calculated on these RTs. Furthermore, RTs more than 2.5 standard deviations beyond an individual participant’s mean, by condition, were also excluded as outliers.

Three participants (1 young, 2 old) were each missing data on one response-distractor inhibition task. The young adult was missing data on the picture-word interference task, and for the two older adults, one was missing data on the flanker task and the other on the Stroop task. The picture-word interference and flanker missing data points were due to experimenter error; the Stroop missing data point was due to color blindness. Additionally, two older adults were missing Ospar data, also due to experimenter error. Unless otherwise indicated, these participants’ were excluded (pairwise) from analyses.
Chapter 4: Aging and Inhibition

The large literature on healthy cognitive aging has aimed to elucidate factors that influence and/or cause age-related cognitive decline. The present chapter focuses on one very influential process-specific account – that of Hasher and Zacks (1988; Hasher, Stolzfus, Zacks, & Rypma, 1991; Hasher, Zacks, & May, 1999) – which proposes that age-related cognitive decline results from inhibitory control deficits. Given that inhibition is assumed to be an important process in many aspects of cognition, Hasher, Zacks, and colleagues posit that age-related cognitive declines are mediated by impairment to this single core capacity, resulting in a wide range of associated deficits. In particular, inhibition deficits are thought to result in cognitive clutter that causes excessive interference and leads to impaired performance. As discussed below, however, not all findings are consistent with this hypothesis (e.g., Fisk & Sharp, 2004; Shilling, Chetwynd, & Rabbitt, 2002; Verhaeghen & Cerella, 2002; Verhaeghen & De Meersman, 1998), and instead, some further specifications may be warranted.

In particular, even Hasher, Zacks, and colleagues (Hasher & Zacks, 1988; Hasher et al., 1999; among others, as discussed in Chapter 2) maintain that there is more than one type of inhibitory function. For example, Hasher et al. (1999) propose that there are three major inhibitory functions that act on working memory: access, deletion, and restraint over preponent thoughts and actions. The access function serves to restrict access to working memory so that only relevant information is accessed. The deletion function serves to remove no longer relevant information from attentional focus, enabling the focus of attention to be updated with currently relevant information. And lastly, restraint
over preponent thoughts and actions serves to withhold strong, automatic responses (or thoughts) until they can be evaluated.

Friedman and Miyake (2004) investigated the relationship among inhibitory control processes in an individual differences study of young adults, examining three types of inhibition that are similar to those identified by Hasher and colleagues. Resistance to distractor interference, which is similar to Hasher and Zacks’ access function, was measured by the ability to resist interference from irrelevant information in the external environment. Second, resistance to proactive interference, which related to the deletion function investigated by Hasher and colleagues (May, Hasher, & Kane, 1999), measured the ability to resist interference from previously relevant information. Lastly, preponent response inhibition, conceptually similar to Hasher and Zacks’ (1988) restraining function of inhibition, measured the ability to inhibit dominant or automatic responses. Even though Friedman and Miyake (2004) had hypothesized three distinct types of inhibition, confirmatory factor analyses supported only two types of inhibition, as preponent response inhibition and resistance to distractor interference were very closely related. Friedman and Miyake (2004) proposed that these two types of inhibition “share the requirement to actively maintain task goals in the face of interference” (p. 126). As a result, they combined these two types of inhibition into a single construct called “response-distractor inhibition”. Importantly, the response-distractor inhibition construct was unrelated to the resistance to proactive interference construct, which is a measure of the ability to resist interference from information in memory. Thus, Friedman and Miyake proposed a two-factor model of inhibitory control consisting of response-distractor inhibition and resistance to proactive interference (PI). Using this same
inhibition dichotomy, the present study investigated whether these two types of inhibition show different patterns of decline with age, as age-related dissociations provide strong evidence that the processes are separable (Verhaeghen & Basak, 2005).

There is a preponderance of evidence suggesting that older adults are more susceptible to proactive interference than younger adults in a variety of tasks, including span tasks (e.g., May et al., 1999; McCabe, Robertson, & Smith, 2005), recent-probe tasks (e.g., Jonides et al., 2000; Thompson-Schill et al., 2002), and the build-up of PI over lists (e.g., Hasher, Chung, May, & Foong, 2002). Hasher and colleagues, for example, found that young adults have better working memory spans than older adults, though these span differences are substantially reduced – and sometimes eliminated – with task manipulations that attenuate PI (May et al., 1999). In line with the notion that older adults are more susceptible to PI, Jonides and colleagues (Jonides et al., 2000) found that older adults show reduced activation of the left inferior frontal lobe in interference conditions, a region hypothesized to be a critically important in PI resolution (Jonides & Nee, 2006).

In contrast, the evidence for age-related impairments in response-distractor inhibition is less consistent. While a number of studies have found exaggerated interference effects on individual response-distractor inhibition tasks such as the Stroop task (e.g., Comalli, Wapner, & Werner, 1962; Dempster, 1992; Spieler, Balota, & Faust, 1996; West & Baylis, 1998; see Kok, 1999 for a brief discussion), other researchers have failed to find differences or suggested these exaggerated interference effects are better attributed to general slowing (e.g., Fisk & Sharp, 2004; Madden, 1990; Wheatley, Scialfa, Boot, Kramer, & Alexander, 2012; for meta-analyses on this issue, see Verhaeghen & Cerella, 2002 and Verhaeghen & De Meersman, 1998) or other aspects of
cognition such as fluid intelligence (Shilling et al., 2002). In fact, Shilling et al. (2002) suggested that studies investigating the effects of aging many times fail to make appropriate adjustments to account for global slowing. And in fact, several recent aging studies using a variety of methods have failed to find age-related response-distractor inhibition impairments. In their study using Stroop-like interference tasks, for example, Shilling et al. found no evidence for age-related impairments when processing speed was adequately accounted for. Such a finding is consistent with Salthouse (1994), who has suggested that age-related declines are mediated by processing speed, rather than other core capacities such as inhibition. In particular, slowed processing speed can contribute to impaired processing in a variety of ways, for example by slowing information encoding or activation (Salthouse, 1992; Salthouse & Babcock, 1991) or the efficiency of processing (Salthouse, 1994).

The present study investigated the hypothesis that older adults have a global inhibition deficit by examining the two distinct inhibitory control mechanisms of resistance to PI and response-distractor inhibition. To do so, the same younger and older adults were tested on multiple resistance to PI and response-distractor inhibition tasks to determine whether consistent patterns of age-related impairments could be found across multiple measures. The use of multiple tasks to assess each type of inhibition seems especially important for response-distractor inhibition, where inconsistencies across measures have been reported in previous research. Thus, this study will investigate whether consistent age effects are found on a “variety of tests of inhibition that share a common structure [and] make logically similar demands” (Shilling et al., 2002, p. 607).
In the bigger-picture context of this dissertation, the present chapter is relevant to whether inhibitory control processes can be dissociated.

**Method**

Participant, task, and data processing details are thoroughly described in the method chapter (Chapter 3). The tasks and dependent variables used herein are reviewed in Table 4.1. RTs reflect correct responses, and analyses using RTs (in ms) exclude extreme outliers (< 250 ms, > 10,000 ms) as well as outliers lying beyond 2.5 standard deviations of an individual subject mean, for each condition. Log RTs reflect RTs that exclude extreme outliers only. Three subjects (1 young, 2 old) were missing data on one response-distractor inhibition task, due to experimenter error in two cases and color blindness for the third. These subjects were excluded from the analyses reported below.

Table 4.1. Resistance to proactive interference and response-distractor inhibition task conditions and dependent variables. The ‘Conditions’ column shows the conditions included in the analyses reported below, and the ‘DV’s’ column shows the relevant dependent variables.

<table>
<thead>
<tr>
<th></th>
<th>Conditions</th>
<th>DVs</th>
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<tr>
<td>Resistance to PI Tasks</td>
<td></td>
<td></td>
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<tr>
<td>Recent negatives</td>
<td>No-PI: Non-recent negative trials PI: Recent negative trials</td>
<td>a. RT &amp; log RT</td>
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<tr>
<td></td>
<td></td>
<td>b. Errors</td>
</tr>
<tr>
<td>Cued recall, directed</td>
<td>No-PI: One-block trials (/14) PI: Two-block control trials (/13)</td>
<td>a. Proportion correct</td>
</tr>
<tr>
<td>forgetting</td>
<td>[PI: Two-block interference trials (/13)]</td>
<td>b. List 1 intrusions on 2-block interference trials</td>
</tr>
<tr>
<td>Release from PI</td>
<td>No-PI: List 1 recall PI: List 2 recall</td>
<td>a. Words recalled (/8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. List 1 intrusions during list 2 recall (/8 possible)</td>
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<tr>
<td>Response-distractor Inhibition</td>
<td></td>
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<tr>
<td>Flanker task</td>
<td>Neutral: OOOKOOO</td>
<td>a. RT &amp; log RT</td>
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Background Measures

**Mini-mental state examination (MMSE).** The standard version of the MMSE-2 (Folstein, Folstein, & McHugh, 1975; Folstein, Folstein, McHugh, & Fanjiang, 2001) was used to screen older adults for dementia; one adult scored less than 25 (out of 30) and was therefore excluded from further testing. The remaining older adults performed quite well ($M = 28.8$, $SD = 1.1$, $N = 60$).

**Working memory.** Two measures of working memory were obtained, including an automated version of the Operation Span task (Ospan; Unsworth, Heitz, Schrock, & Engle, 2005) and the backwards digit span from the Weschler Adult Intelligence Scale-Revised (WAIS-R; Weschler, 1981). Given the high correlation between these two measures ($r = .47$, $p < .001$), a working memory (WM) span composite was computed by averaging the z-scores for each measure, for each subject. Replicating previous research, young adults ($M = .27$, $SD = .78$) had significantly higher WM scores than older adults ($M = -.48$, $SD = .80$; $F(1, 160) = 33.00$, $p < .001$).

**Vocabulary.** A measure of vocabulary was obtained from all subjects, using the vocabulary subtest of the WAIS-R (Wechsler, 1981). Young ($M = 52$, $SD = 7$) and old adults ($M = 52$, $SD = 8$) did not differ on this measure ($F(1, 160) = 0.07$, $p = .79$).

**Processing speed.** Processing speed was measured for all subjects using the MMSE-2’s symbol-digit coding test. Replicating previous work demonstrating reductions
in processing speed with age (e.g., Salthouse, 1994), older adults ($M = 16.3, SD = 3.2$) completed significantly fewer designs than younger adults ($M = 24.8, SD = 5.8$; $F(1, 160) = 168.39, p < .001$).

Background measures were included to ensure that the older adults were comparable in cognitive status to other studies reported in the literature. Typically, despite having more years of education and better performance on measures of vocabulary, older adults have reduced measures of WM capacity and processing speed. The results of the background measures suggest relatively standard patterns of cognitive performance between age groups, as typically reported in aging studies.

**Analyses**

Age effects in each task were investigated with repeated-measures ANOVAs including age (young, old) as a between subjects factor and condition (listed in Table 4.1) as a within subjects factor. I was mainly interested in interactions between condition and age, which would reveal whether interference effects (i.e., the difference between interference and control conditions) were larger for older than younger subjects, rather than main effects of age. The only exception to this type of analysis was the intrusion analyses in the cued recall task, which assessed intrusions of list 1 items during list 2 interference trial recall; this DV was assessed with a standard ANOVA using age as a between-subjects variable. A main effect of condition was expected for all tasks. Additionally, given previous findings of age-related slowing in processing speed (e.g., Salthouse, 1994), as well as decreases in memory span (e.g., Craik & Jennings, 1992), main effects of age were also expected. Significant age x condition interactions were taken as evidence for age-related performance differences. Additionally, RT-based tasks
were separately analyzed using RT (in ms) and log-transformed RTs to account for the reduced processing speed of older adults (as indicated by the symbol-digit coding task), as log-transformed data are less sensitive to differences in baseline performance (Ratcliff, 1993). While the results from RT analyses are mentioned, only the results from log RT and error analyses are shown. Error analyses were analyzed with and without a speed covariate. This analysis is equivalent to a univariate ANOVA with difference scores between conditions as the dependent variable, age as a fixed factor, and speed as a covariate.

Results

Resistance to PI Tasks

**Recent negatives.** As seen in Figure 4.1 (top), subjects responded more slowly in the recent relative to the non-recent negative condition, and across conditions, older adults responded more slowly than young adults. Additionally, older adults showed a larger interference effect than young adults. These patterns were confirmed statistically. Subjects performed significantly worse on recent negative trials ($M = 3.07, 8.6\%$) relative to non-recent negative trials ($M = 3.03, 2.7\%$), in both log RTs (log RT: $F(1, 160) = 123.97, MSE = 0.14, p < .001, \eta^2 = .44$) and errors ($F(1, 160) = 91.72, MSE = 0.32, p < .001, \eta^2 = .36$). There were main effects of age, as older adults ($M = 3.11, 5.8\%$) were slower ($F(1, 160) = 38.56, MSE = 0.96, p < .001, \eta^2 = .19$) and less accurate ($F(1, 160) = 7.74, MSE = 0.07, p = .006, \eta^2 = .05$) than young adults ($M = 3.01, 4.3\%$). Lastly, the condition x age interactions were also significant, as older adults ($M = 0.05, 8.8\%$) demonstrated significantly larger interference effects than the young adults ($M = 0.03, 4.1\%$), in both log RT ($F(1, 160) = 9.26, MSE = 0.01, p = .003, \eta^2 = .06$) and errors ($F(1,
In errors, this interaction was marginal with processing speed included as a covariate ($F(1, 159) = 2.68, MSE = 0.009, p = .10, \eta^2 = .02$).

**Cued recall.** As seen in Figure 4.1 (middle), subjects recalled fewer items in the PI condition, relative to the no-PI condition. Additionally, older adults were less accurate overall and appeared to show a larger decline in recall than young adults. These patterns were confirmed statistically. There was a main effect of condition as subjects performed less accurately on two-block control trials ($M = .64$) relative to one-block trials ($M = .76$), $F(1, 160) = 85.92, MSE = 1.48, p < .001, \eta^2 = .35$. There was also a main effect of age, as older adults ($M = .47$) were significantly less accurate than young adults ($M = .72$), $F(1, 160) = 61.25, MSE = 3.47, p < .001, \eta^2 = .28$). Lastly, the condition x age interaction was significant, as older adults ($M = .21$) demonstrated larger interference effects than young adults ($M = .07$), $F(1, 160) = 21.75, MSE = 0.37, p < .001, \eta^2 = .12$. This interaction remained marginal with processing speed included as a covariate, $F(1, 159) = 3.35, MSE = 0.06, p = .07, \eta^2 = .02$. Additionally, during recall on two-block interference trials, older adults ($M = .39$) were significantly more likely than young adults ($M = .26$) to intrude category members from the first irrelevant list, as indicated by a main effect of age, $F(1, 160) = 18.76, MSE = 0.65, p < .001, \eta^2 = .11$, even when controlling for processing speed, $F(1, 159) = 4.64, MSE = 0.16, p = .03, \eta^2 = .03$.

**Release from PI.** As seen in Figure 4.1 (bottom), subjects recalled fewer items in the PI condition, relative to the no-PI condition. Additionally, older adults recalled fewer items overall, and appeared to show a larger decline in recall across conditions than young adults. These patterns were confirmed statistically. There was a main effect of
condition, as subjects recalled fewer list 2 items ($M = 3.6$) relative to list 1 items ($M = 4.6$), $F(1, 160) = 459.13$, $MSE = 73.91$, $p < .001$, $\eta^2 = .74$. There was also a main effect of age, as older adults ($M = 3.3$) recalled significantly fewer items than young adults ($M = 4.5$), $F(1, 160) = 49.75$, $MSE = 90.49$, $p < .001$, $\eta^2 = .24$. The condition x age interaction was significant as well; older adults ($M = 1.2$) demonstrated larger interference effects than young adults ($M = 0.8$), $F(1, 160) = 4.04$, $MSE = 2.26$, $p < .001$, $\eta^2 = .08$. This interaction remained significant when controlling for processing speed, $F(1, 159) = 5.56$, $MSE = 0.90$, $p = .02$, $\eta^2 = .03$. Additionally, there was also a condition x age interaction in intrusions, $F(1, 160) = 117.27$, $MSE = 3.28$, $p < .001$, $\eta^2 = .42$. Older adults ($M = .58$) intruded significantly more list 1 items during list 2 recall than younger adults ($M = .16$), even when controlling for processing speed, $F(1, 159) = 52.21$, $MSE = 1.47$, $p < .001$, $\eta^2 = .25$.

Given the significant WM differences between the young and older adults reported in previous research (e.g., Salthouse & Babcock, 1991; Wingfield, Stine, Lahar, & Aberdeen, 1988), one might ask whether these exaggerated interference effects merely reflect reduced WM capacity. To test this, the WM composite (described above) was included as a covariate in the repeated measures ANOVAs for each task. All three task analyses still resulted in significant condition x age interactions (recent negatives log RT: $F(1, 157) = 7.93$, $MSE = 0.01$, $p = .005$, $\eta^2 = .05$; cued recall: $F(1, 157) = 17.96$, $MSE = 0.31$, $p < .001$, $\eta^2 = .10$; release from PI: $F(1, 157) = 13.77$, $MSE = 2.25$, $p < .001$, $\eta^2 = .08$). These results suggest that the older adults’ exaggerated interference effects reflect more than just reduced WM capacity.
Summary of resistance to PI effects. For all resistance to PI analyses, there were significant main effects of condition, with subjects performing worse in the PI condition relative to the no-PI condition. These main effects demonstrate successful interference manipulations. There were also significant main effects of age, with young adults outperforming older adults. Importantly to the goals of the present study, across all resistance to PI tasks, older adults showed larger PI effects than younger adults (Figure 4.1), even after controlling for speed of processing and WM capacity.

Response-distractor Inhibition Tasks

As seen in Figure 4.2, subjects responded more slowly in the incongruent relative to the neutral conditions across all response-distractor inhibition tasks. Additionally, older adults responded more slowly than young adults. With the exception of the Stroop task, the interference effects for the two age groups were equivalent, as indicated by parallel lines, implying no difference across age groups. In the Stroop tasks, the interference effect for older adults appears to be greater than that for young adults. These patterns were confirmed statistically, as presented below.

Flanker task. Subjects performed significantly worse on incongruent ($M = 2.9, 3.5\%$) relative to neutral trials ($M = 2.8, 2.1\%$) in both log RT ($F(1, 159) = 539.88, MSE = 0.15, p < .001, \eta^2 = .77$) and errors ($F(1, 159) = 16.98, MSE = 0.009, p < .001, \eta^2 = .10$). Additionally, there were main effects of age in both log RT ($F(1, 159) = 48.90, MSE = 0.56, p < .003, \eta^2 = .24$) and errors ($F(1, 159) = 18.45, MSE = 0.03, p < .001, \eta^2 = .10$), though these effects were in the opposite direction: across conditions, older adults ($M = 2.91, 1.3\%$) were slower but less error-prone than young adults ($M = 2.81, 3.0\%$). In log RTs and errors, older adults ($M = .04, 0.3\%$) demonstrated smaller interference effects.
than young adults ($M = .05, 1.9\%$). This interaction was marginal in log RTs, $F(1, 159) = 3.30, MSE = 0.001, p = .07, \eta^2 = .02$). While this interaction was significant in error rates ($F(1, 159) = 9.30, MSE = 0.005, p = .003, \eta^2 = .06$), overall task error rates were low ($M = 2.4\%$) and the interaction did not survive the inclusion of speed as a covariate ($F(1, 158) = 0.57, MSE < 0.001, p = .45, \eta^2 = .004$).

**Picture-word interference task.** Subjects were significantly slower on incongruent (i.e., semantically related; $M = 2.99, 2.3\%$) relative to neutral trials (i.e., semantically unrelated; $M = 2.97, 2.2\%$), $F(1, 159) = 234.46, MSE = 0.03, p < .001, \eta^2 = .60$. However, error rates were equivalent across conditions, $F(1, 160) = .74, MSE < 0.001, p = .39, \eta^2 = .005$. Additionally, older adults ($M = 3.03, 2.9\%$) were slower and more error prone than young adults ($M = 2.96, 1.9\%$). This main effect was significant for log RTs ($F(1, 159) = 65.54, MSE = 0.34, p < .001, \eta^2 = .29$), but only marginal for errors, $F(1, 159) = 3.67, MSE = 0.008, p = .06, \eta^2 = .02$. Lastly, there was no condition x age interaction in log RTs ($F(1, 159) = 2.24, MSE < 0.001, p = .14, \eta^2 = .01$) or errors ($F(1, 159) = .03, MSE < 0.001, p = .85, \eta^2 < .001$), as older adults ($M = .02, 0.1\%$) did not demonstrate larger interference effects than younger adults ($M = .016, 0.2\%$).

**Nonverbal Stroop task.** Subjects performed significantly worse on incongruent ($M = 2.73, 4.3\%$) relative to neutral trials ($M = 2.69, 1.3\%$) in both log RT ($F(1, 160) = 500.86, MSE = 0.15, p < .001, \eta^2 = .76$) and errors ($F(1, 160) = 63.74, MSE = 0.06, p < .001, \eta^2 = .29$). Additionally, older adults ($M = 2.81, 1.5\%$) were slower ($F(1, 160) = 264.13, MSE = 1.85, p < .001, \eta^2 = .62$) but less error prone ($F(1, 160) = 10.54, MSE = 0.03, p = .001, \eta^2 = .06$) than younger adults ($M = 2.66, 2.9\%$). The condition x age interaction was far from significant in log RTs ($F(1, 160) = 0.01, MSE < 0.001, p = .92,$
This interaction was significant in errors, $F(1, 160) = 6.51, MSE = 0.006, p = .01, \eta^2 = .04$; however, older adults ($M = 1.9\%$) showed a smaller interference effect than younger adults ($M = 3.6\%$), though this interaction did not survive the inclusion of speed as a covariate, $F(1, 159) = 2.60, MSE = 0.002, p = .11, \eta^2 = .02$.

**Stroop task.** Subjects performed significantly worse on incongruent ($M = 2.97, 5\%$) relative to neutral trials ($M = 2.88, 2\%$) in both log RT ($F(1, 159) = 1187.91, MSE = 0.70, p < .001, \eta^2 = .88$) and errors ($F(1, 159) = 85.21, MSE = 0.10, p < .001, \eta^2 = .35$). Additionally, older adults ($M = 3.00, 5.9\%$) were slower ($F(1, 159) = 173.54, MSE = 1.26, p < .001, \eta^2 = .52$) and more error prone ($F(1, 159) = 48.28, MSE = 0.17, p < .001, \eta^2 = .23$) than younger adults ($M = 2.88, 1.6\%$). The condition x age interaction was significant in both log RTs ($F(1, 159) = 45.39, MSE = 0.03, p < .001, \eta^2 = .22$) and errors ($F(1, 159) = 23.88, MSE = 0.03, p < .001, \eta^2 = .13$), with older adults ($M = 0.12, 5.5\%$) showing larger interference effects than young adults ($M = 0.08, 1.7\%$). In errors, this interaction remained significant even after controlling for processing speed, $F(1, 158) = 4.70, MSE = 0.005, p = .03, \eta^2 = .03$.

Given the inconsistent effects across tasks, the effect of age across the response-distractor inhibition tasks was further assessed by investigating whether there was a main effect of age on a response-distractor inhibition log RT factor score, computed by taking the z-scored average of the four response-distractor inhibition tasks. With all tasks included in the composite, there was a main effect of age, $F(1, 157) = 8.64, MSE = 2.18, p = .004, \eta^2 = .05$. However, this effect was driven by the Stroop task; when the composite was calculated without the Stroop task, the age effect was far from significant, $F(1, 158) = 0.06, MSE = 0.02, p = .81, \eta^2 = .00$. 
Summary of response-distractor inhibition effects. For all response-distractor inhibition tasks, there were significant main effects of condition, as subjects performed worse in the interference condition; these main effects demonstrate successful task manipulations. Additionally, there tended to be main effects of age in both log RTs and errors, as older adults tended to be slower and more error prone than young adults. The age x condition interactions, on the other hand, varied as a function of the DV used. Using standard RTs (in ms), all response-distractor inhibition tasks (except the Flanker task) showed significant interactions (all \( p \)'s < .007; not shown above) suggesting larger interference effects for older adults. When slowed processing speed was adjusted for by using log RTs (Figure 4.2) and including speed as a covariate in error analyses, however, this interaction only remained significant in the Stroop task. Thus, older adults did not demonstrate a consistent pattern of exaggerated interference effects across response-distractor inhibition tasks once slowed processing speed was controlled.

General Discussion

The present study investigated declines in inhibitory control as a function of age using multiple tasks hypothesized to tap two forms of inhibition (Friedman & Miyake, 2004): resistance to proactive interference and response-distractor inhibition. Resistance to PI measures the ability to resist memory intrusions from information that was previously relevant, but is now irrelevant. In contrast, response-distractor inhibition measures the ability to resist interference from stimuli simultaneously present in the environment, yet irrelevant to the task at hand. Consistent age-differences were found for resistance to PI tasks, but not for response-distractor inhibition tasks. This dissociation is consistent with theories that propose these two inhibition constructs tap different
processes (Friedman & Miyake, 2004), but suggests only one of these inhibitory processes is sensitive to age. These two types of inhibition will be discussed in turn.

**Resistance to Proactive Interference**

Replicating previous work (e.g., Oberauer, 2001, 2005; May et al., 1999; Zacks & Hasher, 1994), there were consistent age-related impairments in resistance to PI tasks, suggesting that older adults are more susceptible to interference from previously relevant – but now irrelevant – items in memory. These findings have been echoed by neuroimaging results. Relative to young adults, older adults demonstrate reduced left inferior frontal gyrus activation (Jonides et al., 2000), a region important for interference resolution in PI tasks (Jonides & Nee, 2006). Critically, Hasher and colleagues (May et al., 1999; Zacks & Hasher, 1994) have argued that such exaggerated susceptibility to interference results in reduced working memory capacities (e.g., May et al., 1999) and has consequences for other aspects of cognition (e.g., Hasher & Zacks, 1988).

What factor(s) might explain older adults’ increased susceptibility to interference? Early accounts (Jonides et al., 2000; Lustig, May, & Hasher, 2001; May et al., 1999; Oberauer, 2001; Zacks & Hasher, 1994; Zacks, Radvansky, & Hasher, 1996) hypothesized that increased interference effects may be caused by inhibition deficits. This account postulates that proactive interference is overcome by inhibiting no longer relevant information, in order to focus on newly relevant information (May et al., 1999; Zacks & Hasher, 1994); the failed inhibitory mechanism was thought to result in difficulty deactivating irrelevant material. As a consequence, more items are activated in memory, resulting in less capacity for relevant information (Oberauer, 2001) and/or disrupted retrieval (Lustig et al., 2001). However, the results of the present study pose a
potential problem for this account: if the inhibition of no-longer-relevant information involves the same type of inhibition used in response-distractor inhibition, the results of the present study question this interpretation, as there was little evidence for age-related impairments in response-distractor inhibition (discussed below). While this account does not rule out the involvement of inhibition in resolving proactive interference, it does rule out a general failed inhibitory mechanisms as a cause for age-related impairments in resisting PI.

In contrast to inhibitory accounts, more recent accounts propose that age effects on PI tasks are caused by inefficient contextual encoding (Hedden & Park, 2003; Jonides et al., 2000; Jonides & Nee, 2006; Li & Lindenberger, 2005; Mitchell, Johnson, Raye, Mather, & D’Esposito, 2000; Oberauer, 2005), source monitoring (Johnson, Hashtroudi, & Lindsay, 1993), or recovery of contexts (e.g., Howard, Kahana, & Wingfield, 2006). According to Oberauer (2005), for example, older adults have deficits in binding content-context information, such that they inefficiently build and maintain bindings that associate list items with their distinguishing context (whether that context be temporal (e.g., presence of an item in list x), visual (e.g., item color), or other). To distinguish between the inhibition and binding accounts, Oberauer administered two recognition probe tasks. In one, a modified Sternberg task with a directed forgetting component, subjects saw two lists simultaneously, with the top list printed in blue and the bottom list in red. Prior to the probe, subjects were cued with a colored box that indicated which list was the target list, and which could be forgotten; Oberauer argued that this task involved both inhibition and binding. Consistent with the exaggerated interference found in the present study, older adults showed larger intrusion costs than young adults in response to
a probe word that came from the to-be-forgotten list, relative to a never-before-seen probe word. Critically, however, the effects found with this task are consistent with both inhibition and binding accounts; in fact, Oberauer (2001) initially interpreted similar results as an inhibition deficit.

To distinguish between the inhibition and binding accounts, Oberauer (2005) tested subjects on a task requiring only binding (no inhibition), which he called the ‘local recognition task’. In this task, to-be-remembered words were simultaneously presented in spatially-separated frames on the screen. At probe, subjects had to indicate whether the memory item was presented in the correct frame. Thus, both identify and context information were important, requiring binding mechanisms; additionally, there was no advantage to inhibiting irrelevant items, as all items had a chance of being probed. Similar to the modified Sternberg task discussed above, older adults showed exaggerated intrusion costs, measured as the difference between memory items presented in the wrong frame and the presentation of never-before-seen items. Thus, given that older adults showed impairments not only on a binding plus inhibition task, but also on a binding-only task, Oberauer concluded that older adults have a deficit in “building and maintaining bindings between representations in working memory” (p. 384).

Additionally, he proposed that similar binding deficits are the source of working memory capacity differences in high- and low-span young adults, and found that tasks requiring the recollection of bound representations correlated highly with measures of WM capacity. With either aging or reduced WM capacity, then, inefficient or weak bindings result in discrimination difficulties at test, including the propensity to respond more slowly to or incorrectly accept no-longer-relevant representations (Jonides & Nee, 2006).
Using this logic, Oberauer presents binding as a unifying account to explain exaggerated interference effects in aging populations and young adults with reduced working memory capacities; importantly, this account is consistent with other work demonstrating binding deficits in older adults (e.g., Howard et al., 2006; Mitchell et al., & D’Esposito, 2000; Li & Lindenberger, 2005). However, future research should investigate whether such deficits are associated with difficulties using contextual information at recall (Jonides & Nee, 2006), an inefficient building of bindings (Mitchell et al., 2000; Oberauer, 2005), poor maintenance of bindings (Oberauer, 2005), or a combination thereof. Additionally, Oberauer did not investigate whether decrements on directed forgetting tasks could be fully (vs. partially) accounted for by binding deficits, also opening an avenue for future research.

**Response-Distractor Inhibition**

In contrast to the resistance to PI tasks, the results for response-distractor inhibition tasks suggest little age-related impairment in inhibitory abilities. While there was evidence for age-related response-distractor inhibition impairments when standard RTs were used, these age effects were mostly eliminated when controlling for processing speed. Specifically, when controlling for processing speed, there were no age effects for the flanker, picture-word interference, or nonverbal Stroop tasks; only age effects in the Stroop task remained. However, it should be noted that although I have used the term “response-distractor” inhibition to refer to the tasks included herein, none of these tasks assess the inhibition of prepared motor responses, as measured by tasks such as stop signal and go/no-go. While Friedman and Miyake (2004) found that these such tasks load
on the response-distractor inhibition factor, it remains possible that these types of motor inhibition tasks show different effects with age.

Given that Stroop is a “gold standard” measure of inhibition, an important question concerns the lack of consistent findings between this task and the other response-distractor inhibition measures used here. In particular, it is unclear what factors drive the Stroop task age deficits in the present study, given meta-analyses have suggested such effects can be attributed to no more than slowed processing speed (Verhaeghen & Cerella, 2002; Verhaeghen & De Meersman, 1998). However, it is of note that the Stroop task induced larger interference effects than the other response-distractor inhibition tasks. This raises the possibility that the use of log-transformed data may not have overcome the non-additive effects of age-related slowing, whereas the methods used by Verhaeghen and De Meersman (mean standardized difference, Brinley analysis) did.

An alternative explanation for finding age effects in the Stroop task, relative to the other response-distractor inhibition tasks, comes from recent accounts of executive control. Rather than distinguishing between executive control processes (such as response-distractor inhibition, resistance to PI, updating, shifting, etc., as done by e.g., Friedman & Miyake, 2004; Miyake et al., 2000), Nee and colleagues (2012) characterize executive processes by content, with separate selection mechanisms for spatial (“where”) and identity (“what”) information. This distinction is similar to those drawn between dorsal and ventral processing streams in posterior cortices. In the Flanker, PWI, and NV Stroop tasks, selection mechanisms can act on spatial location, given the target and distractor are not a single, integrated object. While Flanker stimuli are presented as a
single object, the target and distractors are not superimposed, and while PWI targets and
distractors are superimposed, they are not presented as a single object. In contrast to this,
Stroop targets and distractors are presented as a single, integrated object with
superimposed features, suggesting selection cannot rely on spatial location. Here, then,
selection may need to rely on identity information, with this distinction raising the
possibility that the age effects in the Stroop task are driven by the need to select identity
information in the face of strong competition. Consistent with this, various studies have
found Stroop age effects with target and distractor integration, but not when this
information was separated (e.g., West & Baylis, 1998; West & Bell, 1997; see also
Connelly & Hasher, 1993 and Tipper, Weaver, & Houghton, 1994, for similar effects in
negative priming paradigms). Such selection mechanisms may be especially error prone
in the Stroop task (relative to the other response-distractor inhibition tasks) due to the
difficulty in maintaining task goals (see also West & Baylis, 1998) in the face of a
strong, prepotent (but irrelevant) response. Additionally, although only a small proportion
of trials, the inclusion of congruent trials (the word red written in red ink) may have made
goal maintenance – and therefore selection mechanisms – even more difficult, as these
trials reinforce the incorrect goal of word reading (which is counter to the goal of color
naming). In contrast, the lack of age effects on the other response-distractor inhibition
tasks may be due to the fact that the distractors are spatially separated, allowing for the
use of a different selection mechanism, and also making goal maintenance easier. While
this account does not explain the discrepancy between the age effects found in the present
study and the failure to find age effects in other studies (e.g., Verhaeghen & Cerella,
2002; Verhaeghen & De Meersman, 1998), it does propose a possible explanation for the
distinction between the findings of age effects in the Stroop task versus no age effects in the Flanker, PWI, and NV Stroop tasks.

While above-described selection account attributes response-distractor interference effects to selective attention mechanisms, it does mean there is no role for inhibition – but instead suggests inhibition may be a result of selective attention mechanisms. Munakata and colleagues (2011; see also Desimone & Duncan, 1995; Miller & Cohen, 2001), for example, suggest that inhibition in response-distractor inhibition-like tasks is better conceived as a downstream consequence of selection/biasing mechanisms. Here, task goals are used to bias or select task-relevant information; however, in response-distractor inhibition-type tasks, competition results from the presence of irrelevant information. While selective attention mechanisms function to bias task relevant information, competition is resolved via lateral inhibition of task irrelevant processing streams. While such a theory was not and cannot be tested in the present study, it raises the possibility that response-distractor inhibition may be better conceptualized as depending on selective attention mechanisms.

Nonetheless, it is noteworthy that older adults did not show consistent patterns of impairment across all of the response-distractor inhibition tasks (see also Shilling et al., 2002), which is in stark contrast to the resistance to PI tasks. These findings are in line with recent working memory findings suggesting that older adults have no problem removing information from the focus of attention, but they make more errors in both accessing information that is outside the focus of attention (Verhaeghen & Basak, 2005) and rejecting intrusions from irrelevant information that is in an activated state in long-term memory (Oberauer, 2001, 2005). Moreover, this dissociation questions theories that
propose global inhibition deficits with age, while also providing evidence for dissociable inhibitory control processes.

**Conclusions**

The proposal of an association between cognitive decline in healthy aging and a deficit in inhibition (Hasher & Zacks, 1988) has led to an explosion of research on inhibition in aging, and consequences of inhibition deficits on other areas of cognition. However, little research has investigated whether older adults show consistent patterns of impairments across different types of inhibition tasks (Friedman & Miyake, 2004; Nigg, 2000), nor across multiple tasks tapping the same inhibition construct, in the same group of young and old adults. The results of the present study fail to support the notion of a global inhibition deficit with age (Hasher & Zacks, 1988). Instead, only partial support for the notion of an inhibitory deficit in cognitive aging was found. Older adults show little evidence for impairments on tasks that involve resolving interference from stimuli appearing simultaneously in the environment, but do show age-related impairments on tasks that involve resolving interference from previously relevant (but now irrelevant) items in memory. Additionally, this dissociation in aging provides additional behavioral evidence that inhibition is best conceptualized as not one process, but separable distinct processes.
Chapter 4 Figure Captions

Figure 4.1. Young and older adult performance on resistance to proactive interference tasks. Error bars indicate standard error of the mean.

Figure 4.2. Young and older adult performance on response-distractor inhibition tasks. Error bars indicate standard error of the mean.
Chapter 5: Aging and Task Switching

Cognitive control is important to everyday life, as we balance our desire to focus on a single task while putting other responsibilities aside and simultaneously resisting the urge to be distracted by more trivial tasks. Realistically, however, we rarely maintain focus on a single task, but instead switch between tasks. Despite this being a seemingly effortless process, switching incurs a cost, and research has suggested that at least some aspects of our ability to switch between tasks changes with age. The present study investigates how two components of task switching change with age.

In task switching paradigms, subjects traditionally complete two types of blocks. In single task (or pure) blocks, only a single task is relevant. In mixed task blocks, multiple tasks can be relevant throughout the duration of the block, though only a single task is relevant on a given trial, as specified by some sort of task cue. In such task switching paradigms, performance declines when switching between tasks is required, relative to when only a single task is performed. More specifically, this performance decline – the switch cost – is associated with executive control inherent to a multiple-task situation. The present study will address two costs in these sorts of task switching paradigms: global switch costs and N-2 repetition costs (also referred to as backward inhibition).

Global switch costs are measured as the difference between mixed and pure blocks (e.g., Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976). These costs are hypothesized to measure the ability to update, manipulate, and maintain multiple tasks in working memory (WM; Kray & Lindenberger, 2000; Mayr, 2001), as multiple tasks need to be available in the mixed block whereas only a single task is
relevant in pure blocks. According to Mayr (2001), global costs measure the ability to update “an internal control setting in the face of actual or potential interference” (p. 97) between tasks.

The second cost investigated herein is the N-2 repetition cost. This cost is thought to measure the application of inhibitory processes (backward inhibition) as a mechanism for disengaging from no-longer-relevant tasks at the point of a task switch. To measure task disengagement, Mayr and Keele (2000) used a task switching paradigms with three tasks (tasks A, B, and C). Critically, they compared trials in which task A was recently abandoned – trial sequence ABA – with trials in which task A was less recently abandoned – trial sequence CBA. Mayr and Keele found worse performance on N-2 task repetition sequences (ABA), relative to N-2 task switch sequences (CBA), and this N-2 repetition cost has been taken as evidence for the use of backward inhibition for disengaging from a no-longer-relevant task in order to switch to a new task (see also Gade & Koch, 2005, 2007; Schuch & Koch, 2003; Schneider & Verbruggen, 2008). That is, Mayr and Keele propose that task sets are inhibited once abandoned, therefore making it more difficult to switch back to a recently inhibited task (ABA), as opposed to a less recently inhibited task (CBA). Such hypothesized mechanisms, then, suggest a critical role for inhibition in task switching (Mayr, 2001), with some even suggesting that these backward inhibition mechanisms are more general, functioning also to clear the contents of WM when switching between WM items (Bao, Li, Chen, & Zhang, 2006).

Interestingly, both global and N-2 repetition costs are in some way associated with domains of executive control for which the evidence of decline in healthy aging has been the subject of controversy. In task switching, a large body of work has demonstrated
that older adults show exaggerated global switch costs relative to young adults, even when accounting for general slowing and practice effects (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001; Meiran, Gotler, & Perlman, 2001; Reimers & Maylor, 2005; Verhaeghen & Cerella, 2002; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). Specifically, these authors have hypothesized that older adults have difficulty dealing with multiple task sets in working memory, specifically when the environment poses situations of task ambiguity. That is, in mixed blocks, tasks change relatively often, stimuli are complex and contain features relevant to multiple tasks, and all task responses are typically mapped to the same response modalities (e.g., the same two buttons). As a result, Mayr (2001) has hypothesized that older adults have difficulty selecting among relevant task sets in mixed blocks, especially under such conditions with difficult mappings between stimulus and response. In particular, Mayr hypothesized that age effects are exaggerated under conditions of task set ambiguity, such as when the stimulus is bivalent, has the potential to activate multiple task sets, and the cue does not explicitly indicate which task is relevant on a given trial (e.g., Rogers et al., 1998).

In contrast, a smaller number of studies have failed to find age differences in global costs (Brinley, 1965; Kray, Li, Lindenberger, 2002; Mayr & Kliegl, 2000; Salthouse, Fristoe, McGuthry, & Hambrick, 1998; Wheatley, Scialfa, Boot, Kramer, & Alexander, 2012; Verhaeghen & Basak, 2005; Verhaeghen & Hoyer, 2007). Kray et al. (2002) attribute cross-study differences to the degree of task uncertainty, with older adults having difficulty in selecting and instantiating a task under conditions of high competition between task sets. In their study, for example, on each trial, each of the four possible tasks were explicitly cued with a color coded letter that indicated the relevant
task, removing much task set selection uncertainty upon target presentation. Under these conditions, older adults did not demonstrate global shifting impairments. Thus, Kray et al. suggest that whether or not age differences in global shifting are found may be modulated by the degree of competition involved in choosing between tasks; age effects may only arise when distinct task sets contain overlapping elements and therefore elicit competition during task set selection, as task sets are not easily differentiated (see also, Mayr, 2001).

Similarly, while some have hypothesized that older adults show general inhibitory decline that has critical consequences for other areas of cognition (e.g., Hasher & Zacks, 1988), others have instead suggested that not all aspects of inhibition decline equally (see Chapter 4 for a more thorough discussion of this issue). In particular, the hypothesis of a general, all-encompassing inhibition deficit may be too broad, as inhibition may not be a unitary construct (e.g., Friedman & Miyake, 2004; Nigg, 2000). Additionally, to my knowledge, only one study has investigated whether older adults show impairments in backward inhibition (Mayr, 2001), as would be predicted by theories postulating general inhibitory decline. Using the backward inhibition paradigm described above, Mayr found little evidence for age-related impairments in inhibition, and the evidence he did find was not in the direction predicted by theories of inhibition deficits. That is, Mayr reasoned that if older adults have inhibition deficits, they should show reduced backward inhibition effects: less (or inefficient) inhibition of task A in the N-2 repetition sequence (ABA) would result in easier reactivation of this task, when it again becomes relevant – and as a result, the difference between ABA and CBA conditions would be reduced or eliminated. Critically, Mayr found the opposite pattern of results; older adults showed
significantly *larger* backward inhibition effects than young adults when standard response times (RT) were used, though this effect was only marginal with log-transformed RTs (*p* = .07). In his study, Mayr compared the backward inhibition of young and old adults using a sample of twenty-four subjects per age group. While sizable for investigating simple cognitive effects, it may be the case that there was much variability in the performance within such a small sample size, especially given that the older adults’ RT standard deviations were at least twice as large as those of the young adults. Before definitive conclusions about age-related performance on backward inhibition can be drawn, backward inhibition effects in young and old adults should be replicated. The present study investigates the global shifting and backward inhibition abilities of a large group of young and old adults.

**Method**

Participant, task, and data processing details are thoroughly described in the method chapter (Chapter 3). Additionally, background tasks assessing differences between the young and old adults samples are described and reported in Chapter 4. The present chapter discusses results from the three-task shifting task, which includes both pure and mixed task blocks; this task is reviewed briefly below. RTs reflect correct responses, excluding RTs on trials following errors. Analyses using RTs (in ms) excluded extreme outliers and outliers lying beyond 2.5 standard deviations of an individual subject mean, for each condition. Log RTs reflect RTs that exclude extreme outliers only.

**Shifting Task**

Subjects responded to the target based on the relevant cued task set. Targets were displayed one at a time in the center of the screen, and were preceded by cues that read
either “Number”, “Shape”, or “Size”. Subjects completed three pure blocks and three mixed blocks. In the pure blocks, subjects responded to either “Number, “Shape”, or “Size” throughout the duration of the block. In mixed blocks, subjects responded to any one of the three possible tasks, depending on the cue presented at the start of the trial, and the relevant task changed every trial. Subjects were first familiarized with the task in pure and mixed task practice blocks. Targets were selected pseudo-randomly with the constraint that no exact stimulus repetitions were allowed. Additionally, the task sequence of mixed blocks was restricted such that a) all three tasks occurred equally often, b) there were neither direct task repetitions nor direct stimulus repetitions, c) each stimulus combination (size, shape, number; shape, size number; etc.) appeared equally often within a block, and d) there was an equal number of N-2 task switches (ABC) and N-2 task repetitions (ABA). The dependent variables were a) global switch costs, measured as the difference between mixed and pure blocks, and b) N-2 repetition costs (or backward inhibition), measured as the difference between N-2 repetition (ABA) and N-2 switch (CBA) trials (within the mixed block).

Results

Analyses

In order to take baseline task performance into account, the effects of age on the shifting measures were investigated with a repeated measures ANOVA with age (young, old) as a between-subject factor and condition (for global costs, mixed vs. pure blocks; for backward inhibition, N-2 repetition vs. N-2 switch trial types) as a within-subjects factor. Tasks were separately analyzed using log RT data and errors. Log-transformed RTs were used to account for the slower processing speed of the older adults;
additionally, where relevant, processing speed was used as a covariate in error analyses. For all analyses, a main effect of condition was expected, replicating standard switching or repetition costs. Age x condition interactions that remained significant after controlling for processing speed were taken as evidence for age-related performance differences.

**Global Switch Costs**

Figure 5.1 depicts performance in mixed and pure blocks, as a function of age, for both standard RT (top) and log-transformed (bottom) data. Subjects were slower and more error prone in mixed blocks ($M = 1333$ ms, 4%) relative to pure blocks ($M = 578$, 3%). This main effect of condition was significant for both log RT ($F(1, 160) = 2006.88$, $MSE = 8.78$, $p < .001$, $\eta^2 = .93$) and errors ($F(1, 160) = 33.69$, $MSE = 0.03$, $p < .001$, $\eta^2 = .17$). Additionally, the main effect of age was significant, as older adults were significantly slower ($M = 1412$) than young adults ($M = 921$), $F(1, 160) = 135.84$, $MSE = 2.25$, $p < .001$, $\eta^2 = .46$. However, the main effect of age was not significant in error rates (for both age groups, $M = 4$%), $F(1, 160) = 1.24$, $MSE = 0.002$, $p = .27$, $\eta^2 = .008$. As shown in Figure 5.1 (top), older adults demonstrated larger RT switch costs than young adults; however, this interaction was not significant with log-transformed RTs, $F(1, 160) = 0.33$, $MSE = 0.001$, $p = .57$, $\eta^2 = .002$. Additionally, the effect in errors only approached significance, $F(1, 160) = 3.35$, $MSE = 0.003$, $p = .07$, $\eta^2 = .02$, and it did not survive the inclusion of processing speed as a covariate, $F(1, 159) = 0.12$, $MSE < 0.001$, $p = .73$, $\eta^2 = .001$.

**Backward Inhibition Costs**

Figure 5.2 depicts performance in N-2 switch (CBA) and N-2 repeat (ABA) trial types, as a function of age, for both standard RT (top) and log-transformed (bottom) data.
Subjects were slower and more error prone on N-2 repetition trials ($M = 1431, 5\%$ errors) relative to N-2 switch trials ($M = 1364, 4\%$). This main effect of condition was significant for both log RT ($F(1, 160) = 173.31, MSE = 0.04, p < .001, \eta^2 = .52$) and errors ($F(1, 160) = 7.81, MSE = 0.002, p = .006, \eta^2 = .05$). Older adults were significantly slower ($M = 1781$) than the young adults ($M = 1171$), $F(1, 160) = 80.68, MSE = 2.36, p < .001, \eta^2 = .34$. However, the two groups did not differ in error rates (for both, $M = 4\%$), $F(1, 160) = 0.03, MSE < 0.001, p = .85, \eta^2 < .001$). In RTs, older adults ($M = 96$ ms) showed larger backward inhibition costs than young adults ($M = 49$); however, this interaction did not survive log-transformation ($F(1, 160) = .56, MSE < 0.001, p = .46, \eta^2 = .003$), nor was it significant in error rates ($F(1, 160) = 1.63, MSE < 0.001, p = .20, \eta^2 = .01$).

**General Discussion**

The goal of the present study was to investigate age-related performance on two measures of task switching, global switch costs and N-2 repetition costs. While the effects of age on global shifting measures appear to be mediated by the ease with which task sets can be differentiated (e.g., Kray et al., 2002; Mayr, 2001), the effects of age on N-2 repetition costs have not been extensively investigated. Each measure is discussed below, in turn.

**Global Switch Costs**

Both age groups showed large global switch costs. Although older adults demonstrated slower overall reaction times, they did not show exaggerated switch costs once general slowing was accounted for. In some ways, the present results were surprising – that is, a moderate-sized body of research has demonstrated exaggerated
global switch costs in older adults across many different shifting paradigms (e.g., Kray & Lindenberger, 2000; Mayr, 2001; see also Verhaeghen & Cerella, 2002, for a meta-analysis that includes global costs as a function of age). These studies have suggested that older adults have difficulty in maintaining, manipulating, and selecting between multiple task sets, as needs to be done in mixed blocks, relative to pure blocks.

However, other work has suggested that age effects in global shifting may be reduced – or even eliminated – with reductions in task uncertainty. Kray et al. (2002), for example, did not find age differences in global costs using a cued shifting paradigm with verbal targets. In line with this, Mayr (2001) identified boundary conditions for age effects – when targets contained features of each possible task, and response mappings overlapped, substantial age effects were found. However, when these task set features did not overlap, age differences were minimal. As a result, Mayr suggested that older adults have to rely more strongly on task set updating processes, given they show worse performance as a function of interference between task sets. In particular, Mayr raised the possibility that older adults have difficulties under conditions where task sets are not easily differentiated (see also Mayr & Liebscher, 2001), and that task set differentiation is more easily accomplished when there are close associations among task-relevant features such as possible responses, stimulus-responses mappings, etc.

That is, the notion that older adults may show deficits in measures of global shifting when binding processes play a critical role in differentiating among activated tasks in memory is consistent research from episodic and working memory domains (e.g., Chapter 4; Henkel, Johnson, & De Leonardis, 1998; Oberauer, 2005). In task switching, binding may function to create task sets, or distinct representations of what should be
done in the context of a given task – an attentional set that guides behavior and includes representations of what aspect of the target to focus on, possible responses, and stimuli-response mappings (e.g., Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995). If binding among task features is weak (or fails), task sets may not be easily distinguishable, especially when task set features overlap. Thus, in global task switching settings, weak bindings may cause difficulty for older adults in distinguishing between relevant and irrelevant tasks, with failed binding mechanisms making it more difficult for older adults to form and/or differentiate between tasks, weak bindings increase the likelihood that the irrelevant task set will be inappropriately activated. Supporting the notion that older adults only seem to show global shifting impairments when task sets are not easily differentiated, Henkel et al. (1998) suggested older adults have the most difficulty in binding features in memory when distinct representations have some degree of overlap. Thus, task set binding mechanisms seem critical to task switching performance because shifting requires that task sets be kept apart (Mayr, 2001).

Like Kray et al. (2002), the present study failed to find exaggerated switch costs in older adults. However, the present study used explicit cues that may have provided environmental support, allowing older adults to more easily differentiate between task sets. Further supporting the notion that age effects may depend in part on the ability to differentiate between task sets, Kray, Eber, and Karbach (2008) found that task-relevant strategies (such as producing the name of the upcoming task) reduced (but did not eliminate) age effects. Thus, the design of the present study may have reduced the effect of any binding impairments in older adults. Interestingly, Mayr (2001) found age effects with an almost identical paradigm as used herein, even with explicit cues. Using a larger
group of subjects, the present study questions these results, suggesting that age-related impairments in global shifting are not always found – at least not when task sets can be relatively easily disambiguated.

**Backward Inhibition**

Replicating previous research, both young and old adults showed small but significant N-2 repetition costs. As with global switch costs, older adults were slower overall, but did not show exaggerated measures of backward inhibition once general slowing was accounted for. This replicates the findings of Mayr (2001), who found that older adults showed numerically larger backward inhibition effects, though such differences were not significant once log-transformed. Using a larger sample, then, the present study supports the notion that older adults show no impairment in their ability to disengage from relevant task sets using inhibitory processes (see also Oberauer, 2005).

In one respect, the present results are surprising given findings and theoretical frameworks that propose that older adults have a deficit in inhibitory control processes (e.g., Hasher & Zacks, 1988). From this account, we might have expected older adults to show smaller backward inhibition effects, indicative of impaired inhibitory abilities. Instead, like Mayr (2001), older adults did not show exaggerated costs. Thus, the present results suggest that older adults do not show impairments in this measure of inhibition. As a result, older adults cannot be said to have a deficit to all inhibitory control mechanisms (e.g., Hasher & Zacks, 1988), but may instead show selective deficits to some in only some of these mechanisms (e.g., Chapter 4). Additionally, these results suggest that backward inhibition is somehow distinct from those aspects of inhibitory control in which older adults do show age-related declines.
However, Anderson and Levy (2007) have suggested that the prediction of a relationship between backward inhibition and inhibitory control is quite difficult. As Anderson and Levy point out (and in line with the assumptions of Mayr & Keele, 2000), inhibition has both costs and benefits. The better one is at inhibition, the better one can inhibit previous tasks when switching to a new task. However, the better one is at inhibition, the more difficult it may be to retrieve a previously inhibited task set. In the case of comparing performance in the experimental condition (ABA; N-2 repetition) vs. the control condition (CBA; N-2 switch) in backward inhibition tasks, Mayr and colleagues have focused on the difficulty in retrieving task A in the experimental condition, as this should be harder the better one is at inhibition. They have implicitly assumed that inhibiting task B should be of equivalent difficulty in the two conditions; as a result, the application of inhibition to task B should play no role in explaining individual differences between these conditions. However, as Anderson and Levy point out, this is not the case. Given the prior inhibition of task A in the experimental (ABA) condition, this task set will have a lower activation strength relative to that for task B, than is the case for task A relative to task B in the control (CBA) condition. That is, the more recent inhibition of task A (in the experimental ABA condition) will result in a larger difference in activation levels between task B and task A, requiring more inhibition of task B. In contrast, the less recent inhibition of task A (in the control CBA condition) will result in a smaller difference in activation levels between task B and task A, requiring less inhibition. The better one’s inhibition ability, the better one can suppress task B in the experimental condition with respect to task A, with this ability playing a lesser role in the control condition. Thus, in the experimental condition, better inhibition
results in more difficulty in retrieving task A but a better ability to inhibit task B. Consequently, it is difficult to predict what the relation should be between the size of the backward inhibition effect and individual differences in inhibitory control abilities.

In others respects, however, these findings may not be surprising. First, older adults do not show impairments in measures of local task switching (e.g., Kray & Lindenberger, 2000; Mayr, 2001; see also Verhaeghen & Cerella, 2002, for a meta-analysis that includes local costs as a function of age), measured as the difference between switch and repeat trials within mixed blocks. On switch trials, one must disengage from the previously relevant task (i.e., “switch” tasks), whereas such disengagement is not necessary on repeat trials. Local costs measure the initiation and execution of task switches, and are thought to be a more pure measure of switching (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995). Second, using meta-analytic techniques, Verhaeghen and Cerella (2002) have suggested older adults show impairments in executive tasks that require the manipulation of multiple tasks (as with global switching and dual-tasking), but not on tasks that involve the “active selection of relevant information” (p. 856), such as with local switching and Stroop-like inhibition tasks. Given backward inhibition may be a mechanism for disengaging from no-longer relevant tasks in order to select a newly relevant task, the present findings are in line with this selective attention account. Backward inhibition, then, may be conceptually similar to selective attention tasks mechanisms, insofar as it is involved in the selection between multiple representations in working memory (see also Bao et al., 2006).

How can we reconcile these different predictions of impaired-inhibition vs. intact-selective attention theories? The backward inhibition results fit nicely into embedded
process accounts of working memory (WM; e.g., Cowan, 1995, 2001; Oberauer, 2002). These models posit (at least) two components. The first – the focus of attention – is a capacity-restricted mechanism that holds a single element active; the element (item, representation, etc.) within the focus of attention is that which is currently being processed or acted upon. The second component – the activated portion of long-term memory (LTM) – holds currently activated LTM representations; critically, their activation makes these representations more easily retrievable than other (currently inactive) LTM representations. In looking for dissociations between these two WM components, Oberauer (2001, 2005) found that older adults do not have problems removing items from the focus of attention; this finding is consistent with the present backward inhibition findings, which suggest older adults successfully inhibit no-longer-relevant task representations. In contrast, Oberauer found that older adults do have problems rejecting intrusions from irrelevant information in LTM, consistent with findings suggesting that older adults show deficits in at least some aspects of inhibition, such as resistance to proactive interference (e.g., Chapter 4; Hasher, Chung, May, & Foong, 2002; Jonides et al., 2000; May, Hasher, & Kane, 1999; McCabe, Robertson, & Smith, 2005; Thompson-Schill et al., 2002; but see Oberauer, 2005 for an alternative interpretation).

Interestingly, these embedded process accounts of WM might also account for the exaggerated global switch costs that are more typically found in older results (e.g., Mayr, 2001; counter to the results of the present study). Specifically, mixed blocks require that multiple task sets remain active so they are easily accessible at the point of a task switch; presumably, this information is being maintained in the activated portion of LTM.
Additionally, successful performance of a single task (in the face of interference from the currently irrelevant tasks) requires a strong representation of the task goal (Meiran, 2010); as a result, the start of an individual trial may involve task retrieval or goal “refreshing,” regardless of whether the trial involves a task switch or task repetition (Altmann & Gray, 2008; Mayr & Kliegl, 2000, 2003; see e.g., Bryck & Mayr, 2005; Saeki & Saito, 2004 for evidence that some processes occur on both switch and repeat trials). Given older adults are more susceptible to intrusions from information in the activated portion of LTM (Oberauer, 2001, 2005), it may be the case that older adults suffer from more interference from the activated-but-irrelevant tasks, potentially even as a result of weakly bound task sets (Mayr, 2001). However, such interference may be reduced in some situations – such as that of the present experiment and Kray et al. (2002) – when there is less uncertainty in task selection (e.g., as might be the case with explicit cues; but see Wasylyshyn et al., 2011, for a meta-analysis suggesting no effect of task manipulations on age effects in global task switching¹). This account is consistent with Mayr’s (2001) proposal that age effects might result from a set-updating process that “cleans up” (or helps the system settle on) a task representation when task ambiguity is present. It seems likely that this set updating process is interference-prone; however, at present, this account is speculative and should be closely investigated in future work.

**Summary**

¹ Although the meta-analysis of Wasylyshyn et al. (2011) investigated the contributions of task cueing and task predictability to the interpretation of age-related impairments in task switching, there was very little cross-study variance. That is, the majority of studies included in this meta-analysis were cued and unpredictable. Therefore, more experimental evidence is needed before drawing firm conclusions as to whether task demands affect age-related performance.
To conclude, the goal of understanding cognitive decline associated with healthy aging has led to a large amount of research across many different domains, including executive function, memory, and attention. Although a preponderance of evidence has suggested that older adults show age-related impairments in various aspects of cognition, future research should bridge topic areas in order to ascertain whether the decline associated with healthy aging necessitates multiple accounts, or can be explained by a single process-specific account that is inclusive of all aspects of cognition (e.g., Chapter 8). Such integrative accounts would inform theories of aging and executive control, and the interaction between the two.
Chapter 5 Figure Captions

*Figure 5.1.* Global shifting: Means of RTs (top) and log-transformed RTs (bottom) as a function of block (pure, mixed) and age (young, old). Error bars indicate standard errors.

*Figure 5.2.* Backward inhibition: Means of RTs (top) and log-transformed RTs (bottom) as a function of trial type (N-2 switch, N-2 repetition) and age (young, old). Error bars indicate standard errors.
Chapter 6: Individual Differences in Inhibitory Control Mechanisms and Their Role in Shifting

Working Memory and Executive Function

Multiple accounts of everyday cognition have proposed an important role for executive control and working memory processes in situations requiring organized and coordinated behavior, including planning, managing novel tasks/situations, multi-tasking, shifting between tasks, and resisting interference from irrelevant information (e.g., Baddeley, 1986; Miller & Cohen, 2001; Norman & Shallice, 1986). In particular, a great deal of research has focused on understanding the cognitive processes that contribute to both executive control and working memory (e.g., Kane, Conway, Hambrick, & Engle, 2007; Miller & Cohen, 2001; Miyake et al., 2000; Oberauer, 2002; Unsworth & Engle, 2007), with the goal of developing models of how we behave appropriately in complex, interference-inducing internal and external environments. Recently, researchers have taken an experimental approach to understand these processes (e.g., Friedman & Miyake, 2004; Friedman et al., 2008; Miyake et al., 2000; Munakata et al., 2011; Nee et al., 2012; Oberauer, Süß, Wilhelm, & Wittman, 2003, 2008; Salthouse, Atkinson, & Berish, 2003), many of which have used factor analytic techniques such as confirmatory factor analysis and structural equation modeling.

For example, a well-designed study by Oberauer and colleagues (2003) set out to identify the cognitive functions underlying working memory capacity. Oberauer and colleagues tested participants on an extensive battery of working memory (WM) and other tasks, in order to understand the contribution of various cognitive factors to working memory capacity. As a result of their measurement models, they proposed WM
to be best understood as two highly related factors of a) storage in the context of processing and b) coordination of elements into structures (later called relational integration, Oberauer et al., 2008). Importantly, these two factors were strongly related to performance on complex WM tasks (e.g., operation span). Oberauer and colleagues (2003) also proposed the importance of a third supervision factor, thought to reflect executive functions (discussed next). While still a WM function, the supervision function was less closely related to the other aspects of working memory capacity.

Other researchers have proposed similar WM mechanisms, with their models also being based on individual differences approaches (though not necessarily factor analytic techniques). Unsworth and Engle (2007), for example, have proposed that individual differences in working memory capacity are determined by maintenance in primary memory and retrieval from secondary memory. More specifically, they proposed an attentional mechanism as being important for maintaining information in primary memory (similar to Oberauer et al.’s (2003) storage/processing process). Additionally, access to information in secondary memory is driven by cue-based retrieval that depends at least in part on the successful binding between content and context (similar to Oberauer et al.’s (2003) coordination). Thus, while not identical to the model of Oberauer and colleagues (2003) because of the explicitly articulated need for retrieval mechanisms, these two models do have overlapping features. Regardless, these two WM models illustrate a number of possible WM functions that can contribute to task performance.

In addition to WM models, researchers have also posited models for elucidating executive function (EF) processes. For example, a very influential study used factor analytic methods to examine the factor loadings of three a priori identified executive
functions, those of shifting (also referred to as task switching; the ability to flexibly switch between tasks or mental sets), inhibition (the ability to suppress dominant or automatic responses), and updating (the ability to monitor and refresh the contents of working memory as old information is deemed irrelevant and new information becomes relevant (Miyake et al., 2000). In this study, Miyake and colleagues asked whether factoring out common variance among tasks hypothesized to measure each of these EF mechanisms resulted in a single or multiple EF factors. Their answer to this question was a strong “yes”, supporting both single and multiple factors. While there was evidence that the three aspects of EF were distinct, as indicated by their loadings on separate factors, Miyake et al. also found moderate inter-correlations between the three factors, suggesting some shared variance. Presumably, the diversity of EFs represents distinct abilities associated with each EF measure, while the unity represents a common mechanism.

More specifically, Miyake et al. (2000) raised two possibilities as to what the mechanism underlying unity might reflect. One possibility was a working memory mechanism such as goal maintenance or a controlled attention process (see also Friedman et al., 2008; Kane et al., 2007), which functions to keep task relevant information in an accessible state. The second possibility proposed by Miyake et al. was an inhibitory control mechanism. Recently, Munakata et al. (2011) have linked these two hypotheses, suggesting that the maintenance of a goal leads to both direct and indirect inhibition of responses or representations. Given the possible central role of inhibition in executive function, the present study investigates the organization of inhibitory control mechanisms, and whether these or other working memory mechanisms contribute to our ability to flexibly switch between tasks in a goal directed fashion.
Task Switching

The ability to flexibly switch between tasks is measured in task switching paradigms. In these paradigms, subjects typically complete two types of blocks. In single task (or pure) blocks, only a single task is relevant whereas in mixed task blocks, multiple tasks are relevant throughout the duration of the block, though only a single task is performed on a given trial (as specified by some sort of task cue). In such task switching paradigms, switch costs are observed. Performance in terms of reaction times and error rates declines when switching between tasks is required, relative to when the same task repeats.

Theories of task switching have proposed a critical role for inhibitory control processes (or likewise, interference resolution) in shifting. (Note that at this point in the discussion, I use inhibitory processes as an umbrella term including processes such as the inhibition of irrelevant information and the ability to resist interference from previously relevant information in memory; see Friedman & Miyake, 2004, for evidence of this distinction.) From early studies onward, Allport and colleagues (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 1999; Wylie & Allport, 2000) have suggested that at least some aspects of switch costs can be attributed to the need to resolve interference. More specifically, this literature suggests that switch costs result from proactive interference from a previously relevant task. This account assumes that there is continued priming from previously activated tasks. When tasks repeat, this activation is beneficial; in contrast, when tasks must be switched, this activation results in interference in choosing the appropriate task. Likewise, it has been proposed that the cognitive system overcomes the high activation of no-longer relevant tasks via inhibition of the inappropriate task
when a task switch is required (Mayr & Keele, 2000). Thus, inhibitory control over previously relevant tasks plays an important role in overcoming residual activation (i.e., interference) and allowing for successful switching.

Empirical evidence for the contribution of proactive interference to shifting comes from findings of asymmetrical switch costs, found when one task is more dominant than another (e.g., Allport et al., 1994). Allport et al. embedded a Stroop task (Stroop, 1935) in their shifting paradigm, such that subjects had to switch between the two tasks of color naming (while ignoring the written word) and word naming (while ignoring the stimulus’ ink color). Because word reading is a highly familiar, well practiced task, and thus involves more automatic processes, word reading is the easier, more dominant task with a stronger baseline activation. In contrast, color naming is less practiced task and thus a more difficult task, arguably with a weaker baseline activation. Allport and colleagues found larger switch costs when switching to the dominant task of word reading, relative to switching to the less dominant (more difficult) task of color naming (see Meuter & Allport, 1999, for similar results in language switching studies). As a result, Allport and colleagues (Allport et al., 1994; Allport & Wylie, 1999; Meuter & Allport, 1999) have proposed that asymmetrical switch costs result from the both proactive interference from the most recently performed task and persisting inhibition of the dominant task. More specifically, because the baseline activation of the dominant task is higher, more inhibition is needed to overcome its activation, with the temporal persistence of this applied inhibition being one source of switch costs. In contrast, the lower baseline activation of the less dominant task means less inhibition is required to override the activation of that task. Because less inhibition is needed to suppress this task, there is less
persisting inhibition to overcome when switching back to this task on future trials (i.e., smaller switch costs). Task switching, then, at least in part measures the time cost associated with managing interference from multiple tasks in working memory.

Further evidence supporting the notion that inhibition plays a role in task switching comes from a modified shifting paradigm using three tasks (tasks A, B, and C; Mayr & Keele, 2000). Mayr and Keele compared conditions in which a task had been more recently inhibited (task sequence ABA) to conditions in which a task was less recently inhibited (task sequence CBA). If inhibition is used as a task switching mechanism, switching to a more recently inhibited task (ABA; N-2 repetition) should take longer than switching to a less recently inhibited task (CBA; N-2 switch) due to the persistence of previously applied inhibition. This is exactly what Mayr & Keele found. In accordance with the claims of Allport and colleagues, the recency of task disengagement via inhibition affected performance (see also Gade & Koch, 2005, 2007; Schuch & Koch, 2003; Schneider & Verbruggen, 2008). The greater difficulty in switching back to a recently inhibited task is known as the N-2 repetition cost, and is thought to reflect backward inhibition. Mayr and Keele suggested that backward inhibition enables one to disengage from previously relevant tasks, with at least part of switch costs explained by the need to overcome this applied inhibition.

Lastly, in an individual differences study of older adults, Hedden and Yoon (2006) found a positive relationship between task switching ability and resistance to proactive interference, as individuals with better interference resistance demonstrated reduced switch costs. While this finding is in line with a role for interference resolution in task switching, the interpretation of their result is complicated by the fact that both their
shifting and PI tasks consisted of complex tasks. For example, shifting was measured by the Wisconsin Card Sorting Task (Heaton, 1993; Milner, 1963) and Trail Making Test (Armitage, 1946; Reitan, 1955), and PI was measured by letter and semantic fluency tasks (Lezak, 1995). The use of such complex executive tasks makes it unclear what aspects of task switching and PI were being measured, as complex task performance depends on multiple executive and non-executive processes. Thus, while these results support the notion that inhibitory control mechanisms are involved in shifting, they do not clearly indicate the specific role for interference resolution in shifting.

The above-reviewed work suggests a role for inhibition in task switching, but there are several clarifications that need to be made. First, task switching can be measured by more than one type of switch cost, with each type of switch cost presumably tapping different working memory processes. Global switch costs are measured as the difference between mixed and pure blocks and are argued to reflect the ability to manipulate, maintain, and select between multiple tasks in working memory (Kray & Lindenberger, 2000; Mayr, 2001). In contrast, N-2 repetition costs are measured as the difference between N-2 repetition and N-2 switch trials, within the mixed block and are argued to reflect the inhibition of recently abandoned task sets (e.g., Mayr & Keele, 2000; Mayr, 2001). Finally, local switch costs are measured as the difference between switch and repeat trials within with in the mixed block, and are considered a measure of the ability to initiate, retrieve, and execute a task set shift in the context of having just performed a different task (e.g., Altmann & Gray, 2008; Mayr & Kliegl, 2000). While a critical role for interference resolution has been proposed to account for local shifting and likely modulates the ability to manage multiple task sets in WM in global shifting, WM
functions (e.g., working memory capacity, retrieval) have also played a strong role in the theoretical description of different switch costs. As a result, working WM functions may also play a critical role in explaining shifting measures. For example, global costs involve maintaining multiple tasks in an accessible state, while local costs and N-2 repetition costs at least in part reflect the ability to retrieve new task sets from WM at the point of a task switch.

Additionally, although inhibitory control was discussed as a unitary construct in the above discussion, it has been suggested that inhibition may be better represented by multiple constructs, including response-distractor inhibition and the resistance to proactive interference (PI; Chapter 4; Friedman & Miyake, 2004; Nigg, 2000). Response-distractor inhibition measures the ability to suppress dominant responses and/or distractors present in the environment (cf. Hedden & Yoon, 2006), whereas resistance to PI measures our resistance to intrusions from previously relevant (but now irrelevant) information in memory. Critically, these two types of inhibition are distinguished by whether they involve features of the current environment (such as irrelevant stimuli on the screen, as with response-distractor inhibition) or features of the previously relevant context (such as previously memorized list of words, as with resistance to PI). Moreover, as discussed by Friedman and Miyake, it remains possible that there are other types of inhibition not captured by their two-factor model.

In contrast to the findings of Friedman and Miyake (2004), however, others studies have failed to find consistent evidence for a coherent factor underlying response-distractor inhibition. These studies have found only small correlations between tasks thought to measure this construct and consequently the response-distractor inhibition
tasks did not load on the same factor in structural equation modeling (e.g., Hedden & Yoon, 2005; Hull, Martin, Beier, Lane, & Hamilton, 2008; Salthouse, Atkinson, & Berish, 2003; Shilling, Chetwynd, & Rabbitt, 2002). Studies failing to find consistent response-distractor inhibition effects differed from that of Friedman and Miyake in two important ways: first, all of these studies included older adults, though the Salthouse et al. (2003) study included both young and old subjects. Secondly, unlike the work of Friedman and Miyake, these studies controlled for speed of processing, either by using log-transformed data or including a speed factor in their models. For example, Shilling and colleagues (2002) investigated multiple response-distractor inhibition tasks (e.g., arrows and color-word Stroop tasks, among others) to determine whether they could find consistent task performance across them. However, using log-transformed RT data, little cross-task consistency was found. A different study by Hedden and Yoon (2005) included response-distractor inhibition, resistance to PI, and processing speed measures (among other factors) in their structural equation models of executive function in older adults. In their model, response-distractor inhibition was indistinguishable from processing speed ($r = .97$!). These studies thus call into question whether response-distractor inhibition tasks are robust measures of inhibition, or instead reflect more general processing speed mechanisms. Given these discrepancies, the present study examined measures of inhibitory control with controls for processing speed.

Despite the caveats above regarding the unity of measures of response-distractor inhibition, it is clear that inhibitory processes have been claimed to play important roles in task switching, which begs the question of how inhibition and switching are related to each other. Thus, the questions addressed by the present study are as follows: first, can
we replicate the distinction between response-distractor inhibition and resistance to PI? And if so, do different types of inhibition play different roles in the various measures of task switching? Or, might measures of switching be better understood in terms of WM mechanisms? Before discussing the methods and results, I first briefly review hypotheses for how various control processes might be (differentially) related to measures of task switching.

**Possible Roles for Control Processes in Task Switching**

**Global switch costs.** As discussed above, global switch costs measure the cost associated with manipulating, maintaining, and selecting among multiple task sets in working memory (Kray & Lindenberger, 2000; Mayr, 2001). Specifically, Mayr (2001) attributes at least some of these costs to the need to adopt one task set among others that are potentially relevant, limiting the focus of working memory to “one of several competing mental sets” (Mayr, 2001, p. 107). Such an account emphasizes an important role for WM, though this role is also conceptually similar to mechanisms of PI resolution, which are involved in the selection of relevant information in the face of competition from irrelevant representations that are being held (whether intentionally or not) in WM. As a result, global costs may at least in part reflect the ability to maintain multiple tasks in WM, or alternatively, resolve interference from activated – but currently irrelevant – task sets (as is necessary in mixed blocks), relative to situations where only a single task set is activated (as in pure blocks).

**N-2 repetition costs, or backward inhibition.** By inhibiting no longer relevant (and therefore competing) representations, backward inhibition facilitates task selection (e.g., Mayr & Keele, 2000). However, little work has investigated whether backward
inhibition is functionally similar to other traditional measures of inhibition, such as response-distractor inhibition or resistance to PI. On this issue, theorists have mixed opinions. Koch, Gade, Schuch, and Philipp (2010), for example, have suggested that backward inhibition is “invoked by a conflict-monitoring mechanism similar to the one postulated in the study of response conflict in single-task conflicts” (p. 11). Under this view, backward inhibition may be used as a mechanism for overcoming conflict in some aspects of task switching, suggesting a possible relationship with response-distractor inhibition in order to overcome interference from irrelevant representations. Additionally, some studies have suggested right inferior frontal cortex involvement in both response inhibition and backward inhibition (see Koch et al., 2010 for a discussion), suggesting similar or overlapping neural mechanisms (but see Dreher & Berman, 2002, for an alternative interpretation).

However, backward inhibition is conceptually similar to the deletion function proposed by Hasher, Zacks, and May (1999), which serves to remove no longer relevant information from attentional focus, enabling the focus of attention to be updated with currently relevant information. According to May, Hasher, and Kane (1999), deletion plays an important role in resisting interference. Given that backward inhibition functions to resolve competition between relevant and irrelevant task sets, it seems possible that backward inhibition will show a relationship to resistance to PI measures. That is, conceptually, both resistance to PI and backward inhibition involve overcoming interference from previously relevant – but now irrelevant – information in memory.

In contrast to these views assuming controlled inhibitory processes, other researchers have suggested that backward inhibition involves instead a low-level,
automatic process, instantiated by mechanisms such as lateral inhibition (e.g., Koch et al., 2010; Mayr & Keele, 2000; Schuch & Koch, 2003; Vandierendonck, Liefooghe & Verbruggen, 2010). From these accounts, backward inhibition is simply the downstream effect of selecting new representations, as this active selection of a task may result in the lateral inhibition of competing tasks (Mayr & Keele, 2000; see Munakata et al., 2011, for a similar account of inhibition). If backward inhibition is best understood as a more automatic process, we might not expect a relationship between backward inhibition and more common measures of inhibition (i.e., response-distractor inhibition resistance to PI).

Complicating things further, Anderson and Levy (2007) have suggested that the prediction of a relationship between backward inhibition and inhibitory control is quite difficult. As Anderson and Levy point out (and in line with the assumptions of Mayr & Keele, 2000), inhibition has both costs and benefits. The better one is at inhibition, the better one can inhibit previous tasks when switching to a new task. Additionally, the better one is at inhibition, the more difficult it may be to retrieve a previously inhibited task set. In the case of comparing performance in the experimental condition (ABA; N-2 repetition) vs. the control condition (CBA; N-2 switch) in backward inhibition tasks, Mayr and colleagues have focused on the difficulty in retrieving task A in the experimental condition, as this should be harder the better one is at inhibition. They have implicitly assumed that inhibiting task B should be of equivalent difficulty in the two conditions; as a result, the application of inhibition to task B should play no role in explaining individual differences between these conditions. However, as Anderson and Levy point out, this is not the case. Given the prior inhibition of task A in the experimental condition, this task set will have a lower activation strength relative to that
for task B, than is the case for task A relative to task B in the control condition. That is, the more recent inhibition of task A (in the experimental ABA condition) will result in a larger difference in activation levels between task B and task A (when task A again becomes relevant on trial N) requiring more inhibition of task B. In contrast, the less recent inhibition of task A (in the control CBA condition) will result in a smaller difference in activation levels between task B and task A, requiring less inhibition (see Figure 6.3). The better one’s inhibition, the better one can suppress task B in the experimental condition with respect to task A, with this ability playing a lesser role in the control condition. Thus, in the experimental condition, better inhibition results in more difficulty in retrieving task A but a better ability to inhibit task B. Consequently, it is difficult to predict what the relation should be between the size of the backward inhibition effect and individual differences in other inhibitory control mechanisms.

**Local switch costs.** Lastly, local costs are thought to be a measure of the ability to retrieve and update new task sets in order to switch between tasks (Kray & Lindenberger, 2000; Mayr, 2001; Rogers & Monsell, 1995), with no influence from the requirement to maintain multiple task sets in mind (which is the same for switch and repeat trials). Such accounts assume a role for retrieval mechanisms in local switch costs, as task set retrieval is paramount to accurate switch trial performance (e.g., Altmann & Gray, 2008; Sohn & Anderson, 2001). While little work has investigated the relationship between inhibition constructs and measures of global switch costs and N-2 costs, Friedman and Miyake (2004) found that response-distractor inhibition provided a significant path to local switch costs in structural equation modeling. Friedman and Miyake suggested that response-distractor inhibition functions to filter out information
from the irrelevant task, once a new task set has been established (i.e., at a point of a task switch). As switch trials represent the first implementation of the newly relevant task set, response-distractor inhibition may play a stronger role in enabling one to overcome residual activation of the now-irrelevant stimulus features, in order to firmly establish the new task in working memory. Consistent with this hypothesis, a meta-analysis of neuroimaging studies found overlapping inferior frontal junction activation in both local shifting and the Stroop task (a measure of response-distractor inhibition; Derfuss, Brass, Neumann, & von Cramon, 2005). Derfuss et al. suggested that this region plays an important role in updating task representations in the face of interference in both tasks (but see Nee et al., 2012, for an alternative interpretation).

In contrast, Friedman and Miyake (2004) did not find a relationship between local switch costs and resistance to PI, with this lack of relationship being surprising based on some theories of task switching. As discussed above, Allport and colleagues (e.g., Allport et al., 1994) have proposed a critical role for PI as the source of local switch costs, as selecting between tasks involves resolving interference from recently activated task sets. This theory clearly predicts a relationship between local costs and resistance to PI.

Goals of the Present Study

The present study uses factor analytic techniques – specifically confirmatory factor analysis (CFA) – to achieve several goals. First, previous work has not consistently replicated the loadings and distinctions between inhibition factors, as found by Friedman and Miyake (2004). However, other research does support the notion that these factors are in some way distinct from each other; for example, inhibition factors make differential contributions to performance on other cognitive tasks (e.g., Friedman &
Miyake, 2004) and they show different patterns of decline with age (e.g., Chapter 4). The first goal, then, is to determine whether the results of Friedman and Miyake can be replicated in a different sample. Second, as discussed above, a fair amount of work suggests a critical role for interference resolution in task switching, though not much research has investigated whether individual differences in different types of inhibition and other WM functions relate to various aspects of task switching. Not only is this an important issue for understanding the mechanisms that allow us to switch between tasks, but the findings may show that inhibition constructs may be dissociated in how they relate to the shifting component of executive function. The second goal, then, is to develop a better understanding of the mechanisms that allow us to flexibly switch between tasks by investigating how inhibitory and WM control processes differentially contribute to global switch costs, N-2 repetition costs, and local switch costs.

**Method**

**Participants**

Participants were 162 individuals from two age groups: 102 young adults between the age of 18 and 32 ($M = 21$, $SD = 3.08$) and 60 older adults between the age of 64 and 87 ($M = 71$, $SD = 4.96$). As described in Chapter 3, older adults were screened for both neurological disorders and cognitive impairment using the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975; Folstein, Folstein, McHugh, & Fanjiang, 2001). Performance on background measures (e.g., WM, vocabulary, and processing speed) was reviewed in Chapter 4, and will not be repeated here.

**Materials**

All task details are thoroughly reviewed in the Method Chapter (Chapter 3).
However, the tasks relevant to the present work – and their dependent variables – are briefly summarized below.

**Response-Distractor Inhibition Tasks**

**Picture-word interference task (PWI).** In the PWI task (e.g., Lupker, 1979; Schriefers, Meyer & Levelt, 2002), subjects named a presented picture while ignoring the super-imposed distractor word. Pictures were seen in semantically related (i.e., interference) and semantically unrelated (i.e., no interference) conditions. The dependent variable was the semantic interference effect, measured as the log RT difference between semantically related and semantically unrelated trials.

**Nonverbal Stroop task.** In the nonverbal Stroop task (Hamilton & Martin, 2005), subjects pressed a button to indicate the direction an arrow was pointing (right, left), while ignoring the arrow’s spatial location on the screen (right, central, left). The dependent variable was the log RT Stroop effect, measured as the difference between incongruent and neutral trials.

**Stroop task.** In the Stroop task (Stroop, 1935), subjects saw a colored word or string of asterisks and their task was to name the color of the ink while ignoring the written text. The dependent variable was the log RT Stroop effect, measured as the difference between incongruent and neutral trials.

**Flanker task.** In the Flanker task (e.g., Eriksen & Eriksen, 1974; adapted from Friedman & Miyake, 2004), subjects saw a string of 7 letters; they responded to the central letter (e.g., KKKHKKK). The dependent variable was the log RT difference between incongruent and neutral trials.

**Resistance to Proactive Interference Tasks**
One issue with resistance to PI tasks is that they typically involve recall, with a single trial oftentimes consisting of multiple memory lists (as in the release from PI and cued recall tasks discussed below). As a result, it is generally not possible to collect data on a large number of trials, given each trial takes a long time (relative to a single trial in the Stroop task, for example). As a result, these tasks’ difference scores do not yield good reliability (e.g., Friedman & Miyake, 2004), as not many trials go into the reliability calculation (essentially exaggerating the difficulties associated with low reliabilities of difference scores; Cronbach & Furby, 1970). For example, the resistance to PI tasks used by Friedman and Miyake (2004) showed unacceptably low reliability ($M = .10$).

Friedman and Miyake opted to overcome this reliability issue by using residuals as their PI measure. Because all of their PI tasks were recall tasks, they created a resistance to PI model that contained two latent variables. The “Recall” latent variable tapped performance on non-PI inducing trials, and the “PI” latent variable tapped performance on conditions eliciting PI. Friedman and Miyake then used the “Recall” latent variable (no-PI conditions) to predict the “PI” latent variable, reasoning that the leftover variance reflected “a combination of PI and measurement error” (p. 112).

Given similar issues with difference score reliability on the two resistance to PI recall tasks used here (discussed below), the present study circumvented this reliability issue in a similar way as Friedman and Miyake (2004). As described below, performance on the two recall tasks (release from PI and cued recall tasks) was measured with standardized regression residuals, predicting performance on the interference condition from performance on the no-interference condition. However, unlike Friedman and Miyake, I did not develop “Recall” and “PI” latent variables.
**Recent negatives task.** In the recent negatives task probe task (e.g., Monsell, 1978), subjects heard a list of three words followed by a probe word, and subjects indicated whether the probe word was in the previous list. This task contained three trial types: positive trials (probe word was in the list), non-recent negative trials (probe word was not in any recent lists), and recent negative trials (probe word was not presented in the most recent list (list n), but it was presented in the previous trial (list n-1)). The dependent variable was the accuracy difference between recent and non-recent negative trials, demonstrating a subject’s susceptibility to interference from previously presented (but now irrelevant) information.

**Release from proactive interference (PI) task.** In the release from PI task (Peterson & Peterson, 1959; similar to Friedman & Miyake, 2004), subjects read lists of 8 words that they recalled after a filler task. This task was administered in 10 blocks, with each block containing 4 lists. The first three lists were composed of items from the same semantic category to buildup interference; the fourth list was composed of items from a different semantic category, serving as the release from PI. For each list, proportion of correct recall was calculated. Given the small number of trials, and to circumvent the low reliability of difference scores, the dependent variable was the standardized residual predicting list 2 recall from list 1 recall.

**Cued recall task.** In the cued recall task (Tolan & Tehan, 1999; similar to Friedman & Miyake, 2004), subjects saw either one or two lists of 4 words; following a filler task, subjects saw a category and were instructed to recall the *most recently* presented exemplar from the cued category. In one-block trials, the most recently presented exemplar (the target) was in the single presented list; in two-block trials, the
target was always in the second list. However, half of the two-block trials were interference trials, where both the first and second lists contained an exemplar from the cued category; the category exemplar in the first list was a lure. For each trial type, proportion correct was calculated. Given the small number of trials, and to circumvent the low reliability of difference scores, the dependent variable was the standardized residual predicting two-block control trials from one-block trials.

**Shifting Tasks**

**Global switch costs and N-2 repetition costs.** In the three-task shifting task (e.g., Mayr & Keele, 2000), subjects respond to a target based on the relevant cued task (“Number”, “Shape”, or “Size”). Subjects completed pure (or single task) and mixed blocks. This task design allowed for the measurement of two shifting DVs. Global switch costs were measured as the log RT difference between mixed and pure blocks. N-2 repetition costs were measured as the log RT difference between N-2 repetition and N-2 switch trials within the mixed block.

**Local switch costs.** A subset of young adults (n = 92 of 102) was tested on a short two-task shifting task that allowed for the measurement local switch costs. As with the other shifting task, subjects responded to a target based on the relevant cue. Subjects completed 3 mixed blocks, and in each block, subjects responded to one of two possible tasks (i.e., within a given block, only two tasks could possibly be relevant). This task design allowed for the measurement of local switch costs: log RT difference between switch and repeat trials.

**Retrieval Task**
A retrieval task was included to measure the ability to retrieve task relevant information residing outside the focus of attention.

**Sternberg recognition task.** In the Sternberg recognition task (McElree & Dosher, 1989; Nee & Jonides, 2008), participants saw a list of five serially presented words. The last word was masked, then followed by a probe to which participants indicated whether the probe word was in the most recently presented list. Researchers have hypothesized that the most recent item (serial position 5) remains in the focus of attention and does not require retrieval; in contrast, earlier list items (serial positions 1-4) do require retrieval (e.g., McElree & Dosher, 1989). As a result, the dependent variable was a standardized residual predicting accuracy on trials requiring retrieval (i.e., ‘yes’ trials for which the probe matches a word in the middle serial positions) from accuracy on trials requiring no retrieval (i.e., ‘yes’ trials for which the probe matches the word in the final serial position, within the focus of attention). The difference between these conditions measures one’s ability to disengage from information and retrieve new information into the focus of attention (McElree & Dosher, 1989; Oberauer, 2002).

**Goal 1: Confirmatory Factor Analysis of Inhibitory Control Constructs**

**Data Processing**

Preliminary data processing for log RTs is described in Chapter 3. Two subjects were missing data on a single task due to experimenter error (1 on the PWI task, 1 on the Flanker task); additionally, one other subject was missing data on the Stroop task due to color blindness. To avoid excluding these three subjects, missing values were predicted using multiple imputation in SPSS. Given these were all response-distractor inhibition tasks, missing values were predicted with a regression algorithm including the
incongruent and neutral trials of the other response-distractor inhibition tasks. From these predicted values, difference scores were calculated. Additionally, because the sample includes both young and older adults, age was included in this imputation model as a categorical variable.

**Transformations and Outlier Analyses**

Proportion correct measures (i.e., resistance to PI dependent variables) were arcsine transformed (as done by Miyake et al., 2000; see Judd & McClelland, 1989). Prior to any other outlier analysis, the skew and kurtosis of each dependent variable were first examined. If either skew or kurtosis values were unacceptable, additional transformations occurred. Specifically, for measures with unacceptable skew or kurtosis values, outliers identified as beyond three times the interquartile range were replaced with a value equivalent to 2.5 standard deviations beyond the overall mean. For the response-distractor inhibition tasks, this affected four subject log RT values (2 flanker, 1 NV Stroop, 1 Stroop). For the resistance to PI tasks, this affected three subject values, all in the recent negatives task. For shifting measures, this affected one subject log RT value (global shifting). These transformations and outlier analyses resulted in acceptable distributional normality (i.e., skew and kurtosis, Table 6.1), as values less than |2| are considered acceptable for most purposes, and values less than |1| considered very good for psychometric purposes. The only exception was the kurtosis value for the Stroop task, though this value approached the acceptable range.

Table 6.1. Descriptive statistics for the dependent variables in Chapter 6. Descriptive statistics for log-transformed RT measures are shown in brackets below the RT values. Unless otherwise indicated, dependent variables represent difference scores. For the
resistance to PI and cued recall tasks, descriptive statistics are shown for the no-PI and PI conditions, as well as the standardized residual that was used in the model.

<table>
<thead>
<tr>
<th>Response-Distractor Inhibition</th>
<th>DV</th>
<th>M</th>
<th>SD</th>
<th>Range</th>
<th>Skew</th>
<th>Kurtosis</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWI</td>
<td>RT</td>
<td>45</td>
<td>41</td>
<td>(-81, 161)</td>
<td>0.31</td>
<td>1.2</td>
<td>0.45</td>
</tr>
<tr>
<td>NV Stroop</td>
<td>RT</td>
<td>55</td>
<td>34</td>
<td>(-40, 152)</td>
<td>0.38</td>
<td>0.96</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>Log RT</td>
<td>[.04]</td>
<td>[.02]</td>
<td>[-.05, .11]</td>
<td>[-.18]</td>
<td>[1.0]</td>
<td>[.53]</td>
</tr>
<tr>
<td>Stroop</td>
<td>RT</td>
<td>194</td>
<td>115</td>
<td>(33, 640)</td>
<td>1.4</td>
<td>2.5</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Log RT</td>
<td>[.09]</td>
<td>[.04]</td>
<td>[.02, .23]</td>
<td>[.85]</td>
<td>[1.4]</td>
<td>[.88]</td>
</tr>
<tr>
<td>Flanker</td>
<td>RT</td>
<td>75</td>
<td>44</td>
<td>(-52, 211)</td>
<td>0.21</td>
<td>1.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Resistance to Proactive Interference</td>
<td>Recent negatives</td>
<td>Accuracy</td>
<td>.06</td>
<td>.08</td>
<td>(-.13, .30)</td>
<td>0.85</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>Release from PI</td>
<td>No PI (1-block)</td>
<td>.92</td>
<td>.30</td>
<td>(.00, 1.57)</td>
<td>0.22</td>
<td>-0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI (2-blocks)</td>
<td>.75</td>
<td>.38</td>
<td>(.00, 1.57)</td>
<td>0.28</td>
<td>-0.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>0</td>
<td>1.0</td>
<td>(-2.8, 2.8)</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Cued recall</td>
<td>No PI (List 1)</td>
<td>.62</td>
<td>.18</td>
<td>(.11, 1.06)</td>
<td>-0.02</td>
<td>-0.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI (List 2)</td>
<td>.48</td>
<td>.16</td>
<td>(.14, .87)</td>
<td>0.22</td>
<td>-0.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>0</td>
<td>1.0</td>
<td>(-2.3, 2.9)</td>
<td>0.19</td>
<td>-0.03</td>
</tr>
<tr>
<td>Task switching</td>
<td>Global</td>
<td>RT</td>
<td>743</td>
<td>363</td>
<td>(-72, 1805)</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>N-2 repetition</td>
<td>RT</td>
<td>66</td>
<td>81</td>
<td>(-128, 366)</td>
<td>0.61</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Local (n = 92)</td>
<td>RT</td>
<td>82</td>
<td>94</td>
<td>(-249, 278)</td>
<td>-0.27</td>
<td>1</td>
</tr>
</tbody>
</table>

**Model Estimation**

CFA models were estimated in R (R Development Core Team, 2010), using the Lavaan (latent variable analysis) package (Rosseel, 2010). For each model reported below, model fit was evaluated via multiple fit indices, similar to Friedman and Miyake (2004) and as recommended by Hu and Bentler (1998). The chi-square goodness-of-fit statistic tests model fit by assessing the “discrepancy between the sample and fitted covariance matrices” (Hu & Bentler, 1998, p. 426); for this index, a small, non-
significant value indicates good fit (that is, a large, significant value indicates badness-of-fit). In addition to this dichotomous fit index, other continuous fit indices were also evaluated. The standardized root-mean-square residual (SRMR) is an absolute fit index, measuring a model’s ability to fit sample data; SRMR measures the averaged squared residuals, with lower values (< .05) indicating good fit (Hu & Bentler, 1998). Bentler’s comparative fit index (CFI) is an incremental fit index with range of 0-1; this index compares the fitted model to a restricted baseline model, with higher values indicating better fit (Hu & Bentler, 1998). Blunch (2008) maintains that CFI values >.95 indicate good fit.

Additionally, two-factor models were compared to one-factor models using change in chi-square values across models. To do so, the chi-square value for the fuller model (that with fewer degrees of freedom; the two-factor model) was subtracted from the chi-square value for the one-factor model. A significant chi-square difference indicates that the one-factor model provides a worse fit than the two-factor model, given the loss in degrees of freedom. If multiple models provided good fit, and these models did not differ statistically in cross-model chi-square comparisons, the principle of parsimony dictates that the simplest model is to be preferred, until alternative evidence is presented. All model factor loadings and other statistical analyses reported below use an alpha level of .05.

Given the inclusion of both young and old adults, and previous inconsistencies in finding an response-distractor inhibition factors when processing speed was controlled for (e.g., Hedden & Yoon, 2005; Hull et al., 2008; Salthouse et al., 2003; Shilling et al., 2002), models were estimated using log RT data for response-distractor inhibition tasks.
Use of log RTs controls for differences in processing speed on RT tasks, allowing for the investigation of task loadings independent of speed. For correlational analyses, factor loadings, and composite scores, all difference scores were multiplied by -1 so that positive values reflect better performance.

**Descriptive Statistics**

Descriptive statistics for the seven inhibition and three shifting measures are shown in Table 6.1, for both RTs and log-transformed RTs (though analyses used log-transformed RTs). For each task, internal reliability estimates were calculated using a split-half correlation, adjusted by the Spearman-Brown formula (see Table 6.1). Reliabilities were variable, with some being unacceptably low (e.g., PWI, flanker, release from PI, local switch costs, N-2 repetition costs), others being excellent (e.g., Stroop, global shifting), and everything else falling somewhere in between. These relatively low to moderate reliabilities are consistent with other executive function work (e.g., Friedman & Miyake, 2004; Miyake et al., 2000; Rabbitt, 1997). Of note, the residual recall measures selected as dependent variables for the release from PI and cued recall tasks showed better reliabilities than difference scores based on correct recall between PI- and non-PI lists. For the release from PI task, the difference score (list 2 - list 1) had a reliability of .20 (vs. .31 for the residual). In the cued recall task, the difference score (two-block control trials - one-block trials) had a reliability of .47 (vs. .59 for the residual). Also of note, the residual measures were significantly correlated with the difference scores. For both tasks, these correlations were greater than .90 (release from PI task, $r = -.95$; cued recall task, $r = -.94$). Thus, these scores reflect very similar measures, though use of the residuals allowed for a gain in reliability.
Zero-order correlations between all inhibition and shifting tasks are shown in Appendix A for RT measures and Appendix B for log-transformed RT measures. Consistent with previous work examining individual differences in executive function (Borella et al., 2008; Friedman & Miyake, 2004; Miyake et al., 2000), RT correlations tended to be low to moderate. As seen in Appendix A, tasks hypothesized to tap a single inhibition construct (e.g., response-distractor inhibition) tended to correlate with each other, though some cross-construct correlations were also significant. One exception is the flanker task; the Flanker task failed to show even small correlations with any of the other tasks (correlations $\leq |.09|$). As a result, this task was excluded from further consideration. As seen in Appendix B, in contrast, the log-transformed response-distractor inhibition task correlations showed almost no tendency to correlate with one another, suggesting that previously reported RT correlations may reflect – at least to some degree – differences in overall processing speed. Despite these relatively low zero-order correlations across tasks, it should be noted that, as done by Friedman and Miyake, this work goes beyond looking at simple correlations, instead investigating factor structures that fit the data and relations between cognitive control constructs and measures of task switching.

**Results**

Given that prior work has not found consistent evidence for a coherent factor underlying response-distractor inhibition (e.g., Hedden & Yoon, 2005; Hull et al., 2008), it was an open question as to whether a two-factor model inhibition model would provide the best fit of data, as found by Friedman and Miyake (2004). The two- and one-factor models for log RTs are illustrated in Figure 6.1. In all pictorial representations of the models, the number next to the double-headed arrows indicates the correlation between
the two inhibition latent variables. The numbers next to the left-pointing single headed arrows indicate standardized factor loadings of manifest variables on latent variables. The numbers next to the right-pointing single-headed arrows indicate residual error variance; according to Miyake et al. (2000), the square of these values provides an “estimate of the unexplained variance for each task, which could be attributed to idiosyncratic task demands and measurement error” (p. 70). Fit indices are summarized in Table 6.2.

The two-factor model is shown in Figure 6.1 (top). As shown in Table 6.2, the fit indices indicated good model fit. The chi-square statistic was far from significant ($\chi^2(8) = 1.56$), indicating goodness of fit. Additionally, the SRMR (0.020) and CFI (1.00) indices indicated excellent model fit. However, the response-distractor inhibition factors (PWI, NV Stroop, Stroop) failed to load significantly on the response-distractor inhibition latent variable. While the correlation between the two latent variables was strong, it was nonsignificant ($r = .75, p = .12$).

Table 6.2. Fit indices for confirmatory factor analysis models. The model providing the best fit is indicated in bold.

<table>
<thead>
<tr>
<th>Model</th>
<th>df</th>
<th>$c^2$</th>
<th>SRMR</th>
<th>CFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-factor model</td>
<td>8</td>
<td>1.56</td>
<td>0.020</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Single-factor model</strong></td>
<td>9</td>
<td><strong>1.78</strong></td>
<td><strong>0.021</strong></td>
<td><strong>1.00</strong></td>
</tr>
</tbody>
</table>

The two-factor model was compared to a one-factor model in which the correlation between the two inhibition latent variables was constrained to 1.0, indicating that the response-distractor inhibition and resistance to PI inhibition factors are equivalent. (Using a correlation of 1.0 is equivalent to running a model in which all inhibition tasks (response-distractor inhibition and resistance to PI tasks alike) load on a
single latent variable, as illustrated in Figure 6.1, bottom). This model, shown in Figure 6.1 (bottom), also demonstrated good fit (Table 6.2). To determine whether the one-factor model provided an equivalent fit to the data, I calculated a cross-model chi-square test. This cross-model chi-square test was not significant ($\chi^2(1) = 0.22, p = .64$), indicating that the one-factor model provided an equivalent fit to the data. While this model fails to replicate the findings of Friedman and Miyake (2004), it is consistent with studies that have failed to find response-distractor inhibition factors when taking processing speed into account (e.g., Hedden & Yoon, 2005; Hull et al., 2008).

Concern might arise from the use of difference scores for measuring some variables (the three response-distractor inhibition tasks, the recent negatives probe task), and residuals for others (the cued recall and release from PI tasks). To ameliorate these concerns, I ran an additional model that used residual dependent variables for all tasks. The dependent variables for the cued recall and release from PI tasks were the same residuals as used in the above model. In contrast, the dependent variable used for the remaining four tasks was a RT and accuracy residual composite. For each of these tasks, I calculated residual effects for both the log RT and accuracy data, then averaged these two values. Thus, the dependent variable for these four tasks reflected both response time and accuracy. This model is shown in Appendix C. The patterns of factor loadings and model fits were essentially equivalent to the model just presented. Both the two-factor model (Appendix C, top; $\chi^2(8) = 7.903, p = .44$; SRMR = 0.042; CFI = 1.00) and the one-factor models (Appendix C, bottom; $\chi^2(9) = 7.904, p = .54$; SRMR = 0.042; CFI = 1.00) provided a good fit to the data. As with the model discussed above, the one- and two-factor models provided an equivalent fit to the data, as indicated by a non-significant
cross-model chi-square test ($\chi^2(1) = 0.001, p = .97$); thus, the one-factor model was preferred. Importantly, the pattern of task loadings for the preferred model is equivalent to that of the model discussed above (compare Appendix C, bottom to Figure 6.1, bottom).

An important point to take from the log RT model is the pattern of task loadings in the single-factor model. With processing speed taken into account, one of the response-distractor inhibition tasks – Stroop – loads significantly with the other resistance to PI factors. Additionally, the existence of a single factor model, as well as the loading of the Stroop task on this factor, raises the question what mechanisms are common among the tasks loading on this single factor model. Possible explanations for this pattern of results will be explored in the General Discussion.

**Goal 2: Do Inhibition Factors Differentially Relate to Measures of Task Switching?**

There is strong evidence supporting the notion that inhibition and WM resources are involved in task switching, though task switching abilities can be measured by an assortment of different variables. The second goal of this study is to make progress in determining the role for inhibitory control and WM mechanisms in task switching. To do so, I investigated whether individual differences in the inhibition factor (as identified above) and WM predict shifting measures (global switch costs, N-2 repetition costs, and local switch costs).

**Results**

**Variables and analyses.** The relationships between inhibitory control, working memory functions, and task switching measures were assessed using multiple regressions. Regressions were run on log-transformed RT data. Above, it was determined
that inhibitory control is best reflected by a single factor model. As a result, inhibitory control was measured by a single inhibition composite score, computed by averaging the z-scores of the manifest variables loading on the single factor model (Figure 6.2, bottom). Composite scores were used because very little is lost in using these to estimate latent variable factors, even relative to factor scores (e.g., Alwin, 1973). Two WM measures were also included in order to investigate the contribution of WM variables to measures of shifting, as switch costs theoretically reflect some WM mechanisms (described in more detail below). Working memory capacity was measured by a WM composite, consisting of a z-transformed average of scores from the backwards span and operation span tasks. Additionally, retrieval was measured by a Sternberg recognition task residual, created by predicting accuracy on memory retrieval conditions from non-memory retrieval conditions. The correlations among the inhibition and WM composite scores, the retrieval residual, and switch costs are shown in Table 6.3.

Table 6.3. Correlations among the inhibition and WM composite scores, the retrieval residual, and task switching dependent variables used in the regression analyses.

Correlations with task switching variables use difference scores (though difference scores are not used in the regression analyses). Asterisks indicate significant correlations ($p < .05$); asterisks within parentheses indicate marginally significant correlations ($p < .10$).

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Single ‘inhibition’ factor</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2 WM composite</td>
<td>.49*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 Retrieval residual</td>
<td>.14(*)</td>
<td>.24*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

2 Given I have the factor loadings of for each of the manifest variables, I also ran these same regression analyses using factor scores. The overall pattern of results was no different from those reported above for the composite scores.
Given the difficulties associated with difference score reliability (Cronbach & Furby, 1970), shifting variables were predicted by regressing the difficult shifting condition on the simple shifting condition, inhibition composite, and WM processes. Additionally, because this sample included both young and old adults, regression analyses also included age as a predictor (unless otherwise indicated), as well as the interactions between the age, inhibition, and WM variables. Overall, these regressions allowed the examination of whether inhibition and WM contribute to various aspects of shifting, as a function of age. Regression results are shown in Table 6.4.

**Global switch costs.** Global shifting is measured as the difference between mixed and pure task blocks, and is considered a measure of the ability to coordinate, update, and select and single tasks among multiple in working memory (WM; Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001). Given that global switch costs measure the ability to successfully maintain and manipulate multiple task sets in WM, I also investigated the possibility that WM would make a significant contribution to the prediction of global switch costs. To address the contributions of these variables to global shifting, I regressed mixed block performance on pure block performance, inhibition, WM, age, age x inhibition, age x WM, and inhibition x age. Of these variables, only pure block performance ($\beta = .64, p < .001$) and the age x WM interaction ($\beta = -.41, p = .02$; see Table 6.4) made significant contributions to the prediction of mixed block performance. In contrast, neither age, inhibition, nor any of the remaining interactions
were significant. Additionally, these same predictors remained significant when the non-significant interactions were excluded from the regression analysis (Table 6.5).

To get a sense of the form of the significant age x WM interaction, I used the simpler regression model (excluding non-significant interactions, as shown in Table 6.5) and plugged in values for the predictors. The WM value was varied as 1 (reflecting good WM) and -1 (reflecting poor WM); similarly, age was varied as 21 (the mean age for young adults) and 71 (the mean age for old adults). To get realistic values for predicted mixed block performance, I inserted the mean for each age group on the inhibition composite and on pure block performance. Using these values in the regression equation allows for a visualization of how the varying levels of WM (good, poor) affect global shifting for the two age groups. As can be seen in Figure 6.2 (top), for both age groups, good WM is associated with faster (i.e., better) performance on mixed blocks. This suggests that individuals with better WM capacities perform better on global shifting. This main effect of WM was confirmed in a simpler regression, regressing mixed block performance on pure block performance, age, inhibition, and WM. There were significant main effects of pure block performance ($\beta = .85, p < .001$) and WM ($\beta = -.20, p = .01$), but not age or inhibition. Note that while the WM predictor does not receive a significant weight in the equation shown in Table 6.5 when the age x WM interaction is included, the values for the individual predictors going into the interaction are uninterpretable when the interaction term is included (Aiken & West, 1991; Dallal, n.d.).

The interaction, on the other hand, can be explained by the fact that WM decreases are more detrimental for older adults; older adults with poor WM (relative to good WM) demonstrate a greater slowing in mixed block log RTs, relative to young
adults with poor WM. This indicates that decreases in WM span have a larger effect on the global shifting abilities of older adults, compared to young adults.

The role for WM is in line with previous descriptions of global switch costs (Kray & Lindenberger, 2000; Mayr, 2001), which propose an important role for maintaining and coordinating multiple tasks. Those who are better able to manipulate multiple tasks in WM respond more quickly on mixed blocks. The benefit can likely be attributed to the level of task uncertainty in mixed blocks, resulting in the need to keep multiple tasks in an activated state.

Table 6.4. Regression results for the prediction of shifting variables from age (where relevant) inhibitory control, working memory measures, and the interactions among these variables. Asterisks indicate significant predictors ($p < .05$); asterisks within parentheses indicate marginally significant predictors ($p < .10$).

<table>
<thead>
<tr>
<th>Global costs: Mixed block</th>
<th>$B$</th>
<th>$SE$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure block</td>
<td>0.85</td>
<td>0.10</td>
<td>.64*</td>
</tr>
<tr>
<td>Age</td>
<td>0.000</td>
<td>0.001</td>
<td>-.03</td>
</tr>
<tr>
<td>Inhibition factor</td>
<td>-0.03</td>
<td>0.06</td>
<td>-.08</td>
</tr>
<tr>
<td>Working memory</td>
<td>0.02</td>
<td>0.03</td>
<td>.10</td>
</tr>
<tr>
<td>Age x inhibition</td>
<td>0.002</td>
<td>0.001</td>
<td>.21</td>
</tr>
<tr>
<td>Age x WM</td>
<td>-0.001</td>
<td>0.001</td>
<td>-.41*</td>
</tr>
<tr>
<td>Inhibition x WM</td>
<td>-0.008</td>
<td>0.04</td>
<td>-.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Backward inhibition: N-2 repeat trials</th>
<th>$B$</th>
<th>$SE$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-2 switch trials</td>
<td>0.95</td>
<td>0.02</td>
<td>.97*</td>
</tr>
<tr>
<td>Age</td>
<td>0.00</td>
<td>0.000</td>
<td>.02</td>
</tr>
<tr>
<td>Inhibition factor</td>
<td>0.04</td>
<td>0.01</td>
<td>.09*</td>
</tr>
<tr>
<td>Working memory</td>
<td>0.01</td>
<td>0.006</td>
<td>.06(*)</td>
</tr>
<tr>
<td>Age x inhibition</td>
<td>-0.001</td>
<td>0.000</td>
<td>-.09*</td>
</tr>
<tr>
<td>Age x WM</td>
<td>0.000</td>
<td>0.000</td>
<td>-.07*(*)</td>
</tr>
<tr>
<td>Inhibition x WM</td>
<td>-0.01</td>
<td>0.009</td>
<td>-.03</td>
</tr>
</tbody>
</table>
Local costs: Switch trials (young only)

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE B</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeat trials</td>
<td>0.81</td>
<td>0.06</td>
<td>.83*</td>
</tr>
<tr>
<td>Inhibition factor</td>
<td>-0.02</td>
<td>0.02</td>
<td>-.07</td>
</tr>
<tr>
<td>Working memory</td>
<td>-0.01</td>
<td>0.008</td>
<td>-.08</td>
</tr>
<tr>
<td>Retrieval</td>
<td>-0.007</td>
<td>0.006</td>
<td>-.08</td>
</tr>
<tr>
<td>Inhibition x WM</td>
<td>0.002</td>
<td>0.02</td>
<td>.008</td>
</tr>
<tr>
<td>Inhibition x retrieval</td>
<td>0.002</td>
<td>0.02</td>
<td>.006</td>
</tr>
<tr>
<td>WM x retrieval</td>
<td>0.009</td>
<td>0.008</td>
<td>.09</td>
</tr>
</tbody>
</table>

Table 6.5. Regression results for the prediction of shifting variables using simplified regression models. Asterisks indicate significant predictors ($p < .05$); asterisks within parentheses indicate marginally significant predictors ($p < .10$).

Global costs: Mixed block

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE B</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure block</td>
<td>0.82</td>
<td>0.10</td>
<td>.62*</td>
</tr>
<tr>
<td>Age</td>
<td>0.000</td>
<td>0.001</td>
<td>-.06</td>
</tr>
<tr>
<td>Inhibition factor</td>
<td>0.03</td>
<td>0.02</td>
<td>.07</td>
</tr>
<tr>
<td>WM</td>
<td>0.008</td>
<td>0.02</td>
<td>.05</td>
</tr>
<tr>
<td>Age x WM</td>
<td>-0.001</td>
<td>0.001</td>
<td>-.35*</td>
</tr>
</tbody>
</table>

Backward inhibition: N-2 repeat trials

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE B</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-2 switch trials</td>
<td>0.96</td>
<td>0.02</td>
<td>.97*</td>
</tr>
<tr>
<td>Age</td>
<td>0.000</td>
<td>0.000</td>
<td>.04</td>
</tr>
<tr>
<td>Inhibition factor</td>
<td>0.02</td>
<td>0.01</td>
<td>.06*</td>
</tr>
<tr>
<td>WM</td>
<td>0.001</td>
<td>0.003</td>
<td>.005</td>
</tr>
<tr>
<td>Age x inhibition</td>
<td>0.000</td>
<td>0.000</td>
<td>-.06*</td>
</tr>
</tbody>
</table>

Local costs: Switch trials (young only)

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE B</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeat trials</td>
<td>0.80</td>
<td>0.06</td>
<td>.82*</td>
</tr>
<tr>
<td>Inhibition factor</td>
<td>-0.02</td>
<td>0.01</td>
<td>-.06</td>
</tr>
<tr>
<td>WM</td>
<td>-0.01</td>
<td>0.007</td>
<td>-.11(*)</td>
</tr>
<tr>
<td>Retrieval</td>
<td>-0.002</td>
<td>0.005</td>
<td>-.03</td>
</tr>
</tbody>
</table>

N-2 repetition costs. N-2 repetition costs, also referred to as backward inhibition, reflect the degree to which previously relevant tasks are inhibited when deemed no longer
relevant. While researchers have taken N-2 repetition costs as a measure of inhibition in shifting, no work has looked at whether this type of inhibition reflects other inhibitory mechanisms, or WM mechanisms more generally. To address these questions for N-2 repetition costs, I regressed N-2 repeat trial performance on switch trial performance, inhibition, WM, age, age x inhibition, age x WM, and inhibition x age. Of these variables, only N-2 switch trial performance ($\beta = .97, p < .001$), inhibition ($\beta = .09, p = .01$), and the age x inhibition interaction ($\beta = -.09, p = .03$) made significant contributions to the prediction of N-2 repeat trial performance (Table 6.4). In contrast, none of the other variables were significant. Additionally, these same predictors remained significant when the non-significant interactions were excluded from the regression analysis (Table 6.5).

Although the inhibition predictor received a significant weight in the equation shown in Table 6.5 when the inhibition x age interaction term is included, the values for the individual predictors going into the interaction are uninterpretable when the interaction term is included (Aiken & West, 1991; Dallal, n.d.). When the interaction term is not included in the regression equation, there is a main effect of N-2 switch trial performance ($\beta = .97, p < .001$) and age ($\beta = .05, p = .009$), but the effect of inhibition is non-significant ($\beta = .02, p = .14$).

To understand the significant age x inhibition predictor, I again plugged in values for the predictors into the simpler regression model shown in Table 6.5. Inhibition was varied as 1 (reflecting good inhibition) and -1 (reflecting poor inhibition), and age was varied as 21 (young) and 71 (old). The predictor values of the other variables (pure block performance, WM) were fixed with each age group’s mean. As discussed above,
plugging these values into the regression equation provides predicted values that allows for a visualization of how varying levels of inhibition (good, poor) affect N-2 repeat trial performance as a function of age. As can be seen in Figure 6.2 (bottom), for both age groups, better performance was associated with good rather than poor inhibition abilities, though the difference was larger for the older subjects. That is, for young adults, inhibitory ability had little effect on N-2 repeat trial performance, whereas individual differences in inhibitory ability did effect older adults. Interestingly, this is the opposite direction than predicted by Mayr (2001), who hypothesized that older adults – presumably with poorer inhibition – would be faster on N-2 repetition trials (i.e., the ABA sequence) because poorer inhibition of the first instance of task A on trial N-2 would make this task easier to retrieve when it again becomes relevant, on trial N. This point will be further discussed in the General Discussion.

**Local switch costs.** Local shifting is measured by comparing performance between switch and repeat trials, within the mixed block. In previous work, Friedman and Miyake (2004) found response-distractor inhibition contributed to the prediction of local switch costs. The authors argued that switch trials require one to establish a new task set and in doing so, one must also establish what stimulus features to focus on (which in the present study, could be number, shape, or size). Filtering out irrelevant stimulus features is the key mechanism thought to be involved in response-distractor inhibition. However, switch trials also reflect the need to change task set (whereas this is not necessary on repeat trials), and as a result local costs are thought to measure the ability to retrieve and implement a new task at the point of a task switch. Given this, I also included a measure of retrieval reflecting the ability to retrieve memory representations into the focus of
attention (the Sternberg recognition task). This allowed me to examine the possibility that retrieval would make a significant contribution to local shifting. For local costs, then, switch trial performance was regressed on repeat trial performance, inhibition, WM, retrieval, inhibition x WM, inhibition x retrieval, and WM x retrieval; age was not included, as only a subset of young adults were analyzed.³

In the full model (Table 6.4), only repeat trial performance contributed to the prediction of switch trial performance ($\beta = .83, p < .001$). None of the other variables, nor the interactions among them, approached significance (all $p$s > .20). Because the non-significant interactions render uninterpretable the weights of the individual predictors going into the interaction (Aiken & West, 1991; Dallal, n.d.), I ran a simplified model including inhibition, WM, and retrieval – but excluding the interactions (Table 6.5). In addition to repeat trial performance ($\beta = .82, p < .001$), the contribution of the WM composite was marginal ($\beta = -.11, p = .06$). In contrast, neither the inhibition composite nor the retrieval measure significantly contributed to the prediction of local shifting. In contrast to some theories of local switch costs, which maintain that local costs result from the persistence of no-longer relevant task sets (Allport et al., 1994; see also Friedman & Miyake, 2004), the data from the present study failed to support a role for inhibition in local shifting. Additionally, these results fail to provide evidence for a role for retrieval in local shifting; however, the retrieval results should be interpreted with caution. These regressions included only a single retrieval measure, whereas the inhibition and WM composites were both measured by multiple tasks.

**Summary.** In sum, the present results suggest that various factors contribute to

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³ As discussed in the Method chapter (Chapter 3), only a subset of young adults ($N = 93$) completed this task because it was only administered if time permitted.
different aspects of task switching. I initially set out to investigate the contribution of multiple inhibitory control mechanisms to various measures of task switching. However, the present data suggest that these inhibition tasks are best represented by a single “inhibition” factor, and that individual differences in this inhibition factor make significant contributions to only one aspect of task switching, backward inhibition. In contrast, general WM capacity contributed to the other two aspects of task switching, including both global and local switch costs (though this later effect was only marginal). These findings will be further discussed below.

**General Discussion**

The present study had two goals. First, aspects of inhibitory cognitive control have oftentimes been discussed under the blanket term of “inhibition”, though response-distractor inhibition and resistance to proactive interference do not necessarily represent the same construct (e.g., Chapter 4; Friedman & Miyake, 2004). A question addressed here was whether previous psychometric distinctions between inhibitory processes could be replicated. Results of the present study suggest that this is not the case, as a two-factor model did not provide the best fit to the data, when controlling for processing speed in response-distractor inhibition tasks. Additionally, one of the supposed response-distractor inhibition tasks loaded significantly with the three resistance to PI tasks, raising questions as to what this individual “inhibition” factor actually measures, a point which is discussed below.

Second, given that some theories propose a critical role for interference resolution in task switching, I asked whether various measures of shifting could be predicted from the measure of inhibitory control obtained herein. The goal was to better understand the
role for aspects of executive control and working memory processes in measures of task
switching. The results showed that inhibition only contributed to a single aspect of task
switching (backward inhibition), with working memory capacity playing a larger role in
predicting other aspects of task switching.

**The Unity of Inhibitory Control Tasks**

In their seminal study designed to understand the organization of central executive processes, Miyake and colleagues (2000) found that the executive control processes of inhibition, updating, and shifting were both unitary and diverse in nature. In other words, Miyake et al. found evidence that these processes were distinct, in that tasks designed to measure individual aspects of executive control loaded on their appropriate latent variables; this suggests that these control processes likely measure processes distinct to each function (cf., Nee et al., 2012). Importantly, however, these executive control processes also showed some degree of unity insofar as there were moderate correlations between the three latent variables. Such unity raises the possibility that the executive functions share an underlying mechanism. The above point is highly relevant to the first goal of this study, designed to investigate whether inhibitory control processes are best represented by a one- or two-factor model of inhibition. Inconsistent with the findings of Friedman and Miyake (2004), a two-factor model did not provide the best fit of the data. Instead, only a subset of the interference resolution tasks loaded on the inhibition variable, suggesting inhibitory unity – that there is an underlying mechanism(s) that is common to these tasks. What might this unitary mechanism be?

One possibility is that this common mechanism is the need for goal maintenance. For example, controlled attention accounts of working memory (e.g., Kane, Bleckley,
Conway, & Engle, 2001; Kane & Engle, 2000; Kane & Engle, 2002; see also Hasher & Zacks, 1988 and Munakata et al., 2011, for a similar view) maintain that WM capacity is determined by the ability to keep goal-relevant information active in order to maintain internal representations and avoid distraction/interference (see Friedman & Miyake, 2004, for a similar discussion). However, the goal maintenance hypothesis has difficulty accounting for the pattern of factor loadings found herein. Specifically, it is difficult to imagine no role for goal maintenance in the nonverbal Strop and picture-word interference tasks. Both would likely require maintaining the task goal in the face of interference. In other words, the goal maintenance account does not as easily accommodate inhibitory diversity. When controlling for processing speed, only a subset of tasks load on the inhibition factor. In addition, inhibitory control processes do show evidence of dissociations in healthy aging, as older adults show relatively selective impairments on resistance to PI (but not response-distractor inhibition) tasks (e.g., Chapter 4).

Recent executive control accounts provide a nice reconciliation of the patterns of task loadings found in the present study. Nee and colleagues (2012) proposed that executive processes may be best described as selection mechanisms acting on specific types of content (e.g., identity vs. location information), as opposed to being described by the functions they perform (e.g., response-distractor inhibition, resistance to PI, etc.). Evidence for this account, as well as the corresponding theory (Dual Selection ++), comes from a meta-analysis of neuroimaging research in which the authors found that executive tasks acting on the same type of content consistently activated distinct cortical regions. In contrast, there was much less evidence that tasks tapping the same executive
function activated consistent cortical areas. Nee et al., therefore, suggest that executive control processes may be organized similar to the ventral/what-dorsal/where stream distinction in posterior cortices (Mishkin & Ungerleider, 1982). Under this account, executive processes are best represented by two selection mechanisms which serve to select information based either on a) its identity, corresponding to the “what” stream (e.g., identity, verbal/meaning) or b) its location, corresponding to the “where” stream (e.g., spatial location). These distinct selection mechanisms are thought to provide top-down biasing to their respective posterior processing streams, essentially assigning attentional priority to representations that warrant further processing as a function of goal-relevance. And, in addition to the dual selection mechanisms just described, Nee and colleagues’ Dual Selection ++ model of executive control also includes additional mechanisms for the maintenance of context/rules and goals (the ++ of ‘Dual Selection ++’), thought to reside in more anterior prefrontal regions.

So how does the Dual Selection ++ model fit into the above discussion of inhibitory processing? Remember that response-distractor inhibition measures the ability to resist interference from information that is currently present in the environment. According to the Dual Selection ++ model, response-distractor inhibition tasks may tend to rely on selective spatial attention – that is, top-down biasing to spatial location, enabling one to quickly and selectively process information in the presence of other concurrent, contextual distractors. In contrast, resistance to PI measures the ability to resist memory intrusions from information that was previously – but is no longer – relevant. This inhibitory control mechanism is typically measured by verbal/memory tasks, and may therefore rely much more heavily on the selection of identity information.
In line with this account, Munakata and colleagues (2011) have also recently suggested that inhibition can be best understood as a prefrontal biasing mechanism (see also Friedman et al., 2008; Miller & Cohen, 2001).

From a theoretical standpoint, there are other ways in which response-distractor inhibition and resistance to PI differ. For example, response-distractor inhibition and resistance to PI may differ to the extent that they rely on goal maintenance versus other working memory mechanisms. In response-distractor inhibition tasks, goal maintenance may play a stronger role in guiding selection mechanisms in the face of interference from irrelevant information (Friedman & Miyake, 2004; Unsworth & Engle, 2007). In contrast, goal maintenance may not be the most-demanded resource for recall or recognition tasks. Instead, resistance to PI may rely more heavily on binding mechanisms that allow for successful retrieval (e.g., Unsworth & Engle, 2007; Oberauer, 2005). In recall tasks, binding mechanisms enable memory items to be distinguished from one another via the binding of to-be-remembered information to its context, such as other list items, serial position, or the list it was in. Such bindings play an important role in recall, especially when multiple items interfere across list contexts (as with the resistance to PI tasks used here); during retrieval (or identity selection, according to the Dual Selection ++ account of Nee et al., 2012), binding mechanisms would function to enable item discrimination based on context.

Why, then, does the Stoop load with these identity selection/binding tasks? The answer to this question may lie in the role for binding, with binding providing a possible mechanism uniting the manifest variables. Specifically, all of tasks that load on the inhibition factor may rely on binding mechanisms. While the role for binding in PI tasks
was discussed above, the role for binding mechanisms in the Stroop task needs to be further elaborated. Specifically, Stroop targets and distractors overlap in space, making spatial selection mechanisms ineffective. As a result, identity selection must be used on this task. Beyond selection mechanisms, however, the Stroop task may also involve binding mechanisms that function to create a strong association between the task goal and stimulus attributes (Kimberg & Farah, 1993). When these bindings are weak, subjects are less able to select the relevant identity information, given the co-activation of the target color and distractor color word in incongruent trials. Supporting the notion that the Stroop task involves similar binding mechanisms as resistance to PI tasks, Kimberg and Farah (1993) successfully modeled various frontal/executive deficits using a reduction in the association among elements in working memory. And critically, damage to this single binding mechanism was able to account for impaired performance on the Stroop task as well as a memory for context task.

One strength of the above account is that it can also accommodate dissociations in aging. As discussed above, recent evidence has suggested that older adults show exaggerated interference in resistance to PI tasks, whereas consistent impairments on response-distractor inhibition tasks are not evident (Chapter 4; see also Verhaeghen & Cerella, 2002). However, as found in Chapter 4, older adults did show impairments on the Stroop task. Accordingly, it may be that selection mechanisms show little to no deterioration with age (e.g., Persson et al., 2004), but that older adults show impairments in binding mechanisms. In fact, Oberauer (2005; see also Hedden & Park, 2003 for a similar account) suggested that age effects in PI tasks may be better interpreted as binding deficits, as opposed to inhibition deficits (see also Chalfonte & Johnson, 1996;
Dennis et al., 2008; Howard, Kahana, & Wingfield 2006; Johnson, Hashtroudi, & Lindsay, 1993; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000). Specifically, Oberauer found that older adults showed impaired performance on recognition tasks that required resistance to PI and content-context binding, but also on tasks that required only binding. As discussed above, binding may play a minimal role in response-distractor inhibition tasks whose stimuli allow for the use of spatial selection mechanisms, versus a more critical role in tasks that necessitate a strong association between content and context.

This hypothesis makes the clear prediction that older adults should not show deficits in identity selection tasks that do not require binding mechanisms. Consistent with this prediction, older adults did not show impaired performance on a verb generation task, in which subjects are presented with a noun and are asked to produce an associated verb. The critical contrast is between high selection nouns, which have many associated verbs (e.g., map: open, close, read, draw, etc.; example from Martin & Cheng, 2006), and low selection conditions (scissors: cut; example from Kan & Thompson-Schill, 2004) in which a single verb is highly associated with the target noun. Behaviorally, Persson et al. found that older adults showed no performance differences from young adults (though older adults did differ in patterns of neural recruitment). Clearly further work is required to test this account. However, this account suggests that intact selection mechanisms enable appropriate and correct retrieval of relevant information under some conditions, whereas failed binding mechanisms increase the likelihood that this retrieval mechanism will fail when there is a need to distinguish between relevant and irrelevant information in memory, thus resulting in exaggerated PI.
An additional question concerns the role for inhibition in “inhibition tasks”; that is, do selection/biasing-type accounts (Munakata et al., 2011; Nee et al., 2012) mean inhibition-type tasks do not use inhibitory functions – only selective attention? Not necessarily. Munakata and colleagues (see also Desimone & Duncan, 1995; Miller & Cohen, 2001) suggest that while prefrontal regions do provide top-down biasing, functioning to enhance the activation of goal-relevant representations in posterior cortices, such biased activation results in indirect competition between representations. According to these types of accounts, the activation of task-relevant representations results in lateral inhibition of competing representations to facilitate selection. Thus, it is possible for “inhibition” tasks to still involve inhibition – though according to these sorts of accounts, inhibition is simply a by-product of selective attention (cf. Munakata et al.’s (2011) account of ‘directed global inhibition’ for an discussion of other aspects of inhibition).

In summary, the first goal of this study was to investigate whether inhibition can be best represented by multiple inhibition constructs, as suggested by Friedman and Miyake (2004). The present study failed to replicate their results, as a single factor model provided the best fit to the data. To summarize the above, I have suggested that all of the so-called inhibitory control tasks involve selective attention mechanisms. In addition to this, however, a subset of the tasks also involve binding mechanisms, accounting for the emergence of a one-factor model. Note that this interpretation does not rely on executively controlled/frontally mediated inhibition mechanisms. Instead, this interpretation banks on frameworks that suggest a top-down, frontal biasing or selection mechanism acting on posterior regions, reducing the notion of executively controlled
inhibition to selection mechanisms that result in automatic, lateral inhibition (e.g., Munakata et al., 2011).

The Role for Control Processes in Shifting

The initial goal was to investigate the role for inhibitory control mechanisms in shifting, given that theories of task switching propose a critical role for interference resolution in switching between tasks. Under such theories, it makes sense to ask whether different types of inhibitory control mechanisms make different contributions to measures of task switching. However, as just discussed, there was little support for multiple inhibitory control mechanisms in the present study (cf. Chapter 4; Friedman & Miyake, 2004). Because only one factor was obtained, regression analyses were used to assess the relationship of the single inhibitory control factor and WM measures with global shifting, N-2 repetition effects, and local shifting. Each shifting measure will be discussed below.

Role for working memory mechanisms in shifting. In task switching paradigms, switch costs are only found when the stimuli are bivalent and therefore elicit multiple possible tasks (Jersild, 1927; Spector & Biederman, 1976). For example, switching between producing an antonym of a word and subtracting three from a number results in no switch costs, whereas switching between adding and subtracting three from a list of numbers does result in switch costs. Switch costs, then, are only found when both tasks are performed on the same set of stimuli. As a result, switch costs depend, at least in part, on overlapping task features, which have the potential to result in task uncertainty and task set interference. Given this, researchers have proposed that individuals adopt task sets, which are “mental representations that enable the person to act in accordance to task requirements” (Kiesel et al., 2010). Such task sets are thought to consist of an
association or binding between multiple internal control templates, including the task goal and possible task-relevant responses as well as their corresponding stimulus-response (S-R) mappings. Critically, task sets should be instantiated at trial onset, maintained through the trial, and changed or updated whenever a new task becomes relevant; at the point of a task switch, task sets must be retrieved or reconfigured.

In particular, an influential theory of task switching has proposed that switch costs are at least in part determined by proactive interference from the irrelevant task set(s) (Allport et al., 1994). The logic of this theory maintains that when a task is to be performed on trial N-1, one activates a task set, allowing attention to be focused on specific stimulus features and the response to be made. When a switch in tasks is required, this now-irrelevant task set must be removed from attentional focus so the newly-relevant task set can be retrieved and take center stage. However, while the now-irrelevant task may be removed from attentional focus, it is still maintained in an above-baseline state, as it is likely to become relevant again within a short period; as a result, some aspects of the now-irrelevant task’s activation persists, and this persistence results in proactive interference (e.g., Allport et al., 1994), which is resolved via backward inhibition (e.g., Mayr, 2001; Mayr & Keele, 2000). This inhibitory process acts to delete the now-irrelevant task representations from attentional focus, enabling the instantiation of the newly-relevant task. However, this applied inhibition persists over time, making subjects slower to retrieve this task set when it again becomes relevant.

The findings from the present work were inconsistent with this interference resolution theory, as the single inhibition factor failed to make a significant contribution to the prediction of global or local switch costs. This point will be further discussed
below. However, the present findings are consistent with the notion that aspects of working memory contribute to global and local task switching. Instead of interference resolution, working memory capacity made either significant and marginal contributions to global and local switch costs (respectively).

As discussed previously, global shifting is measured as the performance difference between mixed and pure blocks. In mixed blocks, multiple tasks need to be maintained in an accessible state, as tasks change often. This is in marked contrast to pure task blocks, throughout which only a single task is relevant. Relative to pure blocks, mixed blocks require “sustained processes, responsible for maintaining [multiple] tasks in working memory, and updating and maintaining activation of the currently relevant task set” (p. 253, Koch, Prinz, & Allport, 2005). Consistent with this notion, it was found that global shifting was best predicted by an age x working memory interaction, reflecting individual differences in working memory capacity. WM made a negative contribution to global shifting – those with larger WM capacities demonstrated reduced global shift costs, which implies more efficient (i.e., faster) global shifting. This is consistent with views of WM which posit that working memory capacity reflects “attentional processes that allow for goal-directed behavior by maintaining relevant information in an active, easily accessible state outside of conscious focus” (Kane et al., 2007, p. 23). In order to easily switch between tasks, one must keep multiple task sets in an activated, easily accessible state – a function performed by WM, and measured by working memory capacity.

Interestingly, the contribution of WM capacity to global switch costs interacted with age, insofar as decreases in WM capacity had a greater effect on the global shifting
abilities of older adults, relative to young adults. This finding is consistent with Mayr’s (2001) proposal that older adults have difficulty “in establishing and maintaining the relevant set” (p. 100). The present results suggest that this difficulty for older adults may be at least in part a function of WM capacity; lower capacity older adults have greater difficulty in maintaining multiple task sets in WM, relative to higher capacity older adults.

Additionally, several models of WM pose a critical role for binding in determining working memory capacity (e.g., Oberauer, 2005; Oberauer et al., 2003, 2008; Unsworth & Engle, 2007), raising the possibility that the relationship between global costs and WM reflects the ability to bind task information into coherent task sets. Mayr (2001) has suggested that a critical component of managing multiple tasks in WM is the ability to keep task sets separate from each other by having coherently bound task representations (i.e., task sets). While the present study cannot distinguish between a storage capacity vs. binding account, Oberauer and colleagues (2003) have suggested that these processes are closely related. Thus, global costs may reflect both. Interestingly, such a hypothesis is also consistent with the significant age x WM interaction predictor for global costs, as age differences in binding mechanisms (e.g., Howard, Kahana, & Wingfield, 2006; Mitchell, Johnson, Raye, Mather, & D’Esposito, 2000; Oberauer, 2005) could also contribute to global shifting performance. However, again, the present study cannot distinguish between capacity and binding accounts.

It was surprising to find that working memory capacity also made a significant contribution to the prediction of local switch costs, whereas the inhibition factor and retrieval measure played insubstantial roles. This was surprising because theories of local
shifting propose that switch trials reflect the need to retrieve and update the focus of attention with the newly relevant task set (e.g., Mayr & Kliegl, 2000), and in addition, such processes are likely interference-prone (e.g., Allport et al., 1994; discussed next). Thus, a role for retrieval would have been consistent with such theories. However, the lack of a role for retrieval can be interpreted within other theories of local switch costs that propose that retrieval mechanisms are equally involved on both switch and repeat trials (e.g., Altmann & Gray, 2008; Schuch & Koch, 2003, 2005; Mayr & Kliegl, 2000, 2003). While retrieval may be more difficult or time consuming on switch trials because of the additional need to update WM with a new task set, the use of retrieval on repeat trials would not predict to independent contribution of retrieval mechanisms to switch trials (i.e., independent of repeat trials). Nonetheless, given the present study only included a single measure of retrieval, future work should investigate whether a retrieval composite would do a better job at predicting switch trial performance.

It was also surprising to find no significant independent contribution of interference resolution to prediction of local shifting, given that some accounts propose a critical role for interference resolution in shifting (e.g., Allport et al., 1994). More specifically, it seems reasonable to assume that the requirement to sustain the activation of and retrieve multiple task sets would increase the likelihood of interference, especially given that task sets overlap with each other (e.g., targets elicit features of each task, stimulus-response mappings overlap, etc.). However, it might be the case that interference resolution did not make a significant contribution to the prediction of shifting measures because of the task design used in this shifting paradigm. In the present experiment, relevant tasks were explicitly cued by a word. Emerson and Miyake (2003)
have argued that explicit cues directly identify the task to be performed (e.g., the word “Shape” to indicate that subjects should respond to the shape of the stimulus), and therefore automatically trigger the relevant task set and allow it to be established in WM. This is in contrast to what occurs for implicit cues (e.g., the symbols “%%%%” to indicate the shape task) that only identify the task through a learned association of the cue with the task, and are therefore only indirectly associated with a meaningful verbal label (i.e., the task label “Shape”; Logan & Schneider, 2006) that would be retrieved when the cue is presented. In the present work, the use of such an explicit cue may have enabled the relevant task set to receive a boost in activation, thus facilitating the retrieval of that task set into the focus of attention. As a result of this facilitated retrieval, competition between task sets during retrieval may have been reduced. Such a hypothesis raises the possibility that both interference resolution and retrieval would play a greater role in shifting under less explicitly cued contexts – such as those using implicit cues or requiring that subjects use their memory resources to keep track of the relevant task (e.g., remembering to shift on every fourth trial).

Instead, I found that the WM composite made a marginal contribution to the prediction of local shifting. While not explicitly consistent with the retrieval and interference hypotheses discussed above, it is in line with the idea that switch trials require that WM be updated with the just retrieved, newly relevant task set – whereas repeat trials involve task set repetition and therefore less (or no) role for updating. Consistent with this hypothesis, a meta-analysis of neuroimaging studies found overlapping inferior frontal junction activation in both local shifting and the Stroop task, and as a result, Derfuss et al. suggested that this region plays an important role in
updating task representations in the face of interference. Additionally, such a role for the executive process of updating is consistent with Oberauer et al.’s (2003) model of working memory, which proposes that “supervision” (along with storage in the context of processing and binding) is a distinct working memory function. Although Oberauer and colleagues opted to measure supervision as shifting in their 2003 study, they maintain that the executive functions of updating and inhibition identified by Miyake and colleagues (2000) also serve similar supervisory roles. In line with the role for such supervision processes in measures of working memory, Miyake et al. found that updating (but not inhibition or shifting) provided a significant path for predicting performance on the operation span – one of the WM tasks used herein. Thus, while slightly different from the interpretation discussed for global costs, the contribution of WM to local costs may reflect the ability to update the contents of WM at the point of a task switch. Consistent with this, Miyake and colleagues found a significant correlation ($r = .56$) between their updating and shifting latent variables, suggesting commonality between these supervision mechanisms. Additionally, while speculative, the notion that global and local switch costs reflect different aspects of working memory is consistent with research suggesting that these costs reflect distinct executive control measures (e.g., Kray & Lindenberger, 2000; Mayr, 2001), though future work should include more process pure measures of these aspects of WM processes in order to explicitly test the above accounts.

**Inhibition in task switching.** Authors have taken N-2 inhibition costs – or backward inhibition – as evidence that inhibition is applied to previously relevant task sets (e.g., Mayr & Keele, 2000). And, while N-2 repetition costs have been replicated across a variety of shifting paradigms (e.g., Gade & Koch, 2005, 2007; Schuch & Koch,
2003; Schneider & Verbruggen, 2008), little work has investigated whether N-2 repetition costs reflect a specific type of behavioral inhibition. Interestingly, the results of the present study suggest that N-2 repetition costs are related to individual differences in interference resolution as a function of age, as measured by the inhibition composite derived from the confirmatory factor analysis in the first part of this study. More specifically, backward inhibition was best predicted by an age x inhibition interaction. I will first discuss inhibition and age alone, followed by the age x inhibition interaction.

As discussed above, while it appears that individuals with better inhibition performed better on N-2 trials than did those with poor inhibition abilities, the main effect of inhibition was not significant. In contrast, the main effect of age was significant, with older adults demonstrating significantly slower performance on N-2 repetition trials, relative to young adults. This finding is in contrast to the original predictions of Mayr (2001), who hypothesized that individuals with poor inhibition (e.g., older adults) would show a smaller N-2 repetition costs. Mayr’s logic was that poorer inhibition of task A in the ABA sequence would make this task easier to retrieve when it again became relevant on trial N, resulting in faster RTs. To account for older adults’ dissociations between inhibitory deficits in some domains (e.g., Chapter 4; Hasher & Zacks, 1988), but not backward inhibition, Mayr proposed that “backward inhibition during sequential selection of mental sets is functionally dissociated from inhibition that is used to keep task-irrelevant information from interfering with task-appropriate settings” (p. 100), with the later type of inhibition being that which older adults show age-related deficits. However, the significant age x inhibition interaction questions this conclusion: the age x inhibition interaction in the context of a main effect of age suggests that individual
differences in inhibition have a larger effect on the backward inhibition of older adults, compared to young adults. While this finding does not establish that older adults are overall worse at inhibition than younger adults, it does show that relative inhibition ability plays a greater role in their performance than it does for younger adults, and that these two inhibitory mechanisms are not necessarily dissociable.

One possible explanation for these results is that everyone (regardless of individual differences in inhibition) inhibits previously relevant tasks to some degree, but what is being measured here is the ability to overcome such inhibition via retrieval – with retrieval abilities being worse for some older adults. That is, even though the previously relevant task inhibited, individual differences in retrieval ability could compensate for what would have otherwise been slowed reaction times. To test this possibility, I regressed N-2 repeat trial performance on N-2 switch trials, age, inhibition, retrieval, and the interactions between these variables. With all of these factors included in the model, the contribution of N-2 switch trials was significant ($\beta = .97, p < .001$), and the age x inhibition interaction was marginal ($\beta = -.05, p = .07$). When the non-significant interactions were excluded, the age x inhibition interaction remained significant ($\beta = -.06, p = .04$), whereas retrieval never served as a significant predictor. These results question this retrieval explanation, though again, they should be interpreted with caution as retrieval was measured by only a single task (as opposed to a composite).

In contrast, a more likely possibility was raised by the concerns of Anderson and Levy (2007) in their discussion of the costs and benefits of inhibition. They pointed out that while both the N-2 repeat (ABA; the experimental condition) and N-2 switch (CBA; the control condition) trials involve inhibition of task B, the amount of inhibition required
across these two conditions is not equivalent. Because task A was less recently inhibited in the CBA (control) condition, the relative difference in activation between task B and task A is small (Figure 6.3). In contrast, because task A (trial N-2) was more recently inhibited in the ABA (experimental) condition, the relative difference in activation between task A (on trial N) and task B is large (i.e., larger than that of the control condition). Therefore, more inhibition needs to be applied to overcome the activation of task B in the ABA (experimental) condition, relative to the CBA (control) condition. In fact, the present results are consistent with this idea – at least for older adults. Older adults who are better at inhibition show faster performance on N-2 repeat trials, indicating that they can more quickly inhibit task B. Equivalently, older adults with poor inhibition are slowed in the ABA (experimental) condition because they are slower to (or less effectively) inhibit task B. Again, this finding suggests individual differences in inhibition mechanisms play a role in task switching as a function of age, while also providing experimental evidence for the idea raised by Anderson and Levy – that the experimental and control condition are not, in fact, equally matched.

The finding that individual differences in inhibition were related to backward inhibition for older adults is interesting from a theoretical standpoint, as some authors have hypothesized that backward inhibition reflects the suppression of competitors during episodic memory retrieval (e.g., Mayr & Kliegl, 2003, p. 370) or the inhibition of items within WM that should no longer occupy the focus of attention (e.g., Bao, Li, Chen, & Zhang, 2006). For example, May and colleagues (May, Hasher, & Kane, 1999) have hypothesized that the deletion function (functionally similar to backward inhibition) works to delete no longer relevant information from the contents of working memory,
and is important for resisting proactive interference. As a result of this hypothesized function, we might have expected a main effect of inhibition in predicting N-2 repetition costs: those better at inhibition would also be better able to overcome interference from previously relevant tasks (or information in WM). While it is unclear whether individual differences in inhibition only affect the backward inhibition abilities of older adults, this relationship does raise the possibility that inhibitory control (as measured by the inhibition composite) and backward inhibition are somehow related. As suggested by Mayr and Kliegl (2003), “it is tempting to speculate that task-set inhibition and suppression of competitors during episodic memory retrieval may be identical or at least highly related processes” (p. 370).

However, from the present results, one cannot determine whether these inhibitory processes are controlled, or instead reflect a more automatic form of inhibition such as lateral inhibition within local networks (e.g., Hübner, Driesbach, Haider, & Kluwe, 2003; Koch et al., 2010; Mayr & Keele, 2000; Mayr, 2001; Philipp & Koch, 2006; Schuch & Koch, 2003; Vandierendonck, Liefooghe & Verbruggen, 2010; see also Desimone & Duncan, 1995; Miller & Cohen, 2001; Munakata et al., 2011). Such theories propose that inhibition is not under cognitive control, but instead, is a downstream consequence of selective attention mechanisms. Similarly, in task switching, “the idea of lateral inhibition in task switching suggests that task inhibition is a direct byproduct of task activation” (p. 636, Philipp & Koch, 2006). Importantly, such a mechanism is consistent with the account discussed in reference to inhibition, above, in which measures of inhibition reflect by-products of selective attention (Munakata et al., 2011) to spatial locations or identify information in memory (Nee et al., 2012). Thus, selective attention
to any WM item could result in lateral inhibition of competitors. While speculative, a recent study has provided evidence for the role for backward inhibition in switching attention between items within WM (Bao et al., 2006). However, whether backward inhibition is the mechanism used to clear the contents of WM should be further investigated in future work.

Summary

The goal of this work was to gain a better understanding of two aspects of executive control: inhibition and task switching. In doing so, another goal was to develop a clearer picture of the contribution of so-called inhibitory control processes to task switching. To summarize the findings, there was no evidence that the inhibitory control processes of response-distractor inhibition and resistance to proactive interference load on separate latent variables. Instead, only some of these inhibitory control tasks loaded on a single factor. The unity among these inhibitory control mechanisms was explained under the Dual Selection ++ model (Nee et al., 2012), which suggests that these inhibitory control processes involve selection mechanisms that are applied to different types of information (spatial vs. content). However, this is not to say that inhibition tasks do not involve inhibition, because the consequence of the application of such selection mechanisms is likely the automatic (or lateral) inhibition of competing representations (e.g., Munakata et al., 2011). Separate from selection mechanisms, what remained was a single factor model that included tasks for which binding plays a critical role. Thus, some interference resolution mechanisms involve not only selection, but also binding processes.

This inhibitory control mechanism underlying the single factor played little role in
predicting global and local task switching performance, though other aspects of working memory performance predict these measures of shifting. In particular, individuals with larger working memory capacities were better able to manage multiple tasks sets in WM, which benefitted global shifting. Additionally, those who could more efficiently update WM with information from the activated portion of LTM (e.g., Miyake et al., 2000) were also better able to switch from one task to another on switch trials. In contrast, individual differences in inhibition related to backward inhibition; those better able to inhibit previously relevant tasks demonstrated faster performance on N-2 repetition trials, with effect being greater for older adults. In summary, these findings are consistent with the notion that working memory and executive control processes contribute to cognitive stability and flexibility, providing empirical evidence for the contribution of these processes in different measures of shifting.
Chapter 6 Figure Captions

*Figure 6.1.* Confirmatory factor analysis models for inhibitory control mechanisms. The two-factor model is shown on the top, and the single-factor model is shown on the bottom. Significant values ($p < .05$) are indicated in bold. Values next to left pointing arrows indicate factor loadings. Values next to double-headed errors indicate correlations between latent variables. Values next to right pointing arrows indicate residual error variance.

*Figure 6.2.* Graphical depiction of the significant interactions that predict mixed block performance (top) and N-2 repeat trial performance (bottom). The top graph depicts the interaction between age and WM, and its contribution to predicting mixed block performance. The bottom graph depicts the interaction between age and inhibition, and its contribution to predicting performance on N-2 repetition trials.

*Figure 6.3.* Hypothetical activation levels of task sets as a function of condition (control condition CBA, experimental condition ABA), as discussed by Anderson and Levy (2007).
Chapter 7: Inhibition and Shifting:

An Examination of Two Cases with Frontal vs. Non-Frontal Damage

The notion that the frontal lobes play an important role in executive control has a long history in neuropsychological literature, as frontal lobe damage causes disruptions in various aspects of controlled processing. More specifically, as discussed below, a fair amount of evidence has suggested a critical role for frontal regions in aspects of both inhibition and task switching. The association between these two aspects of executive control and their similar localization in frontal regions provides a mechanism by which these two processes may interact. Specifically, given the role for interference resolution in task switching, damage to inhibitory mechanisms may affect performance on both inhibition tasks and shifting tasks. Thus, the present study investigates whether impairments to particular interference resolution mechanisms (response-distractor inhibition, resistance to proactive interference) are associated with impairments in task switching performance.

Localization of Inhibitory Control and Shifting Mechanisms

As discussed in previous chapters, inhibition is not a unitary construct, and may instead be better represented by (at least) two inhibitory control mechanisms: response-distractor inhibition and resistance to proactive interference (PI). In particular, several independent research methods have provided evidence that these two mechanisms are distinct, including individual differences approaches using structural equation analyses (e.g., Friedman & Miyake, 2004), dissociations in healthy aging (Chapter 4), and neuroimaging studies (Jonides & Nee, 2006; Nee, Jonides, & Berman, 2007; Nee, Wager, & Jonides, 2007). As the first of these two distinctions has been discussed in previous
chapters, I will not belabor those points here. However, neuroimaging work has also provided converging evidence on this point, as these two types of inhibition involve different frontal regions. Response-distractor inhibition-type tasks such as the Stroop task tend to activate regions of the left dorsolateral prefrontal cortex (DLPFC) as well as right inferior frontal regions (see Nee et al., 2007, for a meta-analysis). The left DLPFC regions are thought to be involved in the resolution of stimulus conflict, perhaps via selective attention mechanisms, whereas right frontal regions are thought to play a more general role in response selection\(^4\). In contrast, Jonides, Nee, and colleagues (e.g., Jonides & Nee, 2006; Nee, Jonides, & Berman, 2007) have implicated the ventrolateral prefrontal cortex (VLPFC) in the resolution of interference in resistance to PI-type tasks. In particular, Jonides and Nee (2006) proposed that this region is involved in biasing memory representations that match an attentional template.

More recent work by Nee and colleagues (2012) tells a slightly different story in the dissociation between response-distractor inhibition and resistance to PI. Based on the results of a meta-analysis of neuroimaging studies, Nee and colleague propose that executive control (including inhibitory control mechanisms) may be better understood as two selection mechanisms that act according to task goals. More specifically, these two selection mechanisms are distinguished based on the type of information on which they act. While one selection mechanism primarily reflects selective spatial attention, the other primarily reflects the selection of identity information (analogous to the “what”/“where” distinction in posterior processing streams, e.g., Mishkin & Ungerleider, 1982). Nee and

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\(^4\) It is important to note that although Friedman and Miyake (2004) were unable to find a psychometric distinction between response inhibition and distractor inhibition, there is evidence for neural dissociations. Whereas distractor inhibition tends to rely most heavily on left frontal regions, response inhibition (as measured by go/no-go or stop signal paradigms, for example) appears to rely more heavily on right frontal regions (Nee et al., 2007).
colleagues raised the possibility that response-distractor inhibition tasks tend to tap the selection of spatial information, while resistance to PI tasks tend to tap the selection of identity information. However, as with the above inhibition-based distinction between these two mechanisms, Nee and colleagues proposed that both of these selection mechanisms are localized to left frontal regions, again maintaining a critical role for this area in cognitive control.

The role for frontal regions in executive control has relevance to research on patients with aphasia, some of whom have left frontal damage resulting from stroke. In particular, recent work in the Brain and Language Lab has focused on the executive control abilities of aphasic patients with short-term memory (STM) deficits (e.g., Hamilton & Martin, 2005, 2007), and the consequences of such STM deficits on performance on both executive control (Allen, 2010; Allen, Martin, & N. Martin, 2011) and language production and comprehension (Freedman & Martin, 2001; Hanten & Martin, 2001; Martin, 2005; Martin & He, 2004). In addition to their STM deficits, some of these patients also demonstrate impairments in inhibitory control mechanisms (e.g., Allen, Vuong, & Martin, 2010; Hamilton & Martin, 2005, 2007). For example, in one study, Allen et al. (2010) tested three patients with aphasia on measures of inhibitory control, including two response-distractor inhibition tasks and one resistance to PI task. Critically, only the patients whose brain damage included left frontal regions (EV, ML) demonstrated exaggerated interference (relative to controls) across these interference resolution tasks. In contrast, the patient (MB), whose lesion was restricted to posterior brain regions, showed interference effects that did not differ from age-matched controls. Thus, this dissociation between the performance of frontal and posterior patients supports
the notion that left frontal lobes play a critical role in interference resolution.

Interestingly, however, EV and ML’s impaired performance on interference resolution tasks was found on both of the response-distractor inhibition tasks, as well as the single resistance to PI task included in the Allen et al. study. Similarly, in earlier work (Hamilton & Martin, 2005), patient ML was tested a resistance to PI task and three response-distractor inhibition tasks. Interestingly, he showed a deficit on the resistance to PI task as well as one response-distractor inhibition task (Stroop task), but not on the other two response-distractor inhibition tasks (nonverbal Stroop and anti-saccade tasks). That is, ML’s inhibitory control deficit was constrained to tasks that contained verbal stimuli. Such deficits across these different types of inhibitory control tasks fail to support the distinction between response-distractor inhibition and resistance to PI, as the patients included in both of the previous studies have not shown consistent patterns of impairments across tasks tapping a single type of inhibitory control (resistance to PI, response-distractor inhibition). However, both of these previous studies only included one measure of resistance to PI, and therefore one can ask whether these patients would have shown consistent deficits on other resistance to PI tasks, had additional tasks been administered. This question is addressed in the present study, as multiple response-distractor inhibition and resistance to PI tasks were administered to two of the patients initially reported in the Allen et al. (2010) study.

Some task switching mechanisms have also been localized to left frontal regions (e.g., Braver, Reynolds, & Donaldson, 2003; Crone, Wandelken, Donohue, & Bunge, 2006; Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000), including both left (Braver et al., 2003) and bilateral (Dove et al., 2000) prefrontal regions. Similarly, patient
studies have also converged on the idea that left frontal regions are involved in task switching (e.g., Aron, Monsell, Sahakian, & Robbins, 2004; Keele & Rafal, 2000; Mecklinger, von Cramon, Springer, & Matthes-von Cramon, 1999; Rogers et al., 1998; Shallice, Stuss, Picton, Alexander, & Gillingham, 2008), though some have hypothesized an additional role for right frontal inhibitory task switching mechanisms (e.g., Aron et al., 2004; Mayr, Diedrichsen, Ivry & Keele, 2006). In particular, neuropsychological studies suggest that the switching and inhibition components of shifting are dissociable. Left hemisphere patients – and in particular, left lateral frontal patients (Shallice et al., 2008) – have difficulty in endogenously representing the relevant task set (e.g., Aron et al., 2004; Mayr et al., 2006). Task set representation seems to be particularly exaggerated under conditions of task set ambiguity, such as when the stimulus is bivalent, has the potential to activate multiple task sets, and the cue does not explicitly indicate which task is relevant on a given trial (e.g., Rogers et al., 1998). As a result, Rogers and colleagues have suggested that left frontal regions are involved in establishing the relevant task set in the face of interference from other tasks. More specifically, Rogers et al. state that left frontal regions “play an important role in the control of competing task set activity in the context of reconfiguring task set” (p. 837). It is important to note that this conclusion is conceptually similar to the hypothesized role for left frontal regions in interference resolution.

In contrast, the right frontal regions may support the inhibition mechanisms used to suppress inappropriate responses or task sets (Aron et al., 2004; Mayr et al., 2006; Mecklinger et al., 1999). Aside from the possible neural association, what differentiates these two types of inhibition from those discussed above is the need to resolve
interference from an already-prepared representation. In response inhibition, for example, one must deliberately suppress a prepared response, for example, the suppression of a button press when a “no-go” signal is heard in the go/no-go task. Similarly, the inhibition of task sets – or backward inhibition – is thought to involve the inhibition of previously relevant, but not irrelevant, task representations. That is, backward inhibition is thought to be executed when task sets change, functioning to inhibit previously relevant (but now irrelevant) task sets (e.g., Mayr & Keele, 2000). In contrast, resisting proactive interference and response-distractor inhibition both involve the selection of representations in the face of distractors, either in memory or in the external environment (respectively).

For example, Mayr and colleagues (2006) have suggested that right frontal regions support backward inhibition, with the most convincing evidence coming from right frontal patients who showed decreased N-2 repetition costs, as would be predicted of individuals with inhibition deficits (Mayr, 2001; see also Derrfuss, Brass, Neumann, & von Cramon, 2005, for a similar suggestion; cf. Anderson & Levy, 2007). However, the findings across these right frontal patients were not consistent, and other authors have provided alternative interpretations for the role of these right frontal regions, such as overcoming persisting inhibition (Dreher & Berman, 2002) or providing performance monitoring processes in noticing when switches should occur (Shallice et al., 2008).

But, while the interference resolution mechanisms of resistance to PI, response-distractor inhibition, and backward inhibition can be distinguished from each other, several accounts propose a specific commonality among these mechanisms. Specifically, various accounts propose that these inhibitory control mechanisms result from selective
attention to relevant information, resulting in lateral inhibition of competing representations. For example, Nee and colleagues (2012; see also Miller & Cohen, 2001; Munakata et al., 2011) propose that executive processes function through selective attention mechanisms acting on posterior cortices. When a representation is selected for processing, its competitors are inhibited. Thus, although the neuropsychological and neuroimaging literatures provide a possible dissociation between these inhibitory control mechanisms, theoretical accounts posit that similar mechanisms underlie each.

In summary, the work discussed above suggests that left frontal regions may be involved in response-distractor inhibition, resistance to PI, and establishing a task set representation in the face of interference, whereas right frontal regions may be responsible for backward inhibition. Given this, it may be possible to find an association between inhibition and shifting impairments in patients with left frontal damage, though left frontal damage may not affect performance on measures of backward inhibition.

**Study Goals**

In summary, the goals of the present study are twofold. First, given we have access to a patient who has previously shown evidence of an inhibition deficit, is it possible to dissociate the inhibitory control mechanisms of response-distractor inhibition and resistance to PI? Along similar lines, given inhibitory control mechanisms primarily involve left frontal regions, we might expect to see inhibitory deficits present only in the patient with a left frontal – but not left posterior – lesion. Additionally, given the role for interference resolution in task switching – and in particular, a critical role for PI resistance (e.g., Allport, Styles, & Hsieh, 1994) – we predict an association between impaired PI resistance and impaired shifting performance (or equivalently, an association
between intact PI resistance and intact shifting performance). To address these questions, two patients were tested on a number of response-distractor inhibition and resistance to PI, and also on a shifting task. The present study takes a neuropsychological perspective to investigate shifting by assessing patient shifting performance, and how it relates to the presence or lack of inhibition deficits.

**Method**

**Patient Background**

Patients were selected for this study based on their previous performance on inhibition tasks (Allen et al., 2010); as discussed above, patient EV demonstrated exaggerated interference effects across a number of inhibitory control tasks, whereas patient MB’s performance did not significantly differ from age-matched controls.

**Patient EV.** Patient EV is a 55-year-old right-handed female with a left-hemisphere lesion incurred from a CVA in 2000. She completed 16 years of school, receiving her bachelor's degree in Accounting and was employed as a bank manager prior to her stroke. EV has a left frontal lobe lesion, including BA 44 and 45, with some extension into the middle frontal gyrus. Some insular damage is also present. EV's speech is relatively fluent, with some word-finding difficulties.

**Patient MB.** Patient MB is a 64-year-old right-handed male with a left-hemisphere lesion incurred from a CVA in 2004. He completed 13 years of school, and was employed as consultant/business owner both prior to, and on and off several years following his stroke. MB's lesion includes left parietal and superior temporal regions, posterior insula, and small subcortical infarcts of the right posterior lateral parietal lobe. MB's speech is relatively fluent, with a tendency for phonological errors, especially with
increases in word length.

Both patients have been previously diagnosed with aphasia. Patients were tested on various background assessment measures, including single word-picture matching and auditory discrimination to measure speech perception, reading measures from the Psycholinguistic Assessments of Language Processing in Aphasia (PALPA; Kay, Lesser, & Coltheart, 1996), and short-term memory (STM) measures. These data are shown in Table 7.1. In the single picture-word matching task, patients saw a picture and were asked “Is this a ___?” (54 items; shortened version of that used in Martin, Lesch, & Bartha, 1999); patients indicated yes or no as to whether the spoken word matched the presented picture. In the auditory discrimination task, patients heard pairs of stimuli that were the same or different (N. Martin, Schwartz, & Kohen, 2006). Of the 40 items, half of the pairs were words and half were nonwords; non-matching pairs differed by one phoneme (e.g., for nonwords, /mErd/-/mErg/). In the various PALPA tasks (Kay et al., 1996), patients saw a list of words that they were asked to read aloud, one at a time. Lastly, three measures of STM are reported: the word span task (Martin et al., 1999), the category probe task, and the rhyme probe task (both probe tasks, Martin et al., 1994). In the word span task, patients heard lists of one-syllable, three letter words that they were asked to repeat in serial order; testing started at a list length of one-item and continued until recall accuracy dropped below 50%. The category and rhyme probe tasks were designed to measure the short-term retention of semantic and phonological information, respectively. In both probe tasks, patients heard a list of words, followed by a probe word. Testing began at one-item lists and continued until accuracy dropped below 75%. In the category probe task, patients indicated whether the probe word was in the same
category as any of the previous list items. In the rhyme probe task, patients indicated whether the probe word rhymed with any of the previous list items. For all STM measures, spans were calculated via linear interpolation. For the word span task, I estimated the point at which accuracy would be 50%. For the probe tasks, I estimated the point at which accuracy would be 75%.

As shown in Table 7.1, both patients demonstrate good performance on the assessment tasks of speech perception and reading measures. In contrast, both patients show reduced STM capacities. Given intact speech perception and reading abilities, deficits cannot be attributed to these aspects. Additionally, Glosser and Goodglass (1990) have suggested that patients with aphasia can show executive function impairments that are independent of their language disorders. Also, it is important to note that the two patients cannot be easily distinguished based on their performance on these assessment tasks; however, they can be distinguished on their lesion location, as EV’s lesion is restricted to left frontal regions whereas MB’s lesion is restricted to parietal regions (Figure 7.1).

Table 7.1. Patient performance on background assessment tasks including speech perception, reading, and short-term memory. With the exception of the short-term memory task, all values indicate accuracy; short-term memory value is an estimate of memory span. Control means and variability are shown in the right column; unless otherwise indicated, values in parentheses indicate control range.

<table>
<thead>
<tr>
<th>Speech Perception</th>
<th>Patient EV</th>
<th>Patient MB</th>
<th>Controls a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Picture-word matching</td>
<td>95%</td>
<td>98%</td>
<td>-</td>
</tr>
</tbody>
</table>
Auditory discrimination 100% 100% 94.8%

**(Reading (PALPA))**

30: Syllable length reading 100% 92% 98.9%

31: Imageability & frequency reading 86% 91% 99.3%

32: Grammatical class reading 96% 91% 99.7%

**Short-Term Memory**

Word span 3.0 2.6 4.8

Category probe span 1.8 2.45 5.4

Rhyme probe span 3.34 5.0 7.0

*Unless otherwise indicated, control data are from the reference cited with the task description. Martin et al. (1999) did not administer the picture-word matching task to controls, as they assumed controls would obtain perfect accuracy. Word span control data is from Freeman and Martin (2001). For PALPA measures, standard deviations are estimates; they were calculated by averaging the standard deviations across stimuli types within each test.*

Another concern might stem from the implications of STM impairments for performance on executive control tasks. For example, Allen and colleagues (Allen & Martin, in preparation; Allen, Martin, & N. Martin, 2011) have suggested a critical role for STM resources in supporting some aspects of executive control. This role for STM resources includes a contribution to shifting performance, but only with the use of symbolic (i.e., non-explicit) cues; in contrast, there was found to be little role for STM resources with explicit cues (Allen & Martin, in preparation). As a result, the memory demands of the shifting paradigm used herein are of little concern, given the explicit nature of the cue. Therefore, shifting impairments cannot be attributed to the task’s short-term memory demands. And, while STM deficits may hinder overall recall levels in resistance to PI tasks, patient performance is not assessed as the amount of information
recalled, but the amount of interference demonstrated. It seems reasonable to assume that
STM deficits would affect baseline and interference conditions equally.

Procedure

With two exceptions, patients were tested on unmodified forms the response-
distractor inhibition, resistance to PI, and shifting tasks discussed in Chapter 3 (and see
Table 7.2). All response-distractor inhibition and shifting tasks were production or
button-press, and these patients had previously shown a good ability to make these kind
of responses (Allen et al., 2010). In addition, the recent negatives task given to healthy
subjects only consisted of lists of 3 words, which was close to the span level of these
patients. Thus, the response-distractor inhibition, recent negatives, and shifting tasks were
tested on patients as described in Chapter 3. The two exceptions to using the methods
reported previously for healthy subjects were for the two resistance to PI tasks that
involved recall (cued recall directed forgetting and release from PI). Because of their
reduced STM capacities, new versions of these tasks were developed for patient testing
(described below); adapted versions contained shorted list lengths. For unmodified tasks,
patient performance was compared to the older adults discussed in earlier chapters; for
the adapted recall tasks, patient performance was compared to 5 new age-matched
controls who had not previously been tested in this body of work ($M$ age = 68; $M$
education = 17.2 years). Patient testing took place over 3-4 one-hour sessions, with
approximately one week between sessions.

**Cued recall, directed forgetting task adaptation.** The original cued recall task
contained lists of four words and a 8 second filler task that involved making magnitude
judgments, indicating whether sequentially presented numbers were smaller or larger
than 50. The patient adaptation was similarly designed, with only a few changes. Patients were given additional practice with the task, totaling seven practice trials. List lengths were reduced to three words, with individual list items remaining on the screen for three seconds. Additionally, the filler task was changed to a sequential counting task, and the amount of time granted for recall was not time constrained. Otherwise, the same targets, list items, and probes were used as in the original version.

**Release from PI task adaptation.** The original release from PI task contained lists of eight words and a 16 second filler task that involved counting by both letter and number (for example, if a subject saw H-39, they would say “H-39, I-40, J-41…”) until cued to recall. In the patient adaptation, list lengths were reduced from eight to four items. More specifically, each eight item list was split into two four-item lists, with half of the lists tested in one session and the other half of the lists tested in a second session (lists from the same category were not presented in the same session). Additionally, individual list items remained on the screen for 2500ms, the filler task was changed to a sequential counting task, and the amount of time given for recall was not time constrained. Otherwise, the same targets and list items were used, as in the original version.

**Results**

**Analyses**

To determine whether patient performance differed from that of controls, patient performance was compared to controls using a modified t-test argued to be appropriate for testing whether single cases differ from a control group (Crawford & Howell, 1998). Using this procedure, the standard deviation of a small sample was taken as an estimate
of the population standard deviation, and the individual (patient) was treated as a sample of N = 1. Patients and control data were then entered into a t-test formula to determine whether individual cases were beyond the 95th percentile for the control group. Crawford and Howell (1998) have shown this test appropriate for small sample sizes and neuropsychological research. For the present experiments, only patient effects (i.e., difference scores – not patient performance in each condition) were compared to controls. All t-tests were two-tailed, and all RT measures were analyzed on and reported as log-transformed RTs. Inhibitory control deficits were indicated by significantly exaggerated interference effects (i.e., difference scores) or intrusion errors, relative to controls. Table 7.2 includes a task list and descriptive statistics for controls and patients on all of the tasks described below; RT descriptive statistics are shown in Appendix D. Additionally, patient and control interference effects on response-distractor inhibition tasks are shown in Figure 7.2; interference effects on resistance to PI tasks are shown in Figure 7.3.

Table 7.2. Patient and control performance on response-distractor inhibition, resistance to proactive interference, and shifting tasks. Italicized rows indicate the DV for which patients were compared to controls. Bolded values indicate patient values that were significantly different than controls (Crawford & Howell, 1998, p < .05). See also Figures 7.2 and 7.3.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>EV M</th>
<th>MB M</th>
<th>Controls M</th>
<th>Controls SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Response-Distractor Inhibition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Picture-word interference</td>
<td>Log RT (error rate)</td>
<td>Interference [semantically related]</td>
<td>3.26 (.08)</td>
<td>3.15 (.03)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No interference [semantically unrelated]</td>
<td>3.28 (.03)</td>
<td>3.13 (.06)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Effect</strong></td>
<td><strong>-0.03</strong></td>
<td><strong>0.01</strong></td>
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<tr>
<td></td>
<td></td>
<td>(.05)</td>
<td>(.04)</td>
<td>(.001)</td>
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<td>-------------------------</td>
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<tr>
<td><strong>Nonverbal Stroop</strong></td>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td>Log RT (error rate)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incongruent</td>
<td></td>
<td>3.27</td>
<td>2.85</td>
<td>2.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(.22)</td>
<td>(0)</td>
<td>(.03)</td>
</tr>
<tr>
<td>Neutral</td>
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<td>2.83</td>
<td>2.8</td>
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<td></td>
<td></td>
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<td>(0)</td>
<td>(.01)</td>
</tr>
<tr>
<td>Effect</td>
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<td>0.03</td>
<td>0.04</td>
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<tr>
<td></td>
<td></td>
<td>(.02)</td>
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<td>(.02)</td>
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<tr>
<td><strong>Stroop</strong></td>
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<tr>
<td></td>
<td>Log RT (error rate)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incongruent</td>
<td></td>
<td>3.36</td>
<td>3.30</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(.28)</td>
<td>(.11)</td>
<td>(.09)</td>
</tr>
<tr>
<td>Neutral</td>
<td></td>
<td>3.10</td>
<td>3.07</td>
<td>2.95</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td>Effect</td>
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<td>0.26</td>
<td>0.22</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(.11)</td>
<td>(.09)</td>
<td>(.05)</td>
</tr>
<tr>
<td><strong>Resistance to PI</strong></td>
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<td></td>
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<tr>
<td>Recent negatives</td>
<td>Log RT (error rate)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive (yes) trials</td>
<td></td>
<td>3.20</td>
<td>3.02</td>
<td>3.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(.02)</td>
<td>(.08)</td>
<td>(.04)</td>
</tr>
<tr>
<td>Interference [recent negative]</td>
<td></td>
<td>3.39</td>
<td>3.13</td>
<td>3.16</td>
</tr>
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<td></td>
<td></td>
<td>(.08)</td>
<td>(.46)</td>
<td>(.12)</td>
</tr>
<tr>
<td>No interference [non-recent negative]</td>
<td></td>
<td>3.22</td>
<td>3.10</td>
<td>3.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0)</td>
<td>(.04)</td>
<td>(.03)</td>
</tr>
<tr>
<td>Effect</td>
<td></td>
<td>0.16</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(.08)</td>
<td></td>
<td>(.09)</td>
</tr>
<tr>
<td>Cued recall</td>
<td>Recall proportion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interference [2-block interference]</td>
<td></td>
<td>0.69</td>
<td>0.38</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
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<tr>
<td>No interference [2-block control]</td>
<td></td>
<td>0.77</td>
<td>0.69</td>
<td>0.91</td>
</tr>
<tr>
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<tr>
<td>Effect</td>
<td></td>
<td>0.08</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Intrusions [list 1 lure recall]</td>
<td></td>
<td>0.15</td>
<td>0.38</td>
<td>0.25</td>
</tr>
<tr>
<td>Release from PI</td>
<td>Items recalled</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interference [list 2 recall]</td>
<td></td>
<td>2.55</td>
<td>1.5</td>
<td>3.04</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>No interference [list 1 recall]</td>
<td></td>
<td>3.25</td>
<td>2.85</td>
<td>3.68</td>
</tr>
<tr>
<td></td>
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<td></td>
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<tr>
<td>Effect</td>
<td></td>
<td>0.7</td>
<td>1.35</td>
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</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Intrusions [list 1 intrusions]</td>
<td></td>
<td>0.3</td>
<td>0.5</td>
<td>0.41</td>
</tr>
<tr>
<td><strong>Shifting</strong></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Global shifting</td>
<td>Log RT (error rate)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed block</td>
<td></td>
<td>3.45</td>
<td>3.20</td>
<td>3.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(.01)</td>
<td>(0)</td>
<td>(.04)</td>
</tr>
<tr>
<td>Pure block</td>
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<td>3.07</td>
<td>2.92</td>
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<td></td>
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<td>(.02)</td>
</tr>
<tr>
<td>Global switch cost</td>
<td></td>
<td>.38</td>
<td>.28</td>
<td>.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(.01)</td>
<td>(.03)</td>
<td>(.03)</td>
</tr>
<tr>
<td>Backward Log RT</td>
<td>N-2 repetition</td>
<td>3.47</td>
<td>3.23</td>
<td>3.21</td>
</tr>
</tbody>
</table>
Response-Distractor Inhibition Tasks

**Picture-word interference task.** Control performance was worse on semantically related relative to semantically unrelated trials, indicating interference effects that were significant in log RTs \((M = .02, SD = .01; t(59) = 11.95, p < .001)\), but not error rates \((M = .001, SD = .02; t(59) = .36, p = .72)\). Patient EV’s error interference effects were significantly greater than those of controls; while her log RT effect was also significantly different than controls, the effect was the reverse of that shown by controls, as she demonstrated worse performance on the no interference condition. MB’s interference effects did not differ significantly from controls (Figure 7.2).

**Nonverbal Stroop task.** Control performance was worse on incongruent relative to neutral trials, indicating interference effects that were significant in both log RTs \((M = .04, SD = .03; t(59) = 11.41, p < .001)\) and error rates \((M = .02, SD = .03; t(59) = 4.79, p < .001)\). Patient EV’s interference effects were significantly greater than controls in log RTs, but not error rates; however, it is notable that her error rates were very large across conditions \((M \approx .21)\), relative to controls \((M = .02)\). In contrast, MB showed no evidence of exaggerated interference effects or inflated error rates (Figure 7.2).

**Stroop task.** Control performance was worse on incongruent relative to neutral trials, indicating interference effects that were significant in both log RTs \((M = .12, SD = .04; t(58) = 22.20, p < .001)\) and error rates \((M = .05, SD = .07; t(58) = 6.30, p < .001)\). In log RTs, both patients demonstrated significantly exaggerated interference effects relative
to controls. While neither of the patients’ effects were significant in error rates, patient EV made substantially more errors across both incongruent and neutral conditions ($M \approx .23$), relative to controls ($M \approx .07$), see Figure 7.2.

**Summary of response-distractor inhibition effects.** Across all three response-distractor inhibition tasks, patient EV demonstrated significantly exaggerated interference effects in either log RTs or errors, relative to age-matched controls. Additionally, on two of the inhibitory control tasks, patient EV’s error rates were substantially larger than the error rates for controls. In contrast, patient MB demonstrated significant interference effects on only one task, and his errors were minimal.

**Resistance to PI Tasks**

**Recent negatives.** Control performance was worse on interference (recent negative) relative to no interference (non-recent negative) trials, indicating interference effects that were significant in both log RTs ($M = .05, SD = .05$; $t(59) = 8.17, p < .001$) and error rates ($M = .08, SD = .10$; $t(59) = 6.75, p < .001$). Patient EV’s interference effect was significantly greater than controls in log-RTs, but not error rates; in contrast, patient MB’s interference effect was significantly greater than controls in error rates, but not log-RTs (Figure 7.3, though log RT effects not shown).

**Cued recall, directed forgetting.** Control performance was worse on 2-block interference trials relative 2-block control trials, indicating significant PI ($M = .20, SD = .12$), $t(4) = 3.83, p = .02$. Neither of the patients showed significantly greater interference effects than controls (Figure 7.3), nor did they make significantly more intrusions of list 1 lure items on 2-block interference trials.
**Release from PI.** Controls recalled fewer words on list 2 relative to list 1 \((M = .64, SD = .61)\), and this PI effect was marginally significant, \(t(4) = 2.37, p = .08\). Neither of the patients showed significantly greater interference effects than controls (Figure 7.3), nor did they make significantly more list 1 intrusions during list 2 recall.

**Summary of resistance to PI effects.** Unlike the results for the response-distractor inhibition tasks, neither of the patients demonstrated consistent evidence of exaggerated interference effects across the resistance to PI tasks tested herein.

**Task Switching**

**Global shifting.** Control performance was worse on mixed blocks relative to pure blocks, indicating significant global switch costs in log RTs \((M = .36, SD = .12; t(59) = 22.11, p < .001)\) and errors \((M = .03, SD = .06; t(59) = 3.73, p < .001)\). Neither of the patients demonstrated significantly exaggerated global costs, in log RTs or error rates.

**Backward inhibition.** Control performance was worse on N-2 repetition trials relative to N-2 switch trials, indicating significant N-2 repetition costs in log RTs \((M = .02, SD = .02; t(59) = 9.79, p < .001)\) and errors \((M = .008, SD = .02; t(59) = 2.71, p = .009)\). Neither of the patients demonstrated significantly exaggerated N-2 repetition costs, in log RTs or error rates.

**Summary of task switching effects.** Neither of the patients demonstrated significantly exaggerated measures of task switching, relative to controls.

**General Discussion**

The goals of the present study were twofold. First, given the localization of inhibitory control mechanisms in the left frontal lobe, the present study investigated whether dissociations on inhibition tasks could be found across two patients – one whose
lesion included left frontal lesions (patient EV), and one whose lesion did not (patient MB). Second, given the hypothesized role for inhibition in task switching (see Chapter 2 for a review), and more specifically the role for resistance to PI mechanisms in task switching (e.g., Allport et al., 1994; see Chapter 2 for a review), an association between impairments in PI resistance and shifting performance would be predicted, while an association between response-distractor inhibition impairments and shifting would not be predicted. The findings pertaining to these two goals will be discussed in turn.

Patient EV, whose lesion included left frontal regions, showed evidence of consistently exaggerated interference across all of the response-distractor inhibition tasks assessed herein, whereas she only exhibited exaggerated proactive interference on one of the resistance to PI measures (the recent negatives task). In contrast, patient MB showed no evidence of consistent impairments across any of the inhibitory control tasks. These results demonstrate three interesting dissociations. First, looking only at patient EV, the dissociation between response-distractor inhibition and resistance to PI tasks supports the notion that inhibitory control is not a unitary construct, and might instead be better represented by distinct inhibition factors, as suggested by psychometric studies (Friedman & Miyake, 2004) and healthy aging (Chapter 4). Additionally, while there was no evidence for consistent resistance to PI deficits in the patients included herein, other work has found exaggerated PI. For example, patients with Korsakoff’s amnesia tend to show exaggerated proactive interference, suggesting that processes related to the resistance to PI can become impaired (e.g., Cermak & Butters, 1972; Mayes, Pickering, & Fairbairn, 1987). Additionally, Smith, Leonard, Crane, and Milner (1995) found that patients with frontal lesions (though not necessarily unilaterally left frontal) demonstrated
exaggerated proactive interference relative to patients with posterior lesions. In summary, then, neuropsychological evidence suggests that response-distractor inhibition and resistance to PI can be separately impaired (see also Chapter 4), and therefore care should be taken to distinguish among these inhibitory control processes, as opposed to using the broad umbrella term ‘inhibition’.

The second interesting dissociation relates to the neural correlates of inhibitory control mechanisms. Only patient EV – with a left frontal lesion – demonstrated an inhibition deficit. In contrast, patient MB, whose lesion was more posterior and non-frontal, did not demonstrate an inhibition deficit. At the very least, these results support prior neuroimaging studies that have suggested a critical role for left frontal regions in the resolution of interference in response-distractor inhibition-type tasks (Nee et al., 2007). With respect to lesion localization, patient EV’s left frontal lesion extended into middle frontal gyrus and insular regions, raising the possibility of damage to DLPFC regions, as implicated in response-distractor inhibition. Along these same lines, it is interesting to note that patient EV did not show a deficit across resistance to PI tasks, given that her lesion includes BA 44/45, which are ventral regions, and VLPFC regions are thought to be involved in PI resistance (Jonides & Nee, 2006; Nee et al., 2007; cf. Nee et al., 2012).

Of note, the results of the present work cannot differentiate between accounts that distinguish between two inhibitory control mechanisms (e.g., Friedman & Miyake, 2004; Hasher & Zacks, 1988) versus two selection mechanisms (e.g., Nee et al., 2012). Given many response-distractor inhibition tasks tend to depend on the selection of spatial information (i.e., the target’s location, irrespective of the interfering context), EV’s deficit on these types of tasks could indicate impaired selective spatial attention. The
distinction between these two accounts could be tested in future work by including multiple response-distractor inhibition, some of which depend on the selection of spatial information and others which depend on the selection of identity information.

Lastly, the third interesting dissociation relates to patient EV’s performance on the three resistance to PI tasks. It is interesting to note that EV’s overall recall on the cued recall and release from PI tasks was within the range of controls, despite the fact that she has a STM deficit (Table 7.1). Additionally, she did not demonstrate exaggerated interference effects on these tasks, while she did show exaggerated interference on the recent negatives task. What differentiates these tasks is the presence or absence of filler tasks. Both the cued recall and release from PI tasks included long filler tasks between list presentation and recall (8 and 16 seconds, respectively), while the recent negatives task did not. Given this lengthy distraction, one might posit that these two tasks involve the resistance of PI from information in long-term memory (LTM). In contrast, the use of an immediately presented probe in the recent negatives assessed resistance to PI in STM. For EV, at least, her performance distinction on these PI tasks suggests impaired STM (see Table 7.1), but intact LTM. This posthoc dissociation should be interpreted with caution, as this only allows for STM/LTM comparisons across three tasks; therefore, this should be further explored in future research. However, it provides converging neuropsychological evidence for impaired STM in the presence of intact LTM, in line with other patient work (e.g., Warrington & Shallice, 1969; Shallice & Warrington, 1970).

The second goal of this study was to investigate the relationship between inhibitory control mechanisms and task switching abilities. To this end, if inhibitory
control mechanisms play a critical role in our ability to switch between tasks (e.g., Allport et al., 1994; Mayr & Keele, 2000), we would expect to find an association between deficits in inhibition and task switching. More specifically, theories of task switching have posited a critical role for interference resolution, as switching between tasks requires one to overcome the activation of the previously executed task. This theory of switch costs suggests a critical role for resistance to PI in measures of task switching, as both task switching and PI resistance involve overcoming interference from irrelevant information in memory. In contrast, the role for response-distractor inhibition in task switching is less evident (cf. Friedman & Miyake, 2004), given all trials require one to overcome interference from irrelevant stimulus attributes. Consistent with this notion, both patients showed shifting performance that was within the range of controls. While not particularly telling for the patient with parietal damage (patient MB), it is interesting to note that there was no association between patient EV’s deficit in response-distractor inhibition and shifting performance. Although this finding for EV is a null result that should be interpreted with caution, the result supports the notion that response-distractor inhibition does not play a critical role in measures of global shifting or backward inhibition. Future research should seek a patient with deficits to resistance to PI inhibitory control mechanisms, to see if those deficits are associated with shifting impairments.

**Summary**

In summary, the present study investigated the inhibitory control and task switching abilities in two patients – one with a left frontal lesion and one with posterior lesions. Supporting the notion that inhibition is not a unitary construct, but that at least some aspects of inhibition can be localized to left frontal regions, the left frontal patient –
patient EV – demonstrated a dissociation between inhibitory control mechanisms, showing a deficit across multiple response-distractor inhibition tasks, but no consistent impairment across resistance to PI tasks. As expected, patient EV’s inhibition deficit was not associated with impairments in task switching, consistent with the notion that response-distractor inhibition plays little role in global shifting or backward inhibition.
Chapter 7 Figure Captions

*Figure 7.1.* Patient lesion montages. Patient EV is shown on the left, and MB on the right.

*Figure 7.2.* Patient and control interference effects on response-distractor inhibition tasks, for both log RT (top) and errors (bottom). Error bars indicate 2.5 standard deviations beyond the mean of controls. Asterisks indicate patient effects that differ significantly from controls.

*Figure 7.3.* Patient and control interference effects on resistance to PI tasks. Error bars indicate 2.5 standard deviations beyond the mean of controls. Asterisks indicate patient effects that differ significantly from controls.
Chapter 8: Summary and Conclusions

Overview of Goals and Summary of Results

Executive control allows for goal-directed behavior by enabling us to overcome interference from irrelevant information and switch between tasks in a flexible, yet organized fashion. While executive control processes are thought to include distinct mechanisms, they also demonstrate some degree of unity. To this end, my dissertation explored a) the organization of inhibitory control mechanisms and b) the relationship of these inhibitory control mechanisms with task switching. I will briefly discuss and summarize the results of each point in turn.

Theoretically, inhibitory control is oftentimes consumed under the single term ‘inhibition’. However, theoretical (e.g., Hasher & Zacks, 1988; Kok, 1999; Nigg, 2000) and individual differences work (Friedman & Miyake, 2004) has suggested that it actually consists of multiple constructs. For example, Friedman and Miyake (2004) have distinguished between the inhibitory control processes of response-distractor inhibition (our ability to respond appropriate even when there are distractors in the environment) and resistance to proactive interference (our ability to resist interference from no-longer-relevant information in memory). In contrast, others have attributed some aspects of inhibition – such as response-distractor inhibition – to nothing more than speed of processing (e.g., Hedden & Yoon, 2006; Salthouse, 1994) or selection mechanisms (e.g., Friedman et al., 2008; Munakata et al., 2011). Given this debate in the literature, I investigated the diversity of these inhibitory mechanisms using three methodologies: aging, individual differences, and neuropsychology. The evidence from aging and neuropsychology converged on the idea that inhibitory control processes do, in fact,
dissociate; however, the individual differences work suggested that from a measurement standpoint, some clarification is warranted. In aging (Chapter 4), healthy older adults showed consistent age-related cognitive declines on resistance to proactive interference (PI) tasks, but not on response-distractor inhibition tasks. Age-related impairments on resistance to PI tasks were interpreted in terms of failed binding mechanisms. Interestingly, the opposite dissociation was found in the neuropsychological work (Chapter 7), which tested two patients with left hemisphere brain damage. One patient showed a consistent impairment in response-distractor inhibition tasks, but not resistance to PI tasks. Importantly, these selective impairments (in aging, neuropsychology) to a single inhibitory control mechanism suggest that these mechanisms are not, necessarily, measuring the same thing. These results replicate the distinction between these inhibitory control mechanisms (e.g., Friedman & Miyake, 2004), and provide converging evidence across a variety of methodologies.

However, other considerations must also be made. In the individual differences work (Chapter 6), I found that the two inhibition constructs were strongly correlated, and in fact a one-factor model provided an equivalent fit of the data, with only a subset of the ‘inhibition’ tasks showing significant factor loadings. To account for this model, I suggested that binding serves as the common mechanism uniting these tasks. That is, the Stroop task and all resistance to PI tasks require strong content-context bindings for effective selection to occur, given the need to retrieve information from both relevant and irrelevant information in memory.

To account for the inconsistencies between methodologies, I propose that all of the interference resolution tasks involve selection mechanisms. Prefrontal biasing or
selection mechanisms function to enhance the activation of representations in posterior processing regions, effectively bias posterior representations to enable the selection of goal-relevant information. Additionally, these selection mechanisms result in lateral inhibition of competing representations (e.g., Desimone & Duncan, 1995; Miller & Cohen, 2001; Munakata et al., 2011; Nee et al., 2012). What allows for dissociations among response-distractor inhibition and resistance to PI tasks is the difference in selection mechanisms used. In a recent model, Nee and colleagues (2012) have proposed that executive control mechanisms can be best described as selection mechanisms that act on different types of information, either spatial (location) or identity (what) information. Accordingly, they proposed that response-distractor inhibition tasks tend to rely on spatial selection, while resistance to PI tasks tend to rely on identity selection. Additionally, as discussed in Chapter 6, several of the identity selection tasks also required binding mechanisms. As a result, this model provides lines along which response-distractor inhibition and resistance to PI tasks can be dissociated, while still allowing for some degree of unity.

The second goal was to investigate the relationship between task switching and the inhibitory control processes discussed above. Various theories of task switching have suggested that switching between tasks requires one to overcome interference from the previously relevant task, suggesting a mechanism conceptually similar to that involved in PI resolution. Accordingly, some support was found for this hypothesis, as an interaction between age and the inhibition factor served as significant predictors for performance on N-2 repetition trials, in measuring backward inhibition. Potential explanations for this result were discussed in Chapter 6. In contrast, I found that working memory (WM)
processes contributed to both global and local switch costs, though future research should investigate the role for various WM mechanisms with more process-pure tasks.

Given these findings, and the interpretations discussed therein, below I discuss an integrated model of working memory (WM) that is able to accommodate selection, binding, and inhibition mechanisms – while also being able to account for age-related declines across multiple domains of executive control. This model is predominantly influenced by – and a blending of – the WM models of Oberauer (2002; see also Cowan, 1995) and Unsworth and Engle (2007), but includes the dual selection mechanisms discussed by Nee et al. (2012).

**Integrated Model of Working Memory**

The model discussed below is based on embedded-process accounts of WM, as exemplified by Cowan (1995) and Oberauer (2002). These models maintain that two general ‘regions’ contribute to WM: a focus of attention and an activated portion of long-term memory (LTM). The focus of attention is a limited capacity system that holds information that is currently being processed, and according the Unsworth and Engle (2007), the focus is relatively flexible insofar as its content can be adapted according to task demands. Sometimes the focus of attention may hold a single goal, while other times it may hold multiple to-be-remembered items. The activated portion of LTM is a system that contains representations that are activated above baseline, either because they may soon be relevant to current processing, or because they were recently activated by task demands. These activated representations are thought to decay over time. In contrast to this, representations in LTM are at baseline – accessible, but not as easily accessible as representations in the activated portion of LTM. As task demands/stimuli change,
information can be moved in and out of the focus of attention via selective attention or retrieval mechanisms, which function to bias task-relevant representations. And, importantly, selection or retrieval is required to move information into the focus of attention. But, because of its limited capacity, older information must be displaced or cleared from the focus of attention. While some researchers have raised the possibility that backward inhibition may be used to clear the contents of WM (or the focus of attention; e.g., Bao, Li, Chen, & Zhang; Mayr & Kliegl, 2003), this point is a question for future work.

As suggested by Nee and colleagues (2012), selective attention mechanisms may be organized by the content on which they act, with there being two separate selection mechanisms (that likely function in similar ways): the first allows for the selection of spatial information, and the second for the selection of content/identity information. While the first of these mechanisms biases parietal regions in the selection of relevant spatial locations, the second may bias temporal regions in selecting among representations in memory. For both, lateral inhibition may serve as a consequence of these selective attention mechanisms, serving to overcome competition from competing representations (e.g., Miller & Cohen, 2001; Munakata et al., 2011). Similar to Nee and colleagues (see also Unsworth & Engle, 2007), I propose that these selection mechanisms are guided by the maintenance of a task goal. Goal maintenance includes a representation of task-relevant goals that serve to bias the representations on which selection mechanisms act.

Critically, unlike selection of spatial information, selection (or retrieval) from memory is particularly error prone because it requires that one distinguish among
multiple irrelevant representations in the activated portion of LTM. Unsworth and Engle (2007) have suggested that this is a cue-dependent search process, by which task-relevant cues are used to restrain the search process. However, this successful search relies not only on goal maintenance (i.e., knowing what one is doing on this experimental trial), but also on binding mechanisms (as proposed by both Oberauer, 2002 and Unsworth & Engle, 2007). Specifically, the focus of attention may be used to bind object features together (e.g., content-context bindings), allowing these bound representations to be retrieved for future use. Such bindings are important because they allow for successful cue-based retrieval: when representations are well bound, retrieval will be easier because the cues will better distinguish among activated representations. In contrast, when representations are not coherently bound, cues may match multiple representations, and cause interference. Impaired or failed binding, then, may result in excessive proactive interference (e.g., Oberauer, 2005). Along similar lines, Oberauer, Süß, Wilhelm, and Wittman (2003) have suggested that working memory capacity reflects two processes, including binding and one’s ability to store information while engaging in ongoing processing. This model provides a possible link between the model described above and more general uses of the term “working memory capacity”.

**Advantages to This Model**

One advantage to the integrated WM model described in the previous section is that it has clear applications to a variety of WM and executive control tasks. Additionally, I believe it can clearly explain various patterns of spared and impaired age-related performance across different domains of executive control. That is, a preponderance of evidence has suggested that older adults show impaired performance on executive control
tasks, including measures resistance to proactive interference (e.g., Hasher, Chung, May, & Foong, 2002; Jonides et al., 2000; May, Hasher, & Kane, 1999; McCabe, Robertson, & Smith, 2005; Thompson-Schill et al., 2002) and global task switching (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001; Meiran, Gotler, & Perlman, 2001; Reimers & Maylor, 2005; Verhaeghen & Cerella, 2002; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). In contrast, there is less consistent evidence for impairments in selective attention-type executive tasks, such as response-distractor inhibition (Chapter 4; Verhaeghen & Cerella, 2002) and local task switching (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001; Verhaeghen & Cerella, 2002). As indicated by Verhaeghen and Cerella (2002), these two classes of executive processes differ in the extent that they involve the activation or maintenance of multiple mental sets/representations (resistance to PI tasks, global shifting) versus the active selection among simultaneously presented information. While such an account is likely accurate, it does not explain how age differences emerge, given that resistance to PI and global shifting may also involve selection mechanisms (see Chapter 6). In short, if all of these executive tasks involve similar selection mechanisms, what differentiates them in order to produce age-related impairments in some, but not others? I propose that binding is the critical factor that differentiates these two classes of tasks. Similar to the account put forth by Mayr (2001; among others, e.g., Dennis et al., 2008; Naveh-Benjamin, 2000; Oberauer, 2005), I propose that older adults are impaired when successful performance requires selection among bound representations, but not those that require only selective attention.

For example, across inhibitory control tasks, older adults perform normally on
(most) response-distractor inhibition tasks (Chapter 4) because these tasks rely on spatial selection mechanisms. Beyond age-related slowing (e.g., Salthouse, 1994), selection mechanisms are not impaired (see also Connelly & Hasher, 1993). While resistance to PI tasks also rely on identity selection mechanisms that slow with age, the tasks tested herein also necessitate binding mechanisms, which may become impaired with advancing age (e.g., Howard, Kahana, & Wingfield, 2006; Mitchell, Johnson, Raye, Mather, & D’Esposito, 2000; Li & Lindenberger, 2005; Oberauer, 2005). Thus, older adults show exaggerated interference on PI tasks because they do not form strong content-context associations between items and their list contexts. If representations are not clearly associated with a context, performance is more interference prone. Additionally, once processing speed is accounted for, the residual need for binding among WM elements in the Stroop task (e.g., Kimberg & Farah, 1993) may explain why older adults oftentimes also show exaggerated interference effects on this measure of response-distractor inhibition, like their performance on resistance to PI tasks (e.g., Chapter 4). More specifically, given that the Stroop task’s distractor is a well-practiced response, one must maintain a strong association (i.e., binding) between the task goal and task-relevant stimuli because without this, the dominant reading behavior prevails. Such an account allows us to explain different types of interference resolution using a single mechanism that acts on different types of information.

Additionally, similar logic can be used to explain seemingly contradictory patterns of age-related impairments on global shifting tasks: age effects are typically found when task contexts do not clearly indicate a relevant task (e.g., Kray & Lindenberger, 2000; Mayr, 2001), but are less consistent when this task ambiguity is
reduced (e.g., Chapter 5; Kray, Eber, & Karbach, 2008; Kray, Li, Lindenberger, 2002; Mayr & Kliegl, 2000). The above model can account for these different effects by again calling on age-related impairments in binding mechanisms.

According to Mayr (2001), a critical factor that determines global shifting is the ability to differentiate between task sets, with such differentiation being particularly difficult in mixed blocks, when the task environment is more ambiguous. That is, age-related impairments are present when task sets cannot be easily differentiated, and therefore interfere with each other, because failed binding mechanisms make it more difficult for older adults to form and/or differentiate between task sets. Such failed bindings increase the likelihood that the irrelevant task set will be inappropriately activated due to cue-based retrieval finding matches within multiple task sets (i.e., involuntary retrieval). In contrast, when task set ambiguity is minimized, task set differentiation is facilitated, and age-related impairments are reduced, making binding failures less detrimental. In support of this binding hypothesis, Henkel, Johnson, and De Leonardis (1998) have suggested that older adults have the most difficulty in binding features in memory when distinct representations have some degree of overlap. In shifting contexts, bindings are needed to distinguish possible task sets to enable flexible behavior, as successful shifting performance requires that task sets be kept apart (Mayr, 2001).

Interestingly, the above model can also explain the lack of age-related impairment on local shifting tasks. That is, given the need to differentiate among and select task sets on switch (but not repeat) trials, why are age-related impairments not also found on local shifting tasks (e.g., Kray & Lindenberger, 2000; Mayr, 2001; Mayr & Liebscher, 2001;
Verhaeghen & Cerella, 2002)? In short, these ideas can be reconciled by assuming that switch and repeat trials involve similar processes. In particular, both trial types may involve the retrieval of relevant task sets into WM (e.g., Altmann & Gray, 2008; Koch, 2003, 2005; Mayr & Kliegl, 2000, 2003). However, this retrieval process is more time consuming on switch trials due to the need to overcome PI from a recently performed task (Yeung & Monsell, 2003) as well as the need to overcome backward inhibition of the now-relevant task (Mayr & Keele, 2000). Extending this logic to binding accounts of aging, young adults have less difficulty overcoming the PI that is present on switch because they have well-established (i.e., strongly bound) task sets; once they have established this task set in WM, they can relatively easily apply it on repeat trials. Older adults, in contrast, have weakly bound task sets; although they can establish retrieved task sets in WM (i.e., they can update the contents of WM when new task sets become relevant), the weak bindings result in more competition between sets, and similarly, a greater likelihood that the inappropriate task will interfere with performance. And, critically, weak bindings affect both switch and repeat trials equally. That is, older adults do not necessarily have problems in selecting among mental sets, but this selection process is made more difficult because of weak bindings. This account is consistent with Kray and Lindenberger’s (2000) account of age-related impairments in global costs, which proposed that “impairments of older adults are more strongly related to the organization of cognitive processing within working memory than to the specific dynamics of activating and inhibiting irrelevant stimulus-response sets” (p. 142).

Lastly, the integrated WM account discussed above may also be able to explain the lack of age-related impairments in backward inhibition (as measured by N-2
repetition costs; see also Mary, 2001). If backward inhibition represents a form of lateral inhibition that is a down-stream consequence of selection mechanisms (e.g., Miller & Cohen, 2001; Munakata et al., 2011), we might suggest that it represents an ‘automatic’ or neural inhibition mechanism, given controlled inhibitory mechanisms are not involved. As a result, we have no a priori reason to expect older adults to demonstrate exaggerated backward inhibition effects. In line with this, I have suggested that older adults do not show impaired selection mechanisms. If backward inhibition is a consequence of selection mechanisms, used to clear the focus of attention and/or resolve competition between activated representations, age-related impairments would not be expected if selection mechanisms are intact. Although speculative and worthy of future research, such an account is consistent with other findings. For example, Oberauer (2001, 2005) found that older adults are impaired at keeping information from intruding back into WM, but not in removing information from the focus of attention. Consistent with this, older adults tend to show impaired performance when information in memory interferes with current processing, but not on selective attention tasks (Chapter 4) or backward inhibition measures (Chapter 5).

In summary, this binding account of age-related cognitive decline provides a unitary mechanism for explaining age-related performance impairments across a multiple cognitive domains, including memory and executive control. It integrates nicely with theories of age-related impairments in memory, such as binding impairments in source monitoring (e.g., Henkel et al., 1998). Additionally, it provides a way to account for age-related slowing in processing speed, while not attributing all age-related impairments to the processing speed factor. This is especially important because some authors have
argued that processing speed-only theories of aging are too underspecified to account for the variety of age deficits found across memory domains (e.g., Balota, Dolan, & Duchek, 2000).

In summary, the above account proposes similar selection mechanisms for multiple executive function abilities, such as those measured by both inhibition and task switching. And, although I have argued that selection mechanisms can be used for selecting relevant information across a variety of executive tasks, error-proof selection requires that one be able to differentiate relevant from irrelevant information. Critically, such differentiation might be particularly difficult in the presence of loosely-bound representations. In such situations, active but irrelevant representations have the potential to be incorrectly retrieved and therefore result in interference. Thus, when binding mechanisms are successful, interference is reduced because representations can be clearly distinguished from one another. This account cleanly relates executive control processes – and age-related executive control declines – to theories of memory (e.g., Cowan, 1995; Oberauer, 2002; Unsworth & Engle, 2007) and attentional selection (e.g., Desimone & Duncan, 1995; Miller & Cohen, 2001).

**Future Directions**

There are multiple directions in which future research can proceed, though I only describe a few here. The first, and most obvious, is to conduct a similar study as done here, but include binding-only tasks (e.g., Oberauer, 2005) to verify that older adults are impaired on these tasks, and determine whether these impairments can account for age effects in resistance to PI and shifting tasks. The above account makes the clear prediction that individual differences in binding should be related to performances on PI,
Stroop, and shifting tasks. Consistent with this hypothesis, recent work by Guo (2012) using individual differences in young adults found that both inhibition and binding play a role in PI resolution. Along these same lines, given the proposed importance of binding mechanisms in explaining age-related cognitive decline, and important question for future work is whether binding mechanisms are amenable to interventions or training.

Additionally, while I have used the term “response-distractor” inhibition throughout this body of work, a clarification must be made. I used this term because Friedman and Miyake (2004) initially classified the Stroop task as a response inhibition task (as opposed to a distractor inhibition task), along with the anti-saccade task and a stop-signal task. However, these response inhibition tasks were not distinguishable from their distractor inhibition tasks (hence the term response-distractor inhibition). However, none of my response-distractor inhibition measured the inhibition of an overtly prepared motor response, as in stop signal and go/no-go tasks. And, while Friedman and Miyake (2004) have suggested this type of inhibition to be indistinguishable from distractor inhibition, it is important to note that they did not control for processing speed – which might make a strong contribution to these tasks loading on a single factor. Along these lines, Munakata and colleagues (2011) have suggested that response inhibition may involve entirely different mechanisms than distractor inhibition. Therefore, it would be prudent for future research to control for processing speed in investigating possible dissociations between response and distractor inhibition.

Lastly, from a neuropsychological standpoint, it would be fascinating to find the other side to the dissociation described in Chapter 7 – that is, a patient showing a deficit on resistance to PI tasks, but not response-distractor inhibition tasks. Such a double
dissociation would provide nice evidence for the distinction between inhibitory control processes (or selective attention mechanisms), as found in a meta-analysis of neuroimaging studies (Nee et al., 2012).
References


Gade, M., & Koch, I. (2005). Linking inhibition to activation in the control of task


Appendix A

Correlation coefficients for response-distractor inhibition (RT), release from proactive interference, and shifting tasks. Significant correlations are indicated in bold.

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<td>2. NV Stroop</td>
<td>0.13</td>
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<td>3. Stroop</td>
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<td>4. Flanker</td>
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<td>5. Recent negatives</td>
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<td><strong>.22</strong></td>
<td>-.09</td>
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<td>6. Release from PI</td>
<td>0.12</td>
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<td><strong>.28</strong></td>
<td>-.08</td>
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<td>7. Cued recall</td>
<td><strong>.16</strong></td>
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<td>8. Global costs</td>
<td>.09</td>
<td><strong>.25</strong></td>
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<td><strong>.27</strong></td>
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Notes:
- Bold indicates significant correlations.
- Correlation coefficients range from -1 to 1, with values closer to 1 or -1 indicating stronger positive or negative relationships, respectively.
Appendix B

Correlation coefficients for response-distractor inhibition (log RT), release from proactive interference, and shifting tasks. Significant correlations are indicated in bold.

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Appendix C

Confirmatory factor analysis models for inhibitory control mechanisms using residuals for all dependent variables. Of note, the preferred model’s pattern of task loadings are the same as those presented Figure 6.1 (bottom).
Appendix D

Patient and control performance on response-distractor inhibition, resistance to proactive interference, and shifting tasks. With the exception of response time dependent variables, all values are the same as Table 7.2. The below table shows RT descriptive statistics, whereas Table 7.2 shows log RTs. RT patient measures were not compared to controls.

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<th>Dependent Variable</th>
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<th>EV</th>
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<td>Picture-word interference RT (error rate)</td>
<td>Interference [semantically related]</td>
<td>1935 (.08)</td>
<td>1368 (.03)</td>
<td>1101 (.03)</td>
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<td>No interference [semantically unrelated]</td>
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<td>1336 (.06)</td>
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<td>Effect</td>
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<td>32 (.04)</td>
<td>57 (.001)</td>
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<td>Nonverbal Stroop RT (error rate)</td>
<td>Incongruent</td>
<td>2191 (.22)</td>
<td>714 (0)</td>
<td>702 (.03)</td>
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<td>Neutral</td>
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<td>674 (0)</td>
<td>636 (.01)</td>
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<td>Effect</td>
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<td>40 (0)</td>
<td>66 (.02)</td>
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<td>Stroop RT (error rate)</td>
<td>Incongruent</td>
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<td>Recent negatives RT (error rate)</td>
<td>Positive (yes) trials</td>
<td>1586 (.02)</td>
<td>1041 (.08)</td>
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<td>Interference [recent negative]</td>
<td>2672 (.08)</td>
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<td>Intrusions [list 1 lure recall]</td>
<td>Interference [list 2 recall]</td>
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<td>Effect</td>
<td>Intrusions [list 1 intrusions]</td>
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<td>0.3 0.5 0.41 .33</td>
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**Shifting**

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<th>Global shifting</th>
<th>RT (error rate)</th>
<th>Mixed block</th>
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<th>Global switch cost</th>
<th>Backward inhibition</th>
<th>N-2 repetition</th>
<th>N-2 switch</th>
<th>N-2 repetition cost</th>
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<td>2977 (.01)</td>
<td>1199 (0)</td>
<td>1778 (.01)</td>
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<td>1624 (0)</td>
<td>859 (.03)</td>
<td>765 (-.03)</td>
<td>1826 (0)</td>
<td>1579 (0)</td>
<td>247 (0)</td>
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<td>1715 (.04)</td>
<td>732 (.02)</td>
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<td>652 (.06)</td>
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