The role of inhibitory functioning in age-related working memory decline and the moderating effect of time course changes in inhibitory functioning with age

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A Thesis

In the Department

of

Psychology

Presented in Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy (Psychology) at
Concordia University
Montreal, Quebec, Canada

September 2012

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

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ABSTRACT

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Concordia University, 2012

The current thesis investigated whether and how inhibitory and working memory functioning change with age in the context of a sequential action paradigm. The approach taken was guided by (1) propositions that inhibitory functions decline with age and negatively impact higher order abilities, and (2) the utility of better understanding cognitive mechanisms underlying sequential activities. In Study 1, I examined the extent to which age-related decline in deletion-type inhibition (suppression of no-longer-relevant information) accounted for age differences in working memory performance. Unlike much of the prior research, I examined inhibitory changes with respect to working memory components (processing and storage). I observed that reduced deletion-type inhibition with age accounted for sizable proportions of age differences in working memory components, with significant findings in storage and marginal findings in processing components. This finding indicates that changes in executive function with age, such as inhibitory control, have direct implications for working memory functioning at the componential level. Moreover, given the observation of age-related decline in deletion-type inhibition in Study 1, a finding that has been inconsistent in the literature, in two subsequent studies I examined the nature of inhibitory changes with age. In particular, I examined whether compared to younger adults, older adults' have reduced ability to engage deletion-type inhibition in a timely manner, beyond the effects of age-related general slowing. In Study 2, I did not observe age differences in the time course of deletion-type inhibition when I examined erroneous responses to the prior, no-longer-relevant, item (*n* - 1 repeat). However, this finding may have been limited by low error rates obtained. Thus, in Study 3, response latencies on *n* - 1 repeats were examined for changes in low-level (unintentional) deletion-type inhibition across variable numbers of distractors, corresponding to variable time delays. Compared to younger adults, older adults had difficulty engaging deletion-type inhibition. This finding suggests that more detailed specification of inhibitory changes with age might depend on examining the temporal dynamics of inhibitory functioning in young and older adults. Taken together, this work highlights the important role of inhibitory functioning with age in higher order cognition (working memory) and emphasizes the utility of examining age effects in the time course of cognitive functions in sequential tasks.

ACKNOWLEDGEMENTS

First and foremost, I want to thank my supervisor, Dr. Karen Li, for her patience, support, and guidance throughout this work, without which this work would not have been possible. Special thanks go to current and former Li Lab members who provided much help and advice throughout this work including: Kiran, Joni, Michael, Tara, Claire, Ida, Vanessa, Hilary, Melissa, Kevin, Sarah, Alejandro, Ricco, and Luis. Many thanks go to Jenny for her love, support, and patience over the years. I also want to thank my good pal Thirs for the many ‘wall’ discussions in recent years and my little fellas, Marty and Big Tom, for always being there for me.

I dedicate this thesis to my parents and thank them for their love, support, prayers, and sacrifice during this process. Special thanks go to Dr. Kertesz for inspiring me to pursue this career path. Last but not least, I am indebted to everyone who participated in this work, especially the older adult participants who kindly provided of their time and effort to make this work possible.

TABLE OF CONTENTS

LIST OF FIGURES ix

LIST OF TABLES xi

Chapter 1 1

General Introduction 1

1.1 Cognitive aging 3

1.2 Cognitive theories of cognitive decline with age 4

1.3 Neurocognitive approaches to cognitive decline with age 9

1.4 Summary of cognitive and neurocognitive theories of cognitive aging 11

1.5 Inhibition 13

1.6 Conceptual distinctions in inhibitory functions 14

1.7 The relationship between inhibition and working memory functioning with age .. 17

1.8 Inhibition and aging 21

1.9 Summary of inhibitory and working memory functioning with age 27

1.10 Current studies 29

Chapter 2 30

The role of age and inhibitory efficiency in working memory processing and storage components 30

2.1 Abstract 30

2.2 Introduction 31

2.3 Method 37

2.3.1 Participants 37

2.3.2 Materials and Design 37

2.3.3 Procedure 43

2.4 Results 44

2.5 Discussion 53

Chapter 3 60

Examination of the time course of deletion-type inhibition in young and older adults.... 60

3.1 Abstract 60

3.2 Introduction 62

3.3 Method 65

3.3.1 Participants 66

3.3.2 Materials and Design 66

3.3.3 Procedure 69

3.4 Results 70

3.5 Discussion 72

Chapter 4 76

Time course of deletion-type inhibition in young and older adults using a sequential updating task 76

4.1 Abstract 76

4.2 Introduction 78

4.3 Method 84

4.3.1 Participants 84

4.3.2 Materials and Design 85

4.3.3 Procedure 90

4.4 Results 91

4.5 Discussion 105
Chapter 5 118
General Discussion 120
5.1 Summary of study findings 121
5.2 Inhibition and age-related decline in higher order cognition 122
5.3 Inhibition and aging 129
5.4 Limitations and future directions 132
5.5 Conclusion 135
References 136
Appendix A: Study 3 additional figures 174
Appendix B: Sample consent form for Study 1 178
Appendix C: Sample consent form for Studies 2 and 3 180
Contribution of authors 182

LIST OF FIGURES

Figure 1.1. Inhibitory efficiency as a function of age group.. 24

Figure 2.1. Stimuli for the sequential action control task and an example trial.. 40

Figure 2.2. Intrusion error rates as a function of age group and lag errors. Error bars represent one standard error of the mean 52

Figure 3.1. Stimuli for the sequential action control task and an example trial. 67

Figure 3.2. Intrusion error rates for Lag - 1 as a function of age group and time delay before the prior target repeated. Error bars represent one standard error of the mean. 73

Figure 4.1. Stimuli for the sequential action control task and an example trial. 86

Figure 4.2. Mean RT performance in *n* - 1 repeat and control conditions as a function of age and distractor number without covariate adjustment. Error bars represent ± one standard error of the mean. ms = milliseconds. 97

Figure 4.3. Cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 1-distractor condition without covariate adjustment. Error bars represent ± one standard error of the mean. ms = milliseconds.. 98

Figure 4.4. Cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 2-distractor condition without covariate adjustment. Error bars represent ± one standard error of the mean. ms = milliseconds. 99

Figure 4.5. Cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 3-distractor condition without

coariate adjustment. Error bars represent ± one standard error of the mean. ms = milliseconds.. 100

Figure 4.6. Correlations between deletion-type inhibition in the 3-distractor condition (sum of *n* - 1 bin RTs subtract sum of control bin RTs) and intrusion errors in the reading span task for younger adults (top panel) and older adults (bottom panel)......... 104

Figure 4.7. Log transformed mean RT performance in *n* - 1 repeat and control conditions as a function of age and distractor number. Error bars represent ± one standard error of the mean. ms = milliseconds. 174

Figure 4.8. Log transformed cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 1-distractor condition. Error bars represent ± one standard error of the mean. ms = milliseconds.. 175

Figure 4.9. Log transformed cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 2-distractor condition. Error bars represent ± one standard error of the mean. ms = milliseconds. 176

Figure 4.10. Log transformed cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 3-distractor condition. Error bars represent ± one standard error of the mean. ms = milliseconds.. 177

LIST OF TABLES

Table 2.1 Means *(M)* and standard deviations *(SD)* of task performance by age group... 45

Table 2.2 Correlations among variables controlling for age.. 46

Table 2.3 Results from the hierarchical regression analyses on the relation of inhibition, speed, and working memory 47

Table 2.4 Results from the hierarchical regression analyses on the relation between indices of sequential performance and working memory 50

Table 3.1 Means *(M)* and standard deviations *(SD)* of task performance by age group... 71

Table 4.1 Correlations among variables controlling for age (top part of table) and descriptive statistics by age group (bottom part of table) 92

Chapter 1

General Introduction

To perform everyday tasks, such as trying out a new recipe, a number of cognitive processes are engaged, including paying attention to the necessary ingredients, as well as updating and maintaining our awareness of each step performed. There are times however where we may find ourselves skipping ahead or repeating steps. This is particularly likely when distractions are present within the task such as similarity amongst ingredients to use and/or steps to follow. Difficulty managing such task-specific interference, as well as interference from internal (e.g., mind wanderings) and external sources (e.g. noisy environments), appear to worsen with age (Dempster, 1992; Hasher & Zacks, 1988). Such vulnerability to interference with age suggests that older adults are often at a disadvantage while focusing on attendant tasks. Empirical support for greater performance costs with age during sequential and other activities have been formularized in inhibition deficit accounts of aging (e.g., Dempster, 1992, 1995; Hasher, Zacks, & May, 1999). These accounts stipulate that older adults are sensitive to interference because of reduced ability to inhibit/suppress distracting information during task performance. Thus, given the ubiquitous nature of sequential activities in our daily lives, reduced inhibitory control during task performance may have implications for older adults' independence in activities of daily living (ADLs), a primary factor in considering institutional care (Gaugler, Duval, Anderson, & Kane, 2007; Luppa et al., 2010) and dementia diagnoses (American Psychiatric Association, 2000). Moreover, the ability to concurrently hold and process information online (working memory functioning) is a requirement of many sequential tasks, and has been shown to be age-sensitive (e.g., Bopp & Verhaeghen, 2005).

Together, the involvement of both inhibitory control and working memory functioning in sequential activities in our daily lives is not particularly surprising given the dynamic sequential nature of ADLs. The inhibition-working memory link is also evident in models of sequential performance which often place special emphasis on the ability to maintain representations/task goals in working memory (Kimberg & Farah, 1993) and inhibitory control to avoid repeating steps (Cooper, Schwartz, Yule, & Shallice, 2005; Humphreys & Forde, 1998). In light of the essential roles of inhibitory and working memory functioning in sequential activities, the aim of this thesis is to better understand whether and how these functions change with age, and the relationships therein.

To achieve these goals, I examined inhibitory control within the context of a laboratory based sequential paradigm, given the aforementioned importance of elucidating the nature of cognitive processes underlying sequential activities. Further, I examined working memory performance using a complex span measure, as these tasks have been shown to be reliable and valid measures of working memory functioning (Conway et al., 2005). Moreover, I utilized a combination of approaches employed across cognitive aging research. This included a variance partitioning approach (hierarchical regression analyses) to examine the relationship between inhibitory control and working memory functioning with age, and a process-level analysis of inhibitory functioning in the sequential task to better elucidate the precise nature (temporal dynamics) of inhibitory functioning with age.

Considering the focus of this work, below I review cognitive changes with age, followed by an overview of general cognitive and neurocognitive theories of cognitive decline with age. Subsequently, inhibitory functioning with age and the relation to higher order abilities is closely examined.

1.1 Cognitive aging

In the cognitive aging literature, while stable to positive age trends have been demonstrated in a few areas (e.g., semantic and implicit memory; Graf, 1990; Light, 1992), negative age trends have been demonstrated in a number of areas including episodic and prospective memory, fluid intelligence, perceptual speed, and multiple forms of attention (e.g., selective and divided attention; see reviews McDowd & Shaw, 2000; Salthouse, 2004; Zacks, Hasher, & Li, 2000). In recent decades, much focus in the aging literature has been given to the study of age-related declines in executive functions, defined as “control processes responsible for planning, assembling, coordinating, sequencing, and monitoring other cognitive operations” (Salthouse, Atkinson, & Berish, 2003, p. 566). Age-related declines have been demonstrated in multiple areas of executive functions including the ability to perform multiple tasks simultaneously (dual task coordination) and shifting mental sets (specifically global switch costs which involve maintaining and coordinating between two mental sets) (see review in Verhaeghen & Cerella, 2002). To add to the list of age-related cognitive changes, researchers have given more recent attention to aging and working memory, the latter of which is conceptualized as a multi-component limited capacity system that allows for the storage and processing of information (Baddeley, 1986; Baddeley & Hitch, 1974). Unlike measures of short term memory, which assess information held online for a brief period, measures of working memory functioning have evidenced age-related declines (e.g., Bopp & Verhaeghen, 2005; Salthouse, 1994; Verhaeghen & Salthouse, 1997). Further, Verhaeghen and Basak (2005) and Basak and Verhaeghen (2011) have shown that older adults have difficulty switching individual elements in and out of the focus of attention, which has been proposed as the capacity limited component of working memory (Cowan, 1995, 2001).

These widespread changes with aging are not necessarily mutually exclusive. For instance, Salthouse et al. (2003) observed that executive functioning constructs, based on measures examining the ability to coordinate concurrent activities (time sharing), to update internal representations (updating), and to suppress prepotent responses, mediated age-related decline in various cognitive abilities, including fluid intelligence, episodic memory, and perceptual speed. However, caution was advised in interpreting the mediational aspects of this result due to substantial overlap observed between executive and cognitive abilities measured. For instance, correlations between executive constructs (updating and time sharing) and fluid intelligence was greater than .85.

In light of overlapping and widespread cognitive changes with age, a number of general, single factor theories have been developed that endeavor to explain declines across various cognitive domains. These approaches range from explanations at cognitive levels to changes at neuranatomical/neurochemical levels.

1.2 Cognitive theories of cognitive decline with age

Resource theories of aging emphasize that with aging comes reduced processing resources to adapt to changing environmental dynamics, particularly as processing demands increase. Such reduced resources have been characterized as reduced attentional resources (e.g., Craik 1983, 1986; Craik & Byrd, 1982) and working memory capacity (e.g., Light, Zelinski, & Moore, 1982). Consequently, as noted by Craik and colleagues, age-related declines emerge on measures in which contextual/environmental support is minimal, thereby placing more demands on self-initiated processing, which is presumed to decline with aging. A notable example consistent with this perspective is the observation of strong age effects in free recall, which rely heavily on self-initiated processing, as opposed to minimal age effects in recognition and cued recall tasks (see review in Zacks et al., 2000). Older adults' reduced performance in dual task situations, which involve performing two tasks simultaneously (e.g., talking while driving), is also compatible with reduced cognitive resources with aging (see review in Li, Krampe, & Bondar, 2005). Capacity and processing resource theories have been criticized, however, for lacking specification and for embedded circular logic as age differences in cognitive measures are viewed as evidence of age differences in cognitive resources (Kail & Salthouse, 1994).

The consistent finding of reduced perceptual speed with aging has been formalized in the generalized slowing account of aging (Birren, 1965; Salthouse, 1996). Evidence in favour of this account is the finding of sizeable reductions in age-related variance on cognitive measures (e.g., memory, interference control) when measures of perceptual speed (e.g., Digit Symbol Substitution Test, Wechsler, 1981) are controlled (e.g., Salthouse, 1991; Salthouse & Babcock, 1991; Salthouse &

Meinz, 1995). Two mechanisms have been proposed to explain such negative consequences of reduced processing speed: the limited time mechanism in which early cognitive operations necessary for task performance is slowed, thus, restricting the time available for later operations; and the simultaneity mechanism in which products of early cognitive operations are lost by the time later processing operations are completed (Salthouse, 1996). For instance, working memory functioning, as assessed by the reading span task (Daneman & Carpenter, 1980), provides an apt example of how the limited time and simultaneity mechanism interfere with task performance. In this task, participants process individually presented sentences (e.g., make semantic judgments) while attempting to remember the last words of each sentence. After a set number of sentences are presented (typically ranging from 2 to 6), participants are cued to recall sentence final words. If older adults are slow to process sentences, more time will elapse between when final words are encoded and when they are cued for recall, thereby increasing susceptibility for the words to be lost by temporal decay or interference, consistent with the simultaneity mechanism. If time is limited however and older adults are not able to completely process sentence information and final words, the limited time mechanism predicts reduced performance (see Titz, 2010, for results consistent with these predictions).

While the processing speed account has been studied extensively (Salthouse, 1996), it has been criticized for being too descriptive, for ignoring task-specific processes and slowing, for the observation that age often continues to predict cognitive performance over and above speed, and for the fact that other cognitive functions (e.g., working memory functioning) provide stronger mediational effects (e.g., Fisk, Fisher, & Rogers, 1992; Hertzog, 2008; Madden, 2001). Processing speed measures have also been criticized for tapping mechanisms of interference control, as standard speed measures often present multiple stimuli simultaneously, an approach that may be disadvantageous to older adults, who have difficulty focusing their attention on task-relevant stimuli (Lustig, Hasher, & Tonev, 2006; See Inhibition section below). Further, divergent age-related slowing effects have been shown across cross-sectional and longitudinal studies. For instance, whereas processing speed and memory functioning shared 71% of age-related variance in cross sectional work (Verhaeghen & Salthouse, 1997), this reduces to modest amounts in longitudinal work (e.g., 37%, Lemke & Zimprich, 2005; e.g., 10%, Sliwinski & Buschke, 1999).

Moreover, in the Berlin aging study, mediational effects of speed on intellectual functioning in older adults (age 70-103) were less powerful than measures of visual and hearing acuity (Lindenberger & Baltes, 1994). In combination, visual and hearing acuity accounted for 93.1% of age-related variance in intellectual functioning, comprising measures of reasoning, memory, speed, fluency, and knowledge (with similar findings when individuals with extremely poor sensory acuity were excluded). Such findings are consistent with the ‘common cause’ hypothesis of aging (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994) in which it is postulated that age-related changes in a common underlying factor(s), such as physiological integrity of the brain, is responsible for the observation of increased interdependence between sensory and cognitive functioning with age (for contrary findings, e.g., Anstey, Hofer, & Lucz, 2003; Batterham, Christensen, & Mackinnon, 2011).

The ‘common cause’ hypothesis can be viewed as an extension of the dedifferentiation hypothesis of aging in which cognitive abilities become more differentiated in childhood and less differentiated (dedifferentiate) with the aging process (e.g., Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980). In particular, the dedifferentiation hypothesis is extended to include convergence of abilities within and across domains (e.g., sensory and cognitive). A potential ‘common cause’ for such differentiation is increased ‘neural noise’ stemming from age-related reduction of catecholaminergic (e.g., dopamine and norepinehrine) modulation in cortical and subcortical regions (S-C. Li, Lindenberger, & Sikström, 2001). For instance, increased ‘neural noise’ may reduce distinctiveness of neural representations and interference control (see S-C. Li et al., 2001, for computational modeling of this approach). Alternatively, evidence of such cross-domain dedifferentiation may be the direct consequence of sensory declines with aging reducing the cognitive performance of older adults (see reviews in Burke & Osborne, 2007; Schneider & Pichora-Fuller, 2000; but also see Anstey, Dain, Andrews, & Drobny, 2002; Anstey, Hofer, & Luszcz, 2003).

In their review of cross-sectional and experimental research on the relationship between sensory/sensorimotor and cognitive functions with age, K.Z.H. Li and Lindenberger (2002) suggested that evidence of increased interdependence across domains is also consistent with a shared resource model. In particular, such interdependence may reflect increased cross domain competition for limited resources with age. Thus, a more complete model of aging likely rests on a combination of common cause(s) with subsequent neural reorganization and strategy modification to allocate limited resources accordingly (K.Z.H. Li & Lindenberger, 2002). Together, such an approach bridges cognitive changes to underlying physiological changes. The locus of such common factor(s), neural reorganization to compensate for such changes, and the consequent impact on cognition has been an active area of research.

1.3 Neurocognitive approaches to cognitive decline with age

Advances in neuroimaging and neurophysiological research have allowed researchers to better bridge the cognition-brain gap with aging**.** For instance, older adults often evince bilateral activation during task performance in prefrontal as well as other brain regions (e.g., medial temporal lobes) in functional imaging studies, a finding formalized in the hemispheric asymmetry reduction in older adults (HAROLD) model; this is especially the case as task demands increase, suggesting a three-way interaction between age, task difficulty, and laterality (see reviews in Cabeza, 2002; Daselaar & Cabeza, 2005; Dennis & Cabeza, 2008). Two interpretations have been proposed to explain this result (Cabeza, 2002). In particular, such bilateral activation can be interpreted as evidence of reduced specialization of neural mechanisms mediating cognitive performance, consistent with integration/dedifferentiation of cognitive processes with age (as reviewed above). Alternatively, this reduced lateralization with age may serve a compensatory function, evidenced by observed positive relationships between bilateral activation and task performance in older adults (e.g., Cabeza, Anderson, Locantore, & McIntosh, 2002; Reuter-Lorenz et al., 2000). These two interpretations are not mutually exclusive, however, as the dedifferentiation of neural mechanisms can be construed as serving a compensatory function (Cabeza, 2002).

As noted in Reuter-Lorenz and Cappell (2008) and Reuter-Lorenz and Lustig (2005), the compensatory function of neural over-activation may help older adults address problems of reduced sensory and perceptual functioning, reduced ability to modulate brain regions mediating task-irrelevant processing, and under-activation of task relevant regions. Consistent with the latter are findings of decreased activation in posterior regions (e.g., occipital cortex) coupled with increased activation in anterior regions (e.g., prefrontal cortex) with aging on multiple measures of cognitive functioning (so called posterior-anterior shift in aging, i.e., PASA pattern; Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008; Dennis & Cabeza, 2008; Grady et al., 1994).

Recruitment of anterior regions is often conceptualized as paradoxical especially given findings of the age sensitivity of these regions to cognitive decline across animal, neuropatholgoical, neurophysiological, and neuroimaging research (West, 1996). Notably, areas of cognitive functioning mediated by prefrontal regions, such as executive functioning (Miller & Cummings, 2007; Stuss & Knight, 2002), are more affected by aging, a notion that forms the basis of the frontal lobe hypothesis of aging (Dempster, 1992; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Moscovitch & Winocur, 1992, 1995; West, 1996; but see Greenwood, 2000, for a contrasting view). A related hypothesis is the goal maintenance account of aging in which age-related changes in the lateral prefrontal cortex are posited to cause difficulty representing, maintaining, and updating task-relevant information; such cognitive control is deemed necessary for multiple cognitive operations (episodic retrieval, prospective memory, working memory functioning, inhibitory control;

Braver & West, 2008). Therefore, the compensatory function often indicated by anterior recruitment (e.g., PASA) is likely a reflection of the versatility of prefrontal areas to aid task performance as compared to more functionally dedicated brain areas (e.g., hippocampus for memory and the ventral visual cortex for object recognition, Parker & Reuter-Lorenz, 2009)

Nevertheless, differential age-related decline in prefrontal functioning (Braver & West, 2008; West, 1996) likely limits the extent to which older adults can compensate for task performance. For instance, Cappell, Gmeindl, and Reuter-Lorenz (2010) found that increased activation in prefrontal areas mediated older adults' performance at the level of younger adults, but only when task demands were low; at higher task demands, reduced performance was coupled with reduced prefrontal activation. Such limits to compensatory efforts with aging have been conceptualized in the compensation-related utilization of neural circuits hypothesis (CRUNCH; Reuter-Lorenz & Lustig, 2005; Reuter-Lorenz & Mikels, 2006; see Cabeza & Dennis, in press, for a more expanded model). In line with the compensation account, the lifespan scaffolding theory of aging and cognition (STAC; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2010) posits that cognitive functioning, particularly in older adults, represents a combination of age-related neural deterioration (e.g., dopamine depletion, white matter abnormalities, etc.) and responsive neural reorganization (compensation) efforts.

1.4 Summary of cognitive and neurocognitive theories of cognitive aging

In sum, multiple areas of cognitive functioning are impacted by age, including working memory, attention, perceptual speed, multiple executive functions, and episodic and prospective memory, among others. To explain these changes, multiple approaches have been proposed that range from cognitive (e.g., reduced cognitive resources) to neurocognitive approaches (e.g., structural and functional changes in prefrontal areas). There is likely much overlap between these different approaches to aging as neurochemical changes (e.g., catecholmingergic modulation) with age impact on frontal lobe functioning and other brain regions. Coupled with reduced sensory/sensorimotor functioning, these age-related changes likely result in widespread changes across multiple cognitive domains.

Issues of compensation are dominant throughout aging approaches, such as contextual/environmental support to aid performance given reduced cognitive resources, and bilateral activation to aid task performance. Such compensatory themes across aging theories may reflect attempts by the aging brain to adjust for reduced cognitive control function(s) and/or processing resources that constrain higher order abilities (e.g., memory, reasoning). For instance, Reuter-Lorenz et al. (2000) observed that younger adults recruited frontal regions in the left and right hemispheres during tasks requiring short-term maintenance of verbal and spatial information, respectively. However, older adults had bilateral frontal activation during each task, suggesting that the additional activation may have served to compensate for difficulty maintaining task-relevant information in working memory (e.g., Braver & West, 2008; Verhaeghen & Basak, 2005). Such neural reorganization by the aging brain is suggestive of attempts to address declines in various cognitive abilities. These include the ability to suppress/inhibit irrelevant information during task performance (Dempster, 1992; Hasher & Zacks, 1988), quickly process task-relevant information (Salthouse, 1996), and coordinate activities between multiple tasks, as in mental set shifting (e.g., Verhaeghen & Cerella, 2002) and dual task performance (e.g., Kray & Lindenberger, 2000). While these various abilities have been proposed to mediate wide-spread cognitive decline with age and come from divergent theoretical backgrounds, inhibitory control functions have been posited to underlie the observed age-related declines across these cognitive functions (Dempster, 1992, 1995; Hasher, Lustig, & Zacks, 2007; Hasher et al., 1999; Lustig, Hasher, & Zacks, 2007). In particular, inhibitory control processes are postulated to reduce the extent to which interfering, task-irrelevant information disrupts the speed of ongoing processing, the ability to process and maintain task relevant mental sets (single or multiple) in conscious awareness, and the ability to suppress interference when switching mental sets. To advance this inhibitory account however, it is necessary for the conceptualization of inhibitory control functions and age-related changes therein to be clearly delineated, issues that continue to be challenging in cognition and aging research, as outlined below.

1.5 Inhibition

Central to everyday functioning is the ability to selectively attend to currently relevant goals while resisting interference from distracting information. Interference may emanate from multiple sources in our daily lives (both internal and external), and has been defined in cognitive theories as "cognitive competition among multiple stimuli, processes, or responses" (Harnishfeger, 1995, p. 189). A classic task used to examine the ability to control interference is the Stroop task (Stroop, 1935) in which individuals are required to name the colour of words presented that are printed in incongruent ink colour (e.g., the word RED printed in blue ink). The typical finding is increased response latencies and errors when reading such incongruent coloured words as opposed to congruent coloured words or neutral stimuli in which interference is minimized (e.g., series of Xs or words printed in black ink). Presumably, this difficulty resisting interference in the Stroop task is the result of problems withholding the more dominant (and habitual) tendency to read words in favour of the less dominant requirement to name the colours of words. Such difficulty in the Stroop task has been shown to undergo developmental changes (see review in MacLeod, 1991), with reduced performance in older adults (e.g., Spieler, Balota, & Faust, 1996; West & Alain, 2000).

In the cognitive literature, the ability to resolve interference in measures such as the Stroop task have often been related to the ability to inhibit/suppress irrelevant information during task performance (e.g., Bjorklund & Harnishfeger, 1995; Dempster, 1992, 1995; Hasher & Zacks, 1988; but see MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003 for contrasting views). The Stroop task is one of many such tasks that presumably rely on interference control mechanisms inherent in inhibitory control functions; others include the Wisconsin Card Sort task and Brown-Peterson Task, which assess resistance to proactive interference (see reviews of such tasks in Dempster, 1992). Below I briefly review different approaches developed to conceptualize inhibitory functions in the cognitive literature before narrowing the focus to inhibitory functioning and working memory in the aging literature.

1.6 Conceptual distinctions in inhibitory functions

With origins in the developmental literature, Harnishfeger (1995) distinguished between behavioural inhibition and cognitive inhibition. Behavioural inhibition involves controlling overt behaviour (e.g., suppressing motor response, impulse control). Cognitive inhibition involves controlling cognitive contents or processes, and is further distinguished along an intentional (e.g., suppressing irrelevant information in working memory) and unintentional dimension (e.g., suppressing the context-inappropriate meaning of polysemous words). Similar to Harnishfeger's taxonomy, originating in the psychopathological literature, Nigg (2000) distinguished inhibitory functioning along an intentional (effortful) and automatic dimension. Intentional inhibition included interference control (suppressing interference from resource or stimulus competition), cognitive inhibition (preventing irrelevant information from entering working memory), behavioural inhibition (preventing prepotent response execution), and oculomotor inhibition (restraining reflexive saccades). Automatic inhibition is reflected in suppressing recently viewed stimuli/locations (as in inhibition of return) or suppressing information at unattended locations while focusing elsewhere.

From a cognitive aging perspective, Hasher and colleagues' (Hasher & Zacks, 1988; Hasher et al., 1999) conceptualization of inhibitory function includes the access function, which prevents task-irrelevant information from entering working memory, and the deletion function, which suppresses information that is no longer relevant to task performance. For instance, the access function is posited to suppress/dampen interference in reading with distraction tasks (Connelly, Hasher, & Zacks, 1991; Kim, Hasher, & Zacks, 2007), whereas the deletion function is engaged to suppress encoded items that are instructed to be forgotten in directed forgetting tasks (Zacks, Radvansky, & Hasher, 1996). Together, these two inhibitory functions closely correspond to Nigg's (2000) interference control and Harnishfeger's (1995) cognitive inhibition. Hasher et al. also proposed the restraint function of inhibition to prevent execution of prepotent, but inappropriate, responses, which corresponds to behavioural inhibition in Nigg's and Harnishfeger's taxonomies (see also Dempster, 1993; Rafal & Henik, 1994, for similar distinctions across inhibitory functions).

Recently, Friedman and Miyake (2004) proposed that distinct inhibitory functions may act at different stages of information processing. For instance, inhibitory functions may act at early processing stages when relevant information should be selected while irrelevant information is ignored; at intermediate stages to regulate working memory contents by suppressing activated but irrelevant information; and at output stages to execute appropriate responses, while resisting prepotent but inappropriate responses. At present however, limited evidence exists regarding the commonality and separability of inhibitory functions in young (e.g., Friedman & Miyake 2004; Nee, Wager, & Jonides, 2007; Sylvester et al., 2003) and older populations (e.g., Feyereisen & Charlot, 2008; Titz, Behrendt, Menge, & Hasselhorn, 2008).

Similar to Friedman and Miyake's (2004) information processing account of inhibitory functions, the close relationship between inhibition and concurrent processing (as in working memory storage and processing operations) is emphasized in the definition of inhibition by Lustig and colleagues (2007). They propose that inhibition is an "active, goal-directed process that acts in conjunction with automatic activation processes to control the contents of consciousness" (Lustig et al., p. 152). Consequently, inhibitory functions may have implications for performance across various cognitive domains (e.g., learning, memory retrieval, comprehension, and executive functioning; Dempster, 1992; Hasher et al., 1999, 2007).

1.7 The relationship between inhibition and working memory functioning with age

According to aging accounts of inhibitory functioning (Dempster, 1992, 1995; Hasher et al., 2007; Hasher & Zacks, 1988; Lustig et al., 2007), inhibitory control functions are posited to decline with age and as a consequence, older adults are less able to regulate the contents of working memory. In particular, it is proposed that older adults have difficulties restricting irrelevant information from entering working memory (reduced access function) and preventing no-longer-relevant information from persisting in working memory (reduced deletion function).

Understanding the role of age-related constraints on working memory functioning, such as inhibitory control, is an important endeavor as working memory performance has been shown to predict various higher order abilities (e.g., Conway, Kane, & Engle, 2003; Daneman & Carpenter, 1980; Kyllonen & Christal, 1990; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). More relevant for present purposes, working memory functioning has been shown to decline with aging (e.g. Bopp & Verhaeghen, 2005; Salthouse, 1994; Verhaeghen & Salthouse, 1997), thereby impacting higher order functioning with age, including long term memory, language processing (comprehension and text recall), reasoning, and spatial ability (e.g., Kwong See & Ryan, 1995; Park et al., 1996, 2002; Verhaeghen & Salthouse, 1997).

In cognitive research, examination of working memory performance has largely been conducted with complex span measures, such as the reading span (Daneman & Carpenter, 1980; Daneman & Merikle, 1996) and operation span tasks (Turner & Engle, 1989) (for a review of approaches, see Conway et al., 2005). Whereas simple span measures require maintaining information online (e.g., repeating a short list of items to oneself), complex span measures involve simultaneous maintenance (storage) and processing activities (e.g., read sentences while retaining sentence final words) (Conway et al., 2005; Daneman & Carpenter, 1980). Assessment of working memory performance with complex span measures correspond with Baddeley's model of working memory (Baddeley, 1986; Baddeley & Hitch, 1974) in which two slave systems (phonological loop and visuospatial sketchpad) are responsible for storage operations whereas a central executive component performs processing operations (e.g., monitoring, coordinating, scheduling other operations; also see Baddeley, 2000, 2001, for the more recent addition of the episodic buffer to store multimodal information).

To examine complex span performance with age, the approach has largely been to use variance partitioning procedures (e.g., regression analyses, path analyses, structural equation modeling) to examine the extent to which age-sensitive processes account for age differences in complex span performance. With these approaches, inhibitory control has been shown to be one individual difference factor that undergoes age-related decline and consequently impacts complex span performance (e.g., Persad, Abeles, Zacks, & Denburg, 2002). Other proposed factors include, but are not limited to: storage capacity (e.g., Verhaeghen, Marcoen, & Goossens, 1993), mental set shifting (e.g., Kray & Lindenberger, 2000; Mayr, 2001), processing efficiency/speed (e.g., Salthouse, 1996), goal maintenance (e.g., Braver & West, 2008; McCabe, Robertson, & Smith, 2005), switching the focus of attention (e.g., Basak & Verhaeghen, 2011; Verhaeghen & Basak, 2005) and dual-task coordination (e.g., Verhaeghen & Cerella, 2002). Despite this lengthy list of factors, inhibition deficit accounts (Dempster, 1992; Hasher et al., 1999, 2007) conceptualize inhibitory control as a 'cognitive primitive', irreducible to other cognitive processes; thus, inhibitory changes with age are presumed to significantly underlie changes in these other processes as well, thereby explaining their relation to working memory performance.

For instance, Daneman and colleagues (Daneman & Carpenter, 1980; Daneman & Tardif, 1987) advocated a processing efficiency explanation of complex span performance, noting that increased efficiency on processing components allows individuals more time to rehearse/refresh stored items. Consistent with this reasoning, reduced perceptual speed has been shown to explain age-related variance in working memory performance (Salthouse & Babcock, 1991; Salthouse & Meinz, 1995). However, tasks assessing perceptual speed have been criticized for assessing processes beyond speed. As demonstrated by Lustig et al. (2006), when target items were presented individually in the Digit Symbol Substitution Test (Wechsler, 1997), a frequently utilized measure of perceptual speed, age-related perceptual speed differences were significantly reduced. This result suggest that embedding target stimuli amongst distracting stimuli, as per standard administration of many processing speed tasks, taps into the ability to resist interference. Thus, inhibitory functions may be involved in such speeded measures and partially account for their relation with working memory functioning.

In addition, there has been suggestive evidence that complex span measures involve inhibitory control functions to reduce proactive interference. For instance, in the standard administration of the reading span task, smaller set sizes are presented early whereas larger set sizes are presented later, thereby allowing for proactive interference buildup on these larger set sizes. For groups susceptible to proactive interference, such as older adults, reducing such interference by presenting larger set sizes early has been shown to improve their reading span performance to the same level as younger adults (Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999).

However, despite such supportive evidence of the role of inhibitory functioning in working memory performance (both verbal and visuospatial working memory; e.g., De Beni & Palladino, 2004; May et al., 1999; Oberauer, 2001; Persad et al., 2002; Rowe, Hasher, & Turcotte, 2008), contrary evidence exists. For instance, McCabe and Hartman (2003) examined whether age-related decline in complex span performance (reading and list span tasks) was accounted for by age-related changes in storage capacity, dual task coordination, inhibitory efficiency, perceptual speed, and language processing (syntactic processing and semantic integration). Using a hierarchical regression approach, storage capacity and perceptual speed together completely explained age differences in complex span performance; inhibitory efficiency, measured by intrusion errors in complex span tasks, was not included in the model due to the lack of age-related effects. Such inconsistent findings regarding the inhibition-working memory relationship with aging possibly reflects a number of moderating factors, such as how inhibitory functions are measured and operationalized.

Moreover, research on working memory performance using complex span measures have primarily relied on storage components as the dependent measure (e.g., end-word recall in reading span task; but see Li, 1999; Waters & Caplan, 1996). Thus, the extent to which various factors (e.g., inhibitory efficiency and speed) influence both working memory components remains largely unexplored. Notably, a better understanding of factors that influence both working memory components have implications for clarifying the relationship between working memory performance and higher order abilities (e.g., fluid reasoning; Unsworth, Redick, Heitz, Broadway, & Engle, 2009).

1.8 Inhibition and aging

Despite some successes inhibition deficit accounts have had in explaining higher order cognition (e.g., Dempster, 1992; Hasher et al., 2007; Lustig et al., 2007), process-level analyses to examine the nature of inhibitory changes with age have revealed a mixed picture (e.g., Burke, 1997; McDowd, 1997). This has led to the general acknowledgement among proponents of inhibitory deficit accounts that not all inhibitory mechanisms are age sensitive, such as spatial inhibitory processes (Zacks & Hasher, 1997). Moreover, additional specification of inhibitory changes with age is necessary given the observation of inconsistent age-related changes within specific inhibition functions and within specific tasks. For instance, in regard to a specific inhibition function, such as deletion-type inhibition, Maylor, Schlaghecken, and Watson (2005) observed age-related decline in inhibitory functioning in visual marking tasks (in which moving distracting stimuli had to be inhibited to prioritize target stimuli) and inhibitory aspects of the masked prime paradigm; however, age effects were absent in the Ranchburg effect in which repeated memory items are typically inhibited during serial recall. In regard to specific tasks, inconsistent findings in age-related decline in inhibition have been observed in tasks such as the Stroop task (Verhaeghen & De Meersman, 1998a) and the negative priming task (Gamboz, Russo, & Fox, 2002; Verhaeghen & De Meersman, 1998b). For instance, support for decline in inhibitory functioning with age has been observed in directed forgetting studies in which items presented (words or sentences) are instructed to either be remembered or forgotten; however, subsequent to item presentation, participants are given a surprise recall test for the entire item set. As shown by Zacks, Radvansky, and Hasher (1996), older adults show more intrusion errors in recall from items that were to be forgotten and evidenced smaller differences in recall of to-be-remembered vs. to-be-forgotten words compared to younger adults. Despite such supportive evidence of inhibitory deficits, equally contrary evidence has been observed in this directed forgetting task (e.g., Sego, Golding, & Gottlob, 2006; Zellner, & Bäuml, 2006).

In light of these inconsistencies, a number of moderating factors of age-related inhibition deficits have been proposed, such as the level of inhibitory control, with the stipulation that age-related changes are specific to high-level (consciously controlled) as opposed to low-level (automatically triggered) inhibitory processes (Andrés, Guerrini, Phillips, & Perfect, 2008; Collette, Germain, Hogge, & Van der Linden, 2009; Kramer et al., 1994). Moreover, Guerreiro, Murphy, and Van Gerven (2010) recently suggested that the ability to resist distraction may be modality dependent, with specific age-related effects in the visual, as opposed to the auditory, modality and when resisting distracting information in one sensory modality, rather than across modalities. Others have suggested that age-related effects in inhibitory functioning might be dependent on a number of other factors including the working memory load involved in the tasks used (e.g., McCabe et al., 2005), downstream effects of older adults' reduced processing speed (Salthouse, 1996), and the nature of stimuli employed (e.g., stationary vs. moving stimuli, Watson & Maylor, 2002; target detection vs. colour discrimination, Langley, Fuentes, Vivas, & Saville, 2007).

Another moderating factor and possible confound in regard to mixed findings was recently proposed by Maylor et al. (2005). These authors pointed out that a potential confound in extant research may be the assessment of inhibitory functioning at a single time point (i.e., use of single inter-stimulus intervals within trials and/or across experimental blocks; see also Schlaghecken & Maylor, 2005). Such approaches might make it more difficult to observe whether older adults have more difficulty engaging inhibitory functions in a manner consistent with younger adults, which goes beyond the effects of age-related general slowing and may have negative consequences on cognition. For instance, if older adults have difficulty initiating inhibitory functions, as hypothetically illustrated in Figure 1.1., then research examining inhibitory efficiency at early time points (e.g., Point B in Figure 1.1) may yield age differences. However, if later time points are examined (e.g., Point C in Figure 1.1), no age effects are likely to be observed. Thus, differences in inhibitory functioning might depend on where in the time course age group comparisons are

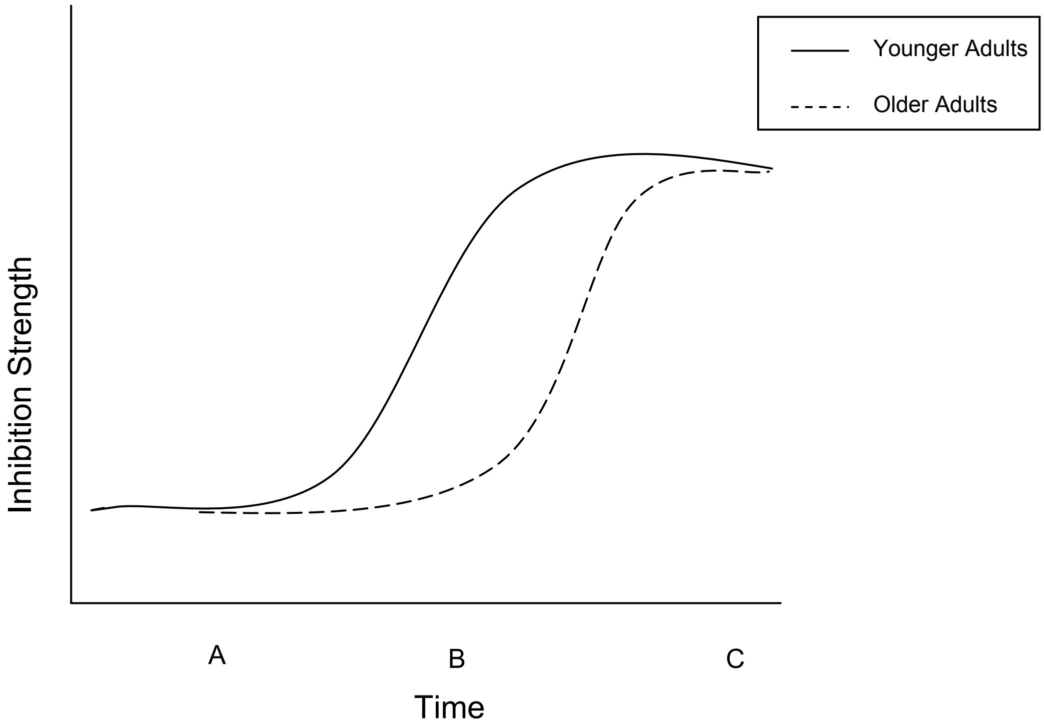

Figure 1.1. Inhibitory efficiency as a function of age group.

performed. As a consequence of assessing inhibitory efficiency at a single time point, studies showing the absence or presence of inhibitory functioning in older adults might be capturing this group at weak or strong points in their inhibitory time course, respectively.

However, findings thus far on the time course dynamics of inhibitory functioning with age are limited and in some cases inconsistent (e.g. Hasher, Stoltzfus, Zacks, & Rympa, 1991; Li & Dupuis, 2008; Schlaghecken & Maylor, 2005). Furthermore, controversy exists as to the validity of measures used to examine the time course of inhibition. For instance, Stoltzfus, Hasher, Zacks, Ulivi and Goldstein (1993) conducted a time course analysis of the negative priming effect, which is observed by slower responses to stimuli that were recently ignored compared to stimuli that were not recently presented; this effect is presumably the result of residual inhibition from previous trials to the same stimulus item. In their time course analysis, Stoltzfus and colleagues found that this effect was maintained as long as 1700 ms for young adults whereas older adults did not show evidence of negative priming at any time point. However, the precise nature of inhibitory functioning assessed in this task remains unclear, as many inhibitory functions are likely to be involved, an issue common to various measures of inhibition (e.g., Stroop task; Lustig et al., 2007). In particular, the response slowing observed on the target stimulus that was recently ignored likely depends on (1) the extent to which this stimulus in the ignore condition gains *access* to working memory, and (2) the extent to which it is consequently *deleted* (suppressed) after entering working memory. Moreover, other viable non-inhibitory explanations of the negative priming effect have been proposed such as the ability to resolve conflicting information when the same stimulus consecutively serves as a distractor and target (Neill & Valdes, 1992; Neill, Valdes, Terry, & Gorfein, 1992).

Unlike negative priming, the backward inhibition effect has been shown to be consistent with an inhibitory rather than a non-inhibitory account (Mayr, 2002). Using a sequential flanker paradigm, Li and Dupuis (2008, Expt. 3) observed age invariance in backward inhibition across time delays of 2000 to 3000 ms. It is possible however that older and younger adults may show differences in inhibitory functioning if earlier time points were examined. Indeed, in a time course analysis of another type of inhibitory process, namely inhibition of return, Castel, Chasteen, Scialfa, and Pratt (2003) found age effects between 50 and 3000 ms. Inhibition of return is typically observed by reduced ability to detect a target that appears (> 300 ms) in a recently cued location. Castel et al. observed that the inhibition of return effect was delayed in older adults compared to younger adults; however, older adults' difficulty disengaging attention from the cued location may have caused a delay in when their inhibition of return was observed. More consistent evidence of age-related changes in the time course of inhibitory functioning has been shown recently in neurophysiological research (Gazzaley, et al., 2008; Jost, Bryck, Vogel, & Mayr, 2001) and in a more low-level cognitive task, the masked prime paradigm (Maylor, Birak, & Schlaghecken, 2011; Schlaghecken, Birak, & Maylor, 2011).

Taken together, the proposition that inhibitory functioning declines with age has evidenced mixed findings. Such process-level findings question the validity of the age-sensitivity of inhibitory functions and suggest that the nature of inhibitory functioning with age needs further specification (Maylor et al., 2005). In light of this, the recent suggestion of time course changes in inhibitory functioning with age warrants closer examination given limited but somewhat consistent recent findings.

1.9 Summary of inhibitory and working memory functioning with age

Interference control mechanisms, namely inhibitory control functions, have been proposed to be integral to everyday functioning and to evidence reduced efficiency with age. Such reduced efficiency presumably allow task-irrelevant information to interfere with ongoing processing, thereby impacting higher order abilities, such as working memory functioning. However, research on age-related decline in inhibitory functioning continues to be mixed. Moreover, the extent to which inhibitory decline accounts for age-related working memory decline has received little attention from a variance partitioning approach. This is particularly in regard to both processing and storage components of working memory functioning, an issue that is not unique to inhibitory explanations of working memory decline (e.g., processing speed explanations). Notably, processing and storage operations are central to the conceptualization of working memory (Baddeley, 1986; Miyake & Shah, 1999) and both have implications for higher order cognition (e.g., fluid abilities). Further, inconsistent findings from process-level research that examines the nature of inhibitory changes with age, such as in deletion-type inhibition, suggest that additional specification of inhibitory functioning with age is needed. To this end, recent research has explored the possibility that older and younger adults may evidence differences in when they are able to engage inhibitory functions, an issue that goes beyond the effects of age-related general slowing. Notably, this possibility is difficult to ascertain as most research thus far has examined inhibitory functioning at a single time point. However, at present, endeavors to examine time course changes have been few, as outlined above.

In the present work, I aimed to address the aforementioned issues in extant research, primarily in regard to examining working memory performance at a global rather than componential level, and the potentially limiting effect of examining inhibitory processes at a single time point. Thus, my first goal was to examine the extent to which inhibitory efficiency accounted for age differences in measures of working memory components (processing and storage). To address this goal, I utilized a variance partitioning approach (hierarchical regression analyses) to examine the relationship between age differences in inhibitory efficiency and working memory components. The strength of this approach is that it reveals the extent to which age-related changes in cognitive processes in one task covary with other processes in another measure, while controlling for (covarying out) variance related to competing constructs (e.g., generalized slowing; Salthouse, 2000). Further, this approach is complemented by process-level approaches that better specify the nature of cognitive constructs of interest in a particular task. Thus, for my second goal, I utilized this process-level approach to examine whether older adults have more difficulty engaging inhibitory functioning in a manner consistent with younger adults, which goes beyond the effects of age-related general slowing.

Moreover, I examined these goals in the context of a sequential paradigm as sequential tasks are ubiquitous to everyday functioning and impaired performance on such tasks has important implications for older adults' ability to live independently. I employed the Sequential Action Paradigm (Li, Blair, & Chow, 2010; Li, Lindenberger, Rünger, & Frensch, 2000) in which participants are required to monitor for a learned sequence of targets among trials of randomly ordered stimuli. In the studies presented, I investigated deletion-type inhibition within this sequential paradigm by examining: (1) intrusion error rates, specifically responses to already-completed targets (Study 1 and Study 2) and response latency on repeated presentations of already-completed targets (Study 3).

1.10 Current studies

Based on inhibition deficit accounts of aging (Dempster, 1992, 1995; Hasher et al., 1999, 2007; Lustig et al., 2007), in Study 1, I predicted that inhibitory efficiency would account for age differences in working memory components, as measured by the reading span task (Daneman & Carpenter, 1980). In Study 2, I predicted that older adults would evidence a delay in the time course of deletion-type inhibitory functioning, consistent with recent studies (e.g., Gazzaley et al., 2008; Schlaghecken et al., 2011). Such a finding has implications for a more detailed specification of how inhibitory functioning changes with aging. However, because of limitations in Study 2, particularly in regard to the low error rates obtained in our dependent measure, the methodology was updated in Study 3. In this study, I attempted to go beyond error data (the primary dependent measure in prior work) and broadened my view to other parameters of time course indices of inhibitory functioning within the sequential paradigm, specifically by using response latency to index inhibitory efficiency.

Chapter 2

The role of age and inhibitory efficiency in working memory processing and storage components

2.1 Abstract

In this study, we examined the extent to which inhibitory efficiency accounted for age-related decline in the processing and storage components of working memory. Older and younger adults performed a sequential task which served as an index of Deletion-Type inhibition (the ability to suppress no-longer relevant information). The reading span task was used to measure working memory components by examining processing accuracy, processing time, and end-word recall of sentences presented. Reduced inhibitory efficiency, which was poorer in older adults, predicted age-related decline in recall, over and above the effects of processing speed. Similar results were observed for processing accuracy, although the age effect in this component was marginal. These results highlight the important role of Deletion-Type inhibition in explaining age-related decline in working memory performance, particularly in the storage component, and extend previous research by examining this relationship at a componential level.

2.2 Introduction

Working memory is a multi-component limited capacity system responsible for the simultaneous storage and processing of goal-relevant information (Baddeley, 1986; Baddeley & Hitch, 1974). Working memory performance as measured by complex span tasks consistently predicts higher-order cognitive abilities including language comprehension (Daneman & Carpenter, 1980), complex reasoning (Kyllonen & Christal, 1990), and fluid intelligence (Conway, Kane, & Engle, 2003). In the aging literature, a large body of research shows age-related decline on measures of working memory (e.g., Bopp & Verhaeghen, 2005; Salthouse, 1994; Verhaeghen & Salthouse, 1997). Although various mediators of age differences in working memory have been proposed, such as speed and inhibition (Dempster, 1992; Hasher, Zacks, & May, 1999; McCabe & Hartman, 2003; Salthouse, 1996), it is unclear how these mediators relate to decline in working memory components (processing and storage). A better understanding of whether mediators of age differences in working memory differentially predict storage and processing components is essential to understanding the predictive utility of working memory in higher-order cognition. Therefore, the goal of the present study was to examine the extent to which indices of inhibition and processing speed independently contribute to age-related decline in processing and storage components of working memory.

Inhibitory control and working memory

Complex span tasks are generally used to measure working memory functioning as they involve simultaneous processing and storage of information (Daneman & Carpenter, 1980; Turner & Engle, 1989; Unsworth, Redick, Heitz, Broadway, & Engle, 2009). For instance, in the reading span task (Daneman & Carpenter, 1980), a typical measure of working memory performance, participants read a series of unrelated sentences while trying to retain the last word of each sentence. Sentences are typically presented individually (usually starting with sets of two) and are subsequently increased depending on whether individuals show correct recall as set sizes increase. Older adults generally show reduced performance on these measures compared to younger adults (Bopp & Verhaeghen, 2005; Borella, Carretti, De Beni, 2008; Salthouse, 1991, 1994; Verhaeghen & Salthouse, 1997; Waters & Caplan, 2001). However, cognitive processes mediating age-related decline on complex span tasks have been a source of debate (e.g., Hale, Myerson, Emery, Lawrence, & DuFault, 2007; Jarrold & Bayliss, 2007; Lustig, Hasher, & Zacks, 2007; Salthouse & Babcock, 1991).

A large body of research shows that deficits in storage capacity (e.g., McCabe & Hartman, 2003; Verhaeghen, Marcoen, & Goossens, 1993) and processing efficiency, as measured by processing speed (e.g., Salthouse, 1996; Salthouse & Babcock, 1991; Salthouse & Meinz, 1995), mediate age-related decline in working memory performance. It is not surprising that storage capacity predicts complex span performance, as the criterion measure of complex span performance is typically based on the highest level of recall. In addition, a slow down in processing speed with age does not completely mediate age-related working memory deficits (e.g., Verhaeghen, Kliegl, & Mayr, 1997), suggesting that other processes may also be important, such as inhibitory control (Dempster, 1992; Lustig et al., 2007). For instance, using an updating working memory task, which shares cognitive processes with complex span measures (Schmiedek, Hildebrandt, Lövdén, Wilhelm, & Lindenberger, 2009), Persad, Abeles, Zacks, and Denburg (2002) showed that a group of inhibition measures accounted for more variance than processing speed in working memory performance. In addition, the inhibition measures used significantly accounted for variance even after controlling for processing speed; however, processing speed did not account for variance above and beyond inhibitory measures. Instead of using a group of inhibition measures from different tasks, an alternative approach would be to isolate a specific inhibitory function and examine its role in working memory functioning of older adults.

Hasher and colleagues (1999, 2007) have proposed that older adults' deficits on complex cognitive tasks are due to the inefficient operation of different inhibitory functions, namely access, deletion, and restraint: the access function prevents irrelevant information from intruding into conscious awareness; the deletion function suppresses activation of no-longer relevant information; and the restraint function prevents the inappropriate execution of overlearnt responses. When assessing age-related working memory decline with complex span tasks, Deletion-Type inhibition is particularly relevant (Hasher et al., 2007; Lustig et al., 2007). With deficient inhibition of no-longer relevant information, interference from smaller set sizes in complex span tasks build up and proactively interfere with performance on larger set sizes, which are presented later in the standard administration format. By this view, reducing proactive interference from previously presented items should improve working memory performance for older adults by increasing end-word recall and reducing intrusive responses. Results consistent with this notion have been found. For instance, in a series of studies from Hasher and colleagues (Chiappe, Hasher, & Siegel, 2000; Lustig, May & Hasher, 2001; May, Hasher, & Kane, 1999; Rowe, Hasher, & Turcotte, 2008), age differences in working memory performance were eliminated or significantly reduced when complex span tasks were presented in mixed or reversed format, allowing for longer span trials to be presented earlier rather than later. Thus, this approach appears to reduce the effects of proactive interference on larger set sizes, thereby reducing the need for Deletion-Type inhibition.

Along similar lines, it is presently unclear whether different cognitive processes, such as inhibition, influence age-related deficits in storage, processing, or both components of working memory, despite a large literature in predicting age-related working memory decline. As pointed out by Unsworth et al., (2009), research thus far with complex span tasks generally uses span score as the criterion measure of working memory performance (c.f. Li, 1999; Waters & Caplan, 1996). Thus, this approach essentially measures the storage component in complex span performance, whereas the processing component is indirectly measured, based on the assumption that processing operations will influence recall.

It has been shown that both storage and processing components of working memory predict higher-order ability (e.g., Unsworth et al., 2009). What is not yet clear is whether and how mediators of age differences in working memory predict storage as well as processing components. From an inhibition deficit viewpoint (Dempster, 1992; Lustig et al., 2007), if older adults have reduced ability to suppress no-longer relevant information, this previously relevant information should proactively impact on storage as well as processing aspects of complex span performance. Thus, in the reading span task, previously relevant information that is not removed from working memory should build up and interfere with the ability to recall and efficiently process sentence information. Consistent with this notion, Li (1999) observed increased age differences when processing and storage stimuli were categorically similar (e.g., processing and storing both verbal information) compared to when they were dissimilar (e.g., processing verbal and recalling numerical information). Amongst other interpretations, reduced inhibitory ability in older adults was proposed to explain older adults' difficulty with interference from overlapping stimuli. It should be noted that older adults' interference deficits in complex span tasks and other measures are also consistent with non-inhibitory explanations, such as deficits in attentional control (McCabe, Robertson, & Smith, 2005).

Current study

Given the general approach to examining inhibitory effects on working memory performance at a global level, we aimed to examine the extent to which inhibitory efficiency accounts for age-related decline in measures of working memory processing and storage. We measured inhibitory efficiency in the context of a sequential task. Sequential activities are ubiquitous in everyday life and proper execution of such tasks is an important factor in deciding whether older adults live independently or need assistance (Gaugler, Duval, Anderson, & Kane, 2007). Theories of sequential action generally make two propositions, namely that (1) upcoming steps are activated and (2) upon completion, steps are dampened/suppressed (Arbuthnott, 1995; Cooper & Shallice, 2006; Estes, 1972; Houghton, 1990; Houghton & Tipper, 1996). Reducing the activation of completed steps has often been attributed to an inhibitory mechanism (e.g., self-inhibition), thereby allowing one to move forward in the sequence (Li, Blair, & Chow, 2010; Li, Lindenberger, Rünger, & Frensch, 2000). The utility of inhibition as an explanatory mechanism in sequential activities has gained support in the context of spelling (e.g., Houghton, Glasspool, & Shallice, 1994), mental arithmetic (e.g., Arbuthnott & Campbell, 2003), serial recall (e.g., Maylor & Henson, 2000), and everyday serial activities (e.g., Humphreys & Forde, 1998; see Schwartz, 2006 for a review).

In this study, older and younger adults overlearned a fixed sequence of target images. In the test phase, they monitored for a learned sequence of targets among trials of randomly ordered stimuli. Intrusion error rates, specifically responses to already-completed targets, were analyzed to assess Deletion-Type inhibitory efficiency (i.e., the ability to suppress no-longer relevant information). In the context of sequential tasks, such repeated responses to completed targets are akin to perseverative responses, which have been linked to reduced inhibitory functioning in older adults and individuals with frontal lobe damage (Humphreys & Forde, 1998; Kramer, Humphrey, Larish, Logan, & Strayer, 1994). On the other hand, anticipatory errors, responding to items ahead of the current goal, have been associated with heightened activation of to-be-completed goals (Goschke & Kuhl, 1993; Marsh, Hicks, & Bryan, 1999). Alternatively, both types of errors (repeated and anticipatory responses) may also represent difficulty updating goals during the sequential task; thus, it was important for us to examine whether repeated and anticipatory error types were distinct in predicting working memory components as proposed.

The reading span task was used to measure working memory performance, with the specific aim to separately examine storage and processing components. Based on the inhibition deficit account (Dempster, 1992; Hasher et al., 1999, 2007), we predicted that differences in Deletion-Type inhibitory functioning in young and older adults would mediate age-related decline in performance on working memory processing and storage, over and above the effects of processing speed.

2.3 Method

2.3.1 Participants

Thirty younger adults ($M = 22.6$, $SD = 3.3$) and 28 older adults ($M = 66.8$, $SD = 4.0$) participated in this study (one older adult was excluded due to a mean error rate that was 3*SDs* away from the mean in the sequential task). Younger adults were recruited from the Concordia University undergraduate participant pool in the Psychology Department. The older adults were recruited through a participant pool established by the Adult Development and Aging laboratories at Concordia University and also through posters placed in neighbourhood shops. Inclusion criteria for both young and older adults included fluency in English, and absence of medical, psychological, or motor conditions that could influence their cognitive performance. Years of education were not significantly different between younger ($M = 15.40$, $SD = 1.4$) and older adults ($M = 15.93$, $SD = 3.6$), $t(56) = 0.74$, $p > .05$. Both groups were also similar in general health status (older: $M = 3.61$, $SD = 1.10$; younger: $M = 3.70$, $SD = .84$), $t(56) = 0.36$, $p > .05$, with options 1 through 5 representing poor, fair, good, very good, and excellent respectively.

2.3.2 Materials and Design

Background information was obtained using a demographic questionnaire which included information on chronological age, years of education, and general health status. Processing speed was assessed using the WAIS-R Digit Symbol test (Wechsler, 1981) and working memory was assessed with a modified version of the reading span task (Daneman & Carpenter, 1980). Measurement of Deletion-Type inhibition was based on data obtained from the Sequential Action Control Task (Li et al., 2000, 2010). The Extended Range Vocabulary Test (ERVT Form V2; Educational Testing Service, 1976) was used to control for age effects in vocabulary (McCabe & Hartman, 2003), which is particularly relevant to the ability to quickly read and interpret the meaningfulness of sentences in the reading span task.

Reading span task (Daneman & Carpenter, 1980). A computerized version of this task was presented (programmed with Superlab v. 4.7). Participants read sentences (8 to 12 words in length) presented individually in the middle of a computer screen and pressed one of two keys to verify whether each sentence made semantic sense or not. After a preset number of sentences were presented (two to six), a blue screen appeared and participants reported aloud, the last word of each sentence in the order presented. In the first set, they saw two sentences sequentially (set size of two), responding as to whether each was meaningful or not, before being prompted for recall of the last word seen in each sentence. This eventually increased to a set size of six (i.e. six sentences presented consecutively) before being prompted for end-word recall. All participants advanced to the sixth set size regardless of whether they were able to recall the last words of sentences presented at lower set sizes. Participants were always given two trials of sentences at each set size.

The time taken (in seconds) to judge the meaningfulness of sentences and the accuracy of this judgment were recorded with the computer program. The time recorded was from the presentation of the sentence to the participant's response. Accuracy measures were based on correct yes/no responses mapped to numbers "1" and "3" on the keypad of a standard PC keyboard. The experimenter recorded the number of end-words recalled after each set size was presented. Based on this, it was possible to examine processing and storage components of the reading span task: storage (recall) was based on the total of correct end-word recall from all set sizes, whether or not participants fully recalled all end-words in each set size; processing time was based on the mean time it took participants to correctly judge the meaningfulness of sentences across all set sizes; and processing accuracy was based on the mean of percent correct responses to sentences across all set sizes.

Sequential Action Control Task. The stimuli for this task consisted of eight animal drawings in bitmap format: butterfly, camel, cat, ladybug, zebra, bird, wolf, and elephant (Beaumont & Selley, 1990; Li et al., 2010; see Figure 2.1). Items were colored and occupied a space of 11 cm x 11 cm in the center of the computer screen. The task was programmed using C-Sharp, and presented on a PC with a 17-inch monitor, using mouse clicks for responses. For each trial, the fixed sequence of eight targets was randomly presented with zero to four distractors (items not currently relevant) interleaved between targets. All trials included the eight targets with nine distractors for a total of 17 items per trial (see Figure 2.1). The position and number of distractors before and after targets were randomly determined. The trials were divided into 11 blocks with eight to ten trials in each block. The first nine were

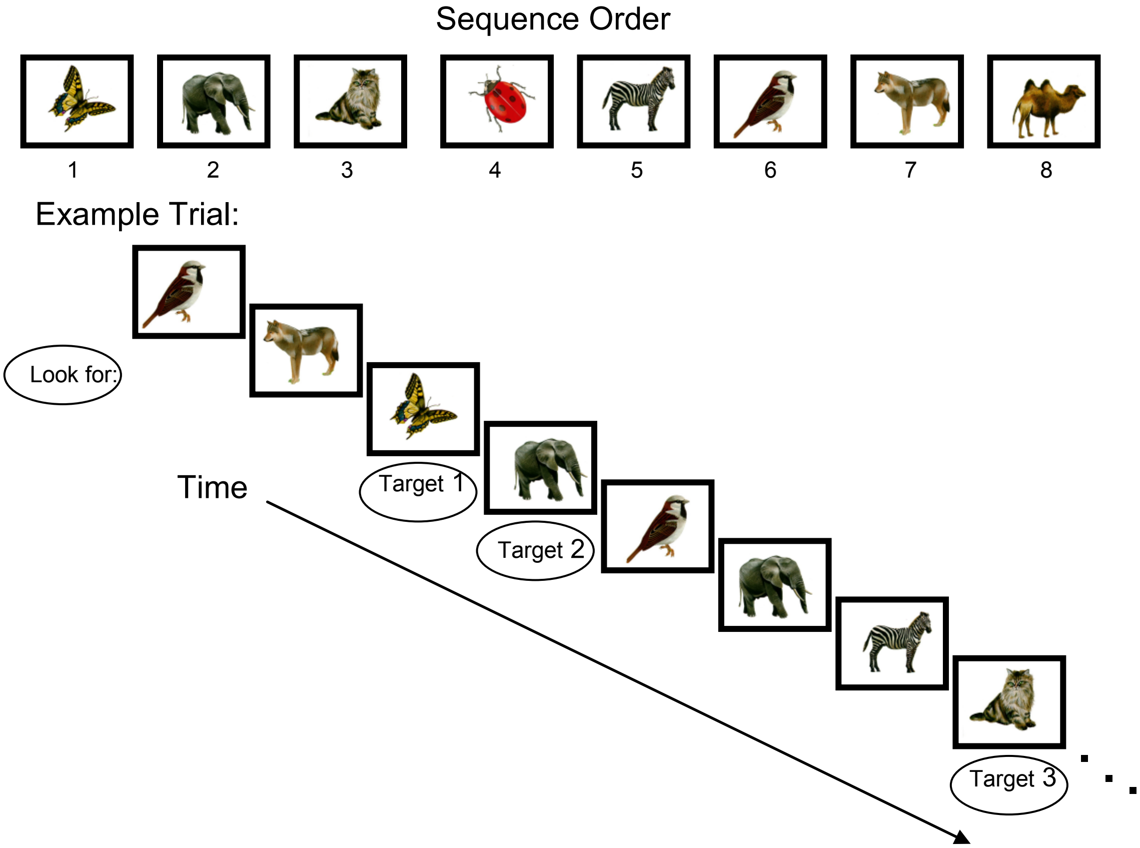

Figure 2.1. Stimuli for the sequential action control task and an example trial.

practice trials, followed by 96 test trials for a total of 105 trials. Each item in the sequence was presented one at a time for 800 ms.

To perform this task, participants memorized the fixed sequence of eight animals and monitored for each item in the memorized order (see Figure 2.1 for one of the sequences used and an example trial). Thus, participants monitored for the presentation of Item 1 (e.g., butterfly in sequence 1) and clicked the mouse button as quickly as possible when Item 1 (target) was shown, but ignored any other items (distractors) that appeared. Following a response to Item 1, participants began monitoring for Item 2 (e.g., elephant in sequence 1)**,** again responding only when the target was shown while ignoring distractors shown in between targets. After 17 items were presented in one trial, with the eighth target as the last item, a screen instructed participants that a new trial was going to begin. After 4000 ms the next trial started. An example trial would be: 7-3-5-**1**-**2**-7-**3**-1-**4**-8-4-**5**-2-**6**-**7**-5-**8**, where each digit represents the serial position of each sequence item, with bolded digits representing targets and non-bolded digits representing distractors. In all practice and test trials, participants saw an error screen for 1500 ms whenever they committed an error of commission or omission. This screen indicated that an error had occurred and instructed participants as to the next target item. Two different sequences were used to counteract order effects, with each participant receiving a different sequence. In one version, the order of the items was: butterfly, elephant, cat, ladybug, zebra, bird, wolf, and camel. In the alternate version, the sequence was: zebra, bird, wolf, camel, butterfly, elephant, cat, and ladybug.

Lag errors were defined as an incorrect response to an item that was either ahead of the target (positive lag errors) or previously completed (negative lag errors). In other words, anticipatory responses to items ahead of the target as noted earlier were indicted by positive lag errors whereas repeated responses to already-completed targets were indicated by negative lag errors. Importantly, the deletion function of inhibition was indexed by negative lag errors, suggesting difficulty suppressing no-longer relevant items. Similar to previous work with the sequential action paradigm (Li et al., 2010), we examined error types ranging from Lag -7 and Lag +7 errors, which included negative lags (from Lags -7 to -1) and positive lags (from Lag +1 to +7). For instance, if one erroneously clicked on the elephant (serial position 2 in sequence 1) when looking for the bird (serial position 6 in sequence 1), this would be classified as a Lag - 4 error. Intrusion error rates were computed by dividing the number of each type of lag error committed by a participant by the maximum number of opportunities to make that error (165, 92, 98, 96, 121, 89, 70, 131, for Lags ≤–4, -3, -2, -1, 1, 2, 3, ≥4, respectively), resulting in a proportion error score for each type of lag error. As response times and overall error rates were comparable across the two versions of animal sequences used in the sequential task, $p > .05$, data were combined across both versions for all analyses. Comparison of pairs of items that were adjacent to each other in the memorized list revealed that one item-pair, wolf-camel, had a higher error rate than other pairs in the two sequences used, $ps < .05$. This was likely due to colour overlap in the wolf-camel images, thus, errors associated with this pair were removed in all analyses.

WAIS-R Digit Symbol Task (Wechsler, 1981). In this task, participants were presented with rows of numbers with empty boxes below each number on a single paper. They filled in symbols to match each number based on a legend at the top of the paper. Participants had 90 seconds to fill in as many symbols as possible. The total score was based on the number of symbols accurately filled in within time limit. In the aging literature, the score on this task has been used to index cognitive processing speed (e.g., Salthouse & Babcock, 1991).

2.3.3 Procedure

Participants first read and signed the consent form and filled out the demographic questionnaire. Subsequently, they completed the sequential task. In order to perform this task, participants first memorized a fixed sequence of eight animals until they could perfectly recite all animals in the order of appearance. Afterwards they completed a paper version of the task until perfect performance was achieved, then they were administered practice and test trials on the computer. Participants were allowed to refer to a memory aid during practice trials only. Of note, participants were not trained to a specific accuracy criterion during practice or test phases as highly accurate performance is commonly observed in this task for young and older adults (Li et al., 2010).

Half way through the sequential task, participants completed the Digit Symbol Test. Participants then completed the second half of the sequential task, and were asked for any specific strategies they used to complete the task. Subsequently, they completed the reading span task, ERVT, and other neuropsychological tests. Lastly, they were debriefed as to the purpose of the experiment and paid or given participation credits for their time. Participants were tested individually in a quiet room and each session lasted between 90 to 120 minutes.

2.4 Results

Independent samples *t*-test revealed that older adults performed significantly worse than younger adults on all measures of the sequential task (average negative lags, $t(56) = 4.95$, $p < .001$; average positive lags, $t(56) = 3.2$, $p = .002$; proportion of omission errors, $t(56) = 5.41$, $p < .001$), the recall component of the reading span task, $t(56) = 3.46$, $p = .001$, but not the processing components, namely time, $t(56) = .27$, $p =.79$, and accuracy, $t(56) = .56$, $p = .58$) (see Table 2.1).

We conducted a series of hierarchical regression analyses to examine the hypothesis that age-related decline in working memory performance is mediated by Deletion-Type inhibitory efficiency, as measured by error rate for responses to already-completed targets (average negative lag errors). This approach allowed us to examine the extent to which the effect of age on reading span performance was attenuated when we controlled for average negative lags. In all regression analyses, outliers in predictor variables were removed (>2*SD*) and criterion measures included components on the reading span task, specifically, processing RT, processing accuracy, and end-word recall (see Table 2.2 for correlations among predictors and criterion measures examined controlling for age).

In each regression analysis (see Table 2.3), vocabulary scores (range: 0 to 24) was entered first as scores on this measure were significantly different between younger ($M = 9.1$, $SD = 4.0$) and older adults ($M = 15.2$, $SD = 5.0$), $p < .05$. In the

Table 2.1

Means (M) and standard deviations (SD) of task performance by age group

Age Group	*N*	Vocabulary **	Digit Symbol **		Sequential Action Control Task								Reading Span Task					
					Reaction Time (ms) **		Negative Lag Errors **		Positive Lag Errors **		Omission Errors **		Processing Time (s)		Processing Accuracy		Recall **	
Young	30	9.07 (4.0)	64.3	(8.9)	525.95	(24.90)	.015	(.01)	.021	(.01)	.024	(.02)	6.15	(1.88)	91.29	(5.41)	26.60	(5.29)
Older	28	15.15(5.0)	49.8	(9.6)	611.11	(32.86)	.031	(.02)	.035	(.02)	.105	(.08)	6.30	(2.38)	90.37	(7.09)	20.86	(7.26)

Note. Values reflect average score per group; standard deviations are shown in parentheses. ** Indicates significant age group differences using independent samples *t*-tests. Digit Symbol refers to WAIS-R Digit Symbol Substitution. Values shown reflect items correctly completed in 90 seconds. Vocabulary refers to Extended Range Vocabulary Test. Values shown reflect total correct answers subtract .2 for each incorrect answer.

Table 2.2

Correlations among variables controlling for age

Variables	1	2	3	4	5	6	7	8
1. Average Negative Lag Errors	-							
2. Average Positive Lag Errors	0.53**	-						
3. Proportion Omissions	0.51**	0.12	-					
4. Digit Symbol	-0.29*	-0.22	-0.16	-				
5. Processing Time	0.03	-0.06	-0.14	-0.15	-			
6. Processing Accuracy	-0.37**	-0.22	-0.26	0.19	-0.35*	-		
7. Recall	-0.12	-0.17	0.07	0.08	0.11	0.03	-	
8. Vocabulary	-0.30*	-0.02	0.00	0.23	-0.38**	0.26	0.23	-

Note: $*p < .05$, $**p < .01$

Table 2.3

Results from the hierarchical regression analyses on the relation of inhibition, speed, and working memory

Predictor	Processing Time		Processing Accuracy		Recall	
	R^2	Incr. in R^2	R^2	Incr. in R^2	R^2	Incr. in R^2
Vocabulary	.091		.022		.017	
Age	.143	.052†	.079	.058†	.298	.281**
Vocabulary	.091		.022		.017	
Av. Neg. Lags	.098	.007	.172	.151**	.164	.147**
Age	.150	.052†	.173	.000	.301	.136**
Vocabulary	.091		.022		.017	
Digit Symbol	.129	.039	.089	.068†	.144	.127**
Age	.147	.018	.098	.009	.299	.155**
Vocabulary	.091		.022		.017	
Digit Symbol	.129	.039	.089	.068†	.144	.127**
Av. Neg. Lags	.130	.001	.175	.086*	.193	.049†
Age	.158	.028	.177	.002	.301	.107**
Vocabulary	.091		.022		.017	
Av. Neg. Lags	.098	.007	.172	.151**	.164	.147**
Digit Symbol	.130	.032	.175	.003	.193	.029
Age	.158	.028	.177	.002	.301	.107*

Note: Av. Neg. Lags = Average negative lag errors; Incr. = increase; $^{*}p < .05$, $^{**}p < .01$; $^{\dagger}p < .1$

first regression analysis depicted in Table 2.3, after controlling for vocabulary, chronological age accounted for a significant proportion of variance in the recall component (28.1%), $p < .01$, and marginally in processing time (5.2%) and processing accuracy (5.8%), *ps* = .08. Next, we examined the extent to which the effect of age on all reading span components was reduced when controlling for mean negative lags and Digit Symbol scores. This examination of all reading span components was deemed appropriate given the theoretical motivation for the study, significant age variance in recall, and marginal age effects in processing components of the reading span task (i.e., age predicted a small amount of variance in processing components; see Table 2.3). Thus, in the second analysis, mean negative lags was entered, followed by age. Mean negative lags significantly accounted for variance in processing accuracy (15.1%) and recall (14.7%), *p*s < .01. In both of these reading span components, mean negative lags reduced the contribution of age by more than half.

In the third regression analysis presented in Table 2.3, Digit symbol score was entered, followed by age. Digit symbol score significantly accounted for variance in the recall component (12.7%), $p < .01$, reducing the contribution of age by approximately 50%. To compare the predictive ability of Digit symbol score and mean negative lags to account for variance in the reading span measure, another analysis was conducted with vocabulary entered first, Digit symbol score second, mean negative lags third, and age as the fourth predictor. As shown in Table 2.3, mean negative lags significantly accounted for variance over and above the effects of Digit symbol score in processing accuracy, $p < .05$, and marginally in recall, $p = .08$.

However, when Digit symbol score was entered after mean negative lags, Digit symbol score did not account for additional variance in reading span components, *ps* > .17.

Of note, the effect of age in accounting for reading span performance was still significant even after accounting for indices of inhibition and processing speed (as shown in Table 2.3), particularly for the recall component, $p < .05$. This suggests that there were still other age-related processes mediating age-related decline in working memory performance.

Lastly, we tested an alternative explanation that might explain why average negative lag errors predicted age-related decline in reading span performance: The sequential task used can be considered a type of updating task as it requires participants to remove the prior target from working memory when completed and update to the next target. Schmiedek et al. (2009) recently showed that updating tasks, such as the *n*-back task, measure the same construct as complex span tasks, presumably working memory functioning. Thus in the present context, predicting the reading span task based on performance in the sequential task may be a case of predicting the criterion with the criterion. If this alternative hypothesis were true, then using predictors that measure efficient performance in the sequential task (negative lag errors, positive lag errors, and omission errors) should similarly predict reading span performance.

In regard to the relationship between positive lag errors in the sequential task and reading span performance, we performed two sets of regression analyses (see Table 2.4): one in which vocabulary was entered first, with average positive

Table 2.4

Results from the hierarchical regression analyses on the relation between indices of sequential performance and working memory

Predictor	Processing Time		Processing Accuracy		Recall	
	R^2	Incr. in R^2	R^2	Incr. in R^2	R^2	Incr. in R^2
Vocabulary	.091		.022		.017	
Av. Pos. Lags	.092	.001	.105	.084*	.133	.116*
Av. Neg. Lags	.100	.008	.176	.070*	.180	$.047^{\dagger}$
Age	.151	$.052^{\dagger}$	.176	.000	.321	.142**
Vocabulary	.091		.022		.017	
Av. Neg. Lags	.098	.007	.172	.151**	.164	.147**
Av. Pos. Lags	.100	.001	.176	.003	.180	.016
Age	.151	$.052^{\dagger}$	.176	.000	.321	.142**
Vocabulary	.091		.022		.017	
Prop. Omissions	.091	.000	.141	.120*	.065	.047
Av. Neg. Lags	.106	.015	.185	.043	.168	.103*
Age	.163	$.058^{\dagger}$	.186	.001	.311	.143**
Vocabulary	.091		.022		.017	
Av. Neg. Lags	.098	.007	.172	.151**	.164	.147**
Prop. Omissions	.106	.008	.185	.012	.168	.004
Age	.163	$.058^{\dagger}$	.186	.001	.311	.143**

Note: Av. Neg. Lags = Average negative lag errors; Av. Pos. Lags = Average positive lag errors; Prop. Omission = Proportion of Omission errors; Incr. = increase; *$p < .05$, **$p < .01$; $^{\dagger}p < .1$

lag errors entered second and mean negative lags third, and another in which the entry of lag errors were reversed. In the first analysis in which mean positive lags was entered after vocabulary, mean positive lags significantly accounted for variance in processing accuracy and recall, *ps* < .05. When mean negative lags was entered after mean positive lags, mean negative lags significantly predicted additional variance in processing accuracy, *p* < .05, and marginally in recall, *p* = .09, over and above the effects of positive lags. In the reverse situation, in which mean positive lag errors was entered after controlling for mean negative lag errors, there was no instance in which mean positive lags accounted for additional variance above the effects of mean negative lags, *ps* > .3.

Given that positive lags and negative lags errors were moderately correlated (*r* = .53), we sought additional evidence that they are measuring different constructs. Figure 2.2 shows the distribution of positive and negative lag errors, with significant age effects at Lag + 4, - 2, - 3, - 4, *ps* < .006 (Bonferroni correction); of note, the negative lag differences indicate that at the presentation rate used (800ms), older adults tended to respond again to prior items more than younger adults. In addition, Figure 2.2 shows that the distribution of positive and negative lag errors are quite different in each age group, which is similar to previous research using the same task despite slight procedural differences (Li et al., 2010). Qualitative examination of Figure 2.2 shows asymmetric error responses at the nearest positions to the present target, notably reduced Lag - 1 errors and elevated Lag + 1 errors compared to most other lag errors. This pattern of results is consistent with inhibitory effects influencing

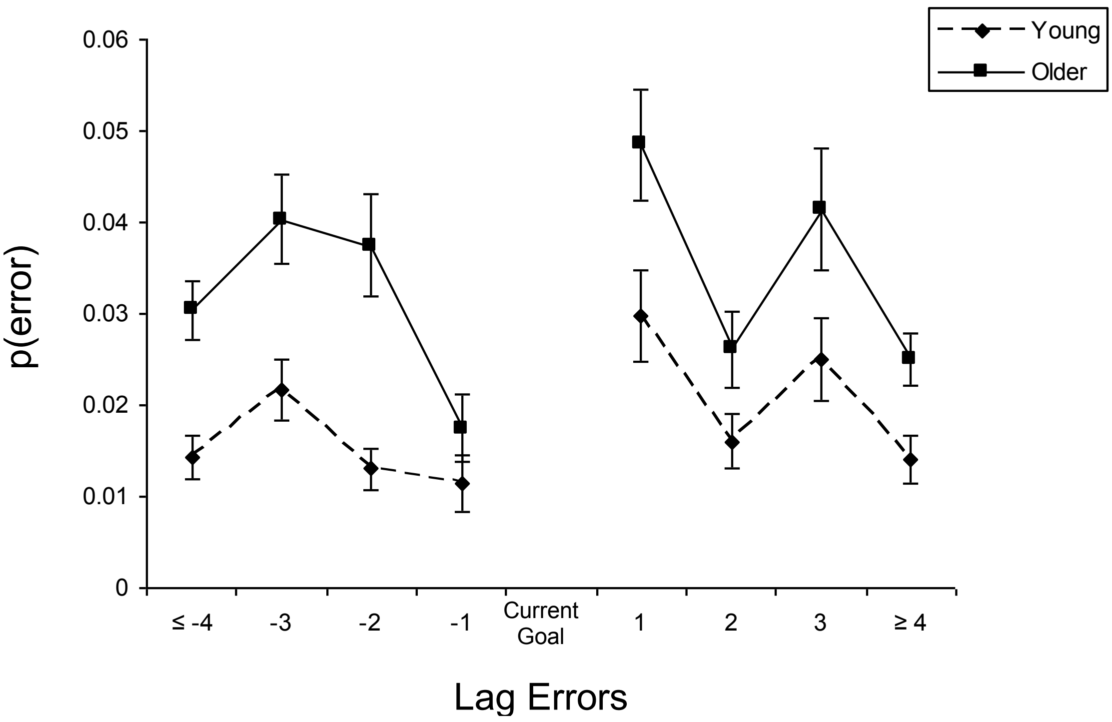

Figure 2.2. Intrusion error rates as a function of age group and lag errors. Error bars represent one standard error of the mean

already completed items and non-inhibitory effects (anticipatory effects) impacting to-be-completed items. In particular, reduced Lag - 1 errors are consistent with strong immediate inhibition of each item as it is completed in the task, as predicted by inhibitory theories of serial actions (Arbuthnott, 1995; Houghton & Tipper, 1996). On the other hand, Lag + 1 errors are elevated, consistent with the intention superiority effect (Goschke & Kuhl, 1993; Marsh et al., 1999) in which upcoming items are highly activated and consequently led to a high rate of anticipatory errors for items ahead of the current target (particularly $n + 1$). Together, the results converge in suggesting that negative lags and positive lags are measuring different constructs in this paradigm.

We also examined the relation between negative lags and omission errors. When we performed the same set of hierarchical analyses as above but with proportion of omission errors instead of positive lag errors, a similar pattern of results emerged. In the first analysis in which proportion of omission errors was entered after vocabulary, proportion of omission errors significantly accounted for variance in processing accuracy only, $p < .05$. With mean negative lags entered after proportion of omission errors, mean negative lags significantly predicted additional variance above the effects of omissions in recall, $p = .02$ and marginally in processing accuracy, $p = .1$. There was no instance in which omissions accounted for additional variance above the effects of mean negative lags, *ps* > .3, similar to the finding with positive lag errors.

Together, these results suggest that mean negative lag errors are distinct from other indices of efficient performance in the sequential task (positive lag errors and omission errors).

2.5 Discussion

In this study, we examined the extent to which Deletion-Type inhibitory functioning mediates age-related decline in working memory components. We observed lower inhibitory efficiency in the sequential task in older adults compared to younger adults. Moreover, reduced inhibition predicted age-related decline in both storage and processing accuracy components of working memory, over and above processing speed effects. However, it should be pointed out that age-related decline was only marginal in the processing components, likely due to measurement limitations (as elaborated upon below). Thus, at least for the storage component, these results provide evidence that reduced inhibitory functioning plays an important role in age-related decline in working memory performance.

To extend prior research, the components of working memory, as measured by the reading span task, were examined in relation to reduced Deletion-Type inhibition with increasing age. In this study, accounting for inhibitory efficiency reduced age-related variance by more than half in the storage component of the reading span task as well as processing accuracy, consistent with inhibition deficits accounts of aging (Dempster, 1992; Hasher et al., 1999; 2007). Moreover, we observed that the predictive utility of inhibition in the sequential task to account for working memory performance was beyond the effects of processing speed in recall (4.9%) and processing accuracy (8.6%) components. Thus, although general slowing accounts for age-related variance in working memory and other higher-order cognitive abilities (Salthouse, 1991; Salthouse & Babcock, 1991; Salthouse & Meinz, 1995), inhibitory control is also an important contributing factor (Persad et al., 2002; de Ribaupierre, 2001).

While our findings are generally consistent with our hypotheses, there are a few limitations regarding the processing accuracy and processing time components. Firstly, the extent to which the inhibitory index (mean negative lags) reduced any age-associated variance in processing accuracy may have been overestimated. This is because mean negative lags and processing accuracy were significantly associated ($r = -.37$) when controlling for age. As demonstrated by Lindenberger and Pötter (1998), when proposed mediator variables are highly related to the criterion measure with the independent variable controlled for, the mediating effect may be overestimated, an issue applicable to various multivariate analytic procedures (e.g., hierarchical linear regression, commonality analysis, path analysis, structural equation models, etc; see also Salthouse & Ferrer-Caja, 2003, for a discussion).

Secondly, only marginal age effects were found in processing time and accuracy. A possible reason for this result may be the way in which the reading span task was administered in that it was participant-, not experimenter-, paced. As shown by Friedman and Miyake (2004), having participants determine when the next sentence is presented as opposed to the experimenter influenced the relationship between processing times and recall as well as the predictive power of the reading span task. Perhaps using an experimenter-paced format or putting a time limit on the processing phase might have influenced the processing demands of the reading span task, and the relationship of inhibitory efficiency with processing time. Future work manipulating the administration format of the reading span task (experimenter vs. participant paced) would help clarify the predictive utility of inhibitory efficiency in the processing time component in reading span performance.

It is important to note that despite controlling for processing speed and inhibitory efficiency, age still accounted for variance in working memory performance. This suggests that there were other factors constraining working memory performance that were not examined. This is not particularly surprising given the complexity of complex span tasks and their utility in predicting higher-level cognitive abilities (Conway et al., 2003; Kyllonen & Christal, 1990; Unsworth & Engle, 2007).

The particular factor (or factors) limiting working memory performance in young or older adults has been a topic of debate (Conway, Jarrold, Kane, Miyake, & Towse, 2007; Miyake & Shah, 1999). Given that complex span tasks involve both storage and processing components (Daneman & Carpenter, 1980; Turner & Engle, 1989), potential mediators of complex span performance may include performance on measures of short-term storage capacity and processing efficiency (Bayliss, Jarrold, Gunn, & Baddeley, 2003). Other potential mediators include executive control abilities involved in switching between (Towse & Hitch, 2007) or executing storage and processing tasks simultaneously (Engle, 2002; Jarrold & Bayliss, 2007; Kane et al., 2007). With respect to the aging literature, a number of studies have shown short-term storage capacity mediates age-related decline in working memory performance (e.g., McCabe & Hartman, 2003; Verhaeghen et al., 1993). Processing efficiency operationalized in terms of language processing efficiency (e.g., sentence processing) has also been shown to account for age-related variance in working memory (e.g., Brébion, 2003; Gick, Craik, & Morris, 1988; but see Waters & Caplan, 2001; McCabe & Hartman, 2003, for conflicting findings). Besides inhibitory control, other executive abilities, such as control processes involved in concurrently performing or switching between storage and processing operations have also been shown to mediate age-related working memory decline (e.g., Levitt, Fugelsang, & Crossley, 2006; but see contrasting findings in McCabe & Hartman, 2003). In a step removed from storage and processing measures, Oberauer and colleagues (Oberauer, Süß, Wilhelm, & Sander, 2007; Oberauer, Süß, Wilhelm & Wittmann, 2003, 2008) have suggested that the capacity to simultaneously bind and maintain several chunks of information constrain working memory performance, and hence mediate age-related decline (Oberauer, 2005; but see Bopp & Verhaeghen, 2009, for contrasting results).

Although the various putative mediators of age-related decline in working memory performance come from diverse theoretical backgrounds, there may be common mechanisms at work across these divergent approaches. One possibility is that a common inhibitory framework may account for age-related variance captured by these approaches. For instance, measures of processing speed often include multiple sets of information, which may be distracting for older adults who presumably have reduced inhibitory ability to ignore interfering information (Hasher et al., 2007). As shown by Lustig, Hasher, and Tonev (2006), older adults’ processing speed improved when distraction in processing speed measures was reduced whereas younger adults’ performance was minimally affected.

Besides inhibitory control, other broad approaches to capture the various theoretical frameworks of age-related working memory deficits may be reduced ability to use controlled attention to maintain goal-relevant information during interference (Kane et al., 2007; McCabe et al., 2005), to switch attention focus (Verhaeghen, Cerella, Bopp, & Basak, 2005; Verhaeghen & Basak, 2005), and to update working memory contents during task performance (see Miyake, Friedman, Emerson, Witzki, & Howerter, 2000, for a discussion). It should be noted however that the controlled attention and working memory updating viewpoints do not necessarily preclude an inhibitory mechanism to suppress/deactivate no-longer relevant information (Lustig et al, 2007; Miyake et al., 2000). Thus, more research is needed to better understand specific factor(s) underlying mediators of working memory decline in older adults. In future work with the present paradigm, including measures of these other potential sources of variance in working memory performance will likely reveal a more comprehensive picture of age-sensitive processes involved in age-related working memory decline**.**

Conclusion

Results from this study show that Deletion-Type inhibitory efficiency plays an important role in predicting age-related decline in working memory performance, particularly recall (beyond processing speed effects), and extend previous research by examining this relationship at a componential level. On a theoretical level, the relationship between components of working memory and moreover, factors that drive the relationship between working memory performance and higher-order ability remains a topic of debate. Given that both storage and processing components make independent contributions to higher-order ability (e.g., Unsworth et al., 2009), understanding the nature of the relationship between age-sensitive processes and working memory components is a necessary endeavor for future research. This work represents an initial step in this direction in regard to inhibitory functioning.

Chapter 3

The previous study took a variance partitioning approach to examine the extent to which age differences in higher order cognition (working memory components) accounted for observed age-related decline in inhibitory functioning (deletion-type inhibition). While the result obtained supported inhibition deficit accounts of aging, in terms of the role of inhibition in working memory functioning with age, inhibition accounts have been criticized for being non-specific regarding the exact nature of inhibitory changes with age (e.g., Burke, 1997; Kramer et al., 1994; McDowd, 1997). Thus, to further specify such changes, in this study we aimed to examine whether older and younger adults might differ in the time course of inhibitory functioning (Maylor et al., 2005).

Examination of the time course of deletion-type inhibition in young and older adults

3.1 Abstract

The Inhibition Deficit Hypothesis of aging (Hasher, Lustig, & Zacks, 2007) posits that inhibitory functioning declines with aging; however, the research thus far has been mixed. In this study, we assessed whether changes in the time course of inhibitory functioning with age might represent a moderating factor. Using a sequential paradigm, older and young adults monitored for a learned sequence of targets among runs of randomly ordered stimuli. Intrusion error rates (responses to already-completed targets) were analyzed to assess deletion-type inhibition, the ability to suppress no-longer-relevant information. There was no age effect of inhibitory efficiency across the time course examined, a potential reflection of the

very low error rates obtained in young and older groups. While the results are inconsistent with the inhibition deficit account of aging, it is possible that using more sensitive measures of inhibitory functioning may yield different findings.

3.2 Introduction

The ability to carry out everyday actions is a primary marker of independent functioning. Difficulty carrying out everyday tasks, namely basic and instrumental activities of daily living (ADLs), often represent an early indicator of incipient dementia (American Psychiatric Association, 2000), and has been linked to institutionalization and mortality (Luppa et al., 2010; Noale et al., 2003). Evidence of difficulty performing ADLs, as reflected in everyday action errors, is not restricted to individuals with dementia, however. Healthy individuals are also susceptible to such errors, particularly when fatigued, distracted, or engaged in concurrent tasks (Giovannetti, Schwartz, & Buxbaum, 2007; Reason, 1990; Reason & Mycielska, 1982; Schwartz, 2006). Thus, a better understanding of cognitive processes underlying sequential performance will better inform the lives of older adults. One such cognitive process is the ability to resist re-executing prior steps, an ability that has been linked to inhibitory control functions during sequential tasks (Arbuthnott, 1995; Cooper & Shallice, 2006; Estes, 1972; Houghton & Tipper, 1996). However, changes in inhibitory functioning with age continue to be an area of debate (e.g., Burke & Osborne, 2007; Hasher, Zacks, & May, 1999). In the present work, we aimed to examine whether and how inhibitory functioning changes with age in the context of a sequential paradigm.

The examination of inhibitory control processes in sequential performance has been a fruitful area of research in different populations (e.g., brain damage; Humphreys & Forde, 1998; Schwartz, 2006; e.g., normal and pathological aging, Giovannetti, Bettcher, et al., 2007; Bettcher & Giovannetti, 2009), cognitive abilities (e.g., mental arithmetic, Arbuthnott & Campbell, 2003; e.g., spelling, Houghton, Glasspool, & Shallice, 1994), and computational modeling of everyday action sequences (Botvinick & Plaut, 2004; Cooper, Schwartz, Yule, & Shallice, 2005). For instance, in research with the Naturalistic Action Test (Schwartz, Buxbaum, Ferraro, Veramonti, & Segal, 2003), in which individuals perform everyday tasks (e.g., making toast with butter and jelly), neuropsychological populations often show high rates of action errors (see review in Schwartz, 2006), which include dissociable error types (e.g., commission vs. omission errors; Giovannetti et al., 2008).

On more sensitive measures of everyday actions, younger adults have also been shown to be susceptible to action errors when attention is divided or when time pressures are imposed (e.g., Giovannetti, Schwartz, et al., 2007; Humphreys, Forde, & Francis, 2000). As outlined by Giovannetti, Schwartz, et al., the sensitivity of these measures in healthy populations is a function of a number of factors, such as comprising multiple sub-goals (Norman & Shallice, 1986), distractors that are visually and functionally similar to targets (Cooper et al., 2005), and time limitation (Cooper & Shallice, 2006). With the inclusion of such ecologically based principles, laboratory measures of sequential performance have showed increased action errors in older adults compared to younger adults (e.g., Blair, Vadaga, Shuchat, & Li, 2011; Li, Blair, & Chow, 2010), many of which were specific to re-executing prior steps. Such findings are consistent with inhibitory deficit accounts of aging (e.g., Dempster, 1992; Hasher, Lustig, & Zacks, 2007; Lustig, Hasher, Zacks, 2007).

According to the inhibition deficit hypothesis proposed by Hasher and colleagues (Hasher & Zacks, 1988; Hasher et al., 1999, 2007), multiple types of inhibitory functions decline with age. These include the ability to restrict *access* of task irrelevant goals to working memory, *delete* / prevent information that is no longer relevant from interfering with ongoing goals, and *restrain* / prevent execution of prepotent responses. For instance, in regard to perseverative tendencies during sequential performance, intact deletion-type inhibition allows for the suppression of previously executed goals, thereby facilitating forward movement in the sequence (Houghton & Tipper, 1996). However, like other inhibitory functions, research has been inconsistent regarding age-related declines in deletion-type inhibition (e.g., Hasher et al., 1999; Maylor, Schlaghecken & Watson, 2005).

Such findings suggest that the inhibition deficit account may have been over-extended and ongoing research need to better specify putative moderators of age-related inhibitory changes observed thus far. One such moderator has been suggested recently by Maylor et al. (2005) who noted that the time course at which inhibitory functioning is examined might be crucial factor in delineating age-related deficits. For instance, studies showing age effects in inhibitory functions might be capturing young and older adults at strong and weak points, respectively, over the activation and decay phases that inhibitory processes purportedly follow (Houghton, 1990; Houghton & Tipper, 1996; Humphreys et al., 2000). However, at present, time course research is limited and in some cases mixed (e.g. Castel, Chasteen, Scialfa, & Pratt, 2003; Hasher, Stoltzfus, Zacks, & Rypma, 1991; Li & Dupuis, 2008; Schlaghecken & Maylor, 2005), with more recent work suggesting that older adults' inhibitory functioning might be intact but delayed compared to younger adults (Gazzaley, et al., 2008; Schlaghecken, Birak, & Maylor, 2011). However, the generalizability of these recent findings to a sequential paradigm remains unclear.

Current study

Our primary goal was to investigate the time course of inhibitory functioning in younger and older adults in the context of a sequential paradigm. A better understanding of processes underlying sequential tasks have implications for daily tasks performed by older adults. With these goals in mind, older and younger adults performed a sequential task (Blair et al., 2011; Li et al., 2010; Li, Lindenberger, Rünger, & Frensch, 2000) in which they monitored for a learned sequence of targets among trials of randomly ordered stimuli. Intrusion error rates, specifically responses to already-completed targets, were analyzed to assess deletion-type inhibitory efficiency, consistent with inhibitory suppression of previous completed items stipulated in sequential theories of inhibition (Arbuthnott, 1995; Cooper & Shallice, 2006; Estes, 1972; Houghton, 1990; Houghton & Tipper, 1996). We deemed it appropriate to analyze error rates because of the rich source of knowledge this approach has provided in the everyday action sequence literature (e.g., Schwartz, 2006; Houghton, Glasspool, & Shallice, 1994) and because of previous successes with this approach (Blair et al., 2011; Li et al., 2000, 2010). We predicted a delayed onset of deletion-type inhibitory efficiency in older adults compared to young adults, as observed in recent research (Gazzaley, et al., 2008; Schlaghecken et al., 2011). Such a finding would attest to this recently observed change in inhibitory functioning with age while generalizing this effect to a sequential task.

3.3 Method

3.3.1 Participants

Twenty four younger adults (*M* = 21.88, *SD* = 1.73) and 24 older adults (*M* = 68.08, *SD* = 3.57) participated in this study. This does not include data from one older and one younger adult who had high rates of omission errors (> 3 SD) in the sequential task. Younger adults were recruited from the Concordia University undergraduate participant pool in the Psychology department. The older adults were recruited through a participant pool established by the Adult Development and Aging laboratories at Concordia University and also through posters placed in neighbourhood shops. Inclusion criteria for both young and older adults included fluency in English, and absence of medical, psychological, or motor conditions that could influence their performance in the tasks used. Years of education was not significantly different between younger (*M* = 15.5, *SD* = .78) and older (*M* = 16.79, *SD* = 3.44) adults, *p* = .08.

3.3.2 Materials and Design

Background information was obtained using a demographic questionnaire regarding chronological age, marital status, years of education and general health status. Processing speed was assessed using the WAIS-R Digit Symbol Substitution test (Wechsler, 1981). Measurement of inhibitory efficiency was based on data obtained from the Sequential Action Control Task (Blair et al., 2011; Li et al., 2000, 2010).

Sequential Action Control Task. The stimuli for this task consisted of eight animal drawings in bitmap format: butterfly, camel, cat, ladybug, zebra, bird, wolf and elephant (Beaumont & Selley, 1990; Li et al., 2010; see Figure 3.1). Items were

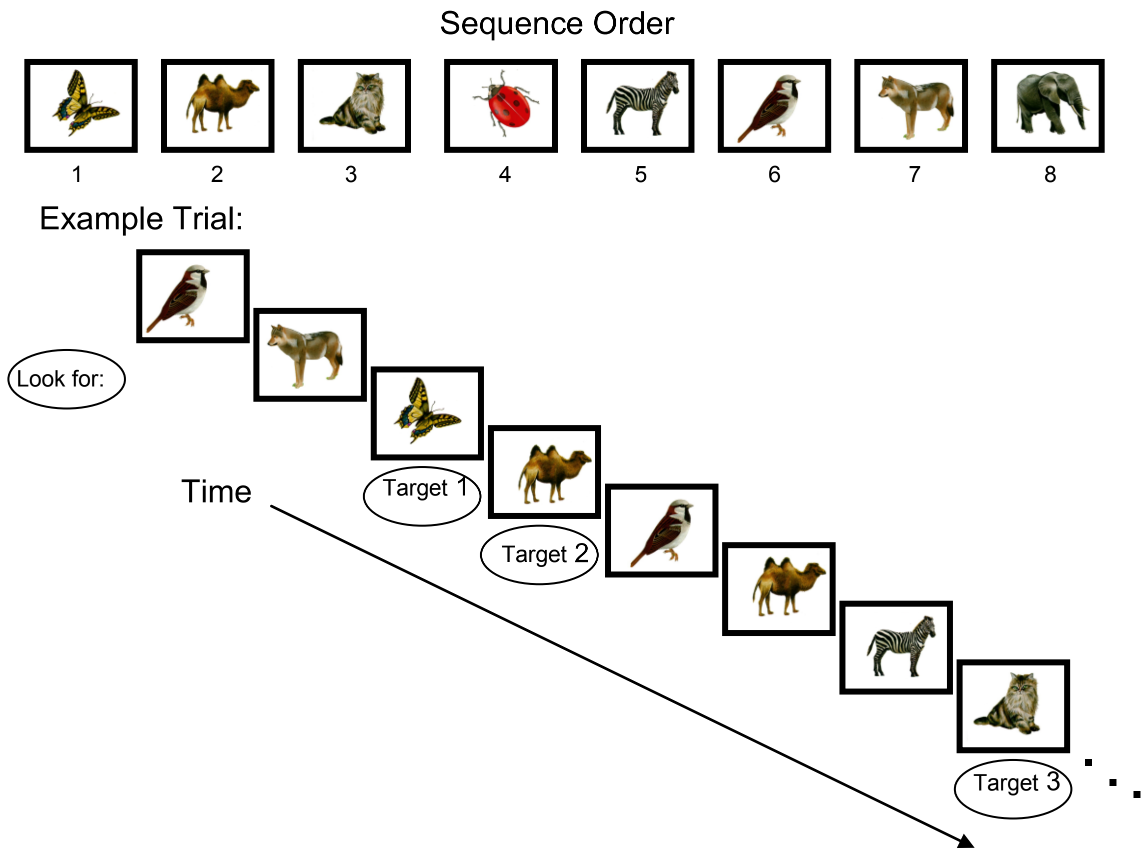

Figure 3.1. Stimuli for the sequential action control task and an example trial.

colored and occupied a space of 11 cm x 11 cm in the center of the computer screen. The task was programmed using C-Sharp, and presented on a PC with a 17-inch monitor, using mouse clicks for responses. For each trial, the fixed sequence of eight targets was randomly presented with zero to four distractors interleaved between targets. All trials included the eight targets with eight distractors for a total of 16 items per trial (See Figure 3.1). The position and number of distractors before and after targets were randomly determined. The trials were divided into 11 blocks with eight to ten trials in each block. The first nine were practice trials, followed by 96 test trials for a total of 105 trials. All targets were presented for 800 ms.

To examine the ability to suppress previously relevant information over time (i.e. the ability to withhold responding again to already presented targets), one target item repeated once in each trial. In between this target item (*n*) and the repeat of this item (*n* - 1), we placed one distractor, which was randomly determined. These distractors (between *n* and *n* - 1 repeats) were equally distributed across all trials to be on screen for 800, 1600, or 2400 ms. An example trial would be: 3-5-**1**-**2**-7-**3**-1-**4**-8-*4*-**5**-2-**6**-**7**-5-**8**, where each digit represents the serial position of each sequence item, with bolded digits representing targets, which require a mouse click response, and non-bolded digits representing distractors. In this trial, the fourth target repeated (italicized), after a distractor ‘8’ was on screen either for 800, 1600, or 2400 ms. This manipulation facilitated a time course analysis of the deletion function by examining the tendency to respond to the already-completed target, thus, suggesting inefficient suppression of no-longer relevant information. In the above example, this tendency would be observed by clicking on the fourth item a second time, instead of withholding that response. Separate from the time course analysis of the previously completed target (*n* - 1 repeats), an overall index of deletion-type inhibitory efficiency was also obtained from this task. This measure was based on overall intrusion errors for already completed targets.

3.3.3 Procedure

In order to perform the sequential action task, participants first memorized a fixed sequence of eight animals. Afterwards they did a paper version of the task followed by nine practice trials on the computer, then 96 test trials. Participants were given a memory aid only for practice trials. To perform this task, participants were instructed to monitor for the presentation of Item 1 (i.e., butterfly) and click the mouse button as quickly as possible when Item 1 (target) was shown, but not to respond if any other items (distractors) appeared. Following a response to Item 1, participants were to begin monitoring for Item 2 (i.e., camel), again responding only when the target was shown while ignoring distractors shown in between targets (see also Figure 3.1). After 16 items were presented in one trial, with the eighth target as the last item, a screen instructed participants that a new trial was going to begin. After 4000 ms the next trial started. In all trials, participants saw an error screen for 1500 ms whenever they committed an error of commission or omission. This screen indicated that an error had occurred and instructed participants as to the next target item.

In terms of the general procedure, participants first read and signed the consent form and subsequently filled out the demographic questionnaire. Participants then completed the sequential task. Halfway through the sequential task, participants completed the Digit Symbol Substitution Test. Participants then completed the second half of the sequential task, and were asked for any specific strategies they used to complete the task. Subsequently, they completed other neuropsychological tests. Lastly, they were debriefed as to the purpose of the experiment and paid or given participation credits for their time. Participants were tested individually in a quiet room and each session lasted between 90 to 120 minutes.

3.4 Results

Lag errors were defined as an incorrect response to an item that was either ahead of the target (positive lag errors) or previously completed (negative lag errors). Importantly, the deletion function of inhibition was indexed by negative lag errors, which occurred when participants responded again to already-completed target items, suggesting difficulty suppressing no-longer relevant items.

Similar to previous work with the sequential action paradigm (Li et al., 2010), we examined error types ranging from Lag +7 and Lag -7 errors. For instance, if one erroneously clicked on the camel (serial position 2) when looking for the zebra (serial position 5), this would be classified as a Lag - 3 error. Intrusion error rates were computed by dividing the number of each type of lag errors committed by a participant by the maximum number of opportunities to make that error (142, 81, 83, 96, 101, 78, 66, 121, for Lags ≤-4, -3, -2, -1, 1, 2, 3, ≥4, respectively), resulting in a proportion error score for each type of lag error. Independent samples *t*-tests revealed that younger adults performed better than older adults on all measures of the sequential task, *ps* < .05 (See Table 3.1).

Table 3.1

Means (M) and standard deviations (SD) of Task Performance by Age Group

Age Group	*n*	Digit Symbol **		Sequential Action Control Task							
				Reaction Time (ms) **		Negative Lag Error **		Positive Lag Error **		Omission Error **	
Young	24	71.8	(10.74)	545.2	(32.55)	.023	(.01)	.031	(.02)	.032	(.02)
Older	24	53.4	(9.40)	646.37	(37.45)	.044	(.02)	.047	(.02)	.132	(.12)

Note. Values reflect average score per group; standard deviations are shown in parentheses. ** Indicates significant age group differences using independent samples *t*-tests. Digit Symbol refers to WAIS-R Digit Symbol Substitution Test. Values shown reflect items correctly completed in 90 seconds.

As shown in Table 3.1, older adults had difficulty across all aspects of the sequential task than younger adults, including higher error rates on previous items (average negative lag errors). To examine the time course of deletion-type inhibition, we examined the error rate for responses to just-completed targets (i.e. lag - 1 errors). Lag - 1 errors were divided into three time bins: when targets repeated after a distractor that was on screen for 800, 1600, or 2400 ms (See Figure 3.2). These three types of errors corresponded to situations in which participants responded to a target, then a distractor appeared for 800, 1600, or 2400 ms (not clicked), followed by a repeat of the prior target, which was erroneously responded to again. To examine the hypothesis that the time course of deletion-type inhibition in the sequential task is different in young and older adults for just-completed targets, we conducted an Age (young, old) x Time delay (800, 1600, 2400 ms) mixed factorial ANCOVA; Digit Symbol scores served as the covariate. There was no significant main effect of age group, $F(1, 45) < 1$, $p = .89$, $\eta_p^2 = 0$, and a marginally significant main effect of time delay, $F(2, 44) = 3.19$, $p = .05$, $\eta_p^2 = .13$. The Age x Time interaction was not significant, $F(2, 44) = 2.35$, $p = .11$, $\eta_p^2 = .10$.

3.5 Discussion

In this study, we aimed to examine age-related changes in the time course of inhibitory functioning, specifically deletion-type inhibition, in the context of a sequential task. This approach is an important extension of previous research as inhibition is usually assessed at a single time point (Maylor et al., 2005). Further, examining cognitive processes underlying sequential performance, such as inhibitory functioning, has provided a rich source of knowledge in neuropsychological and

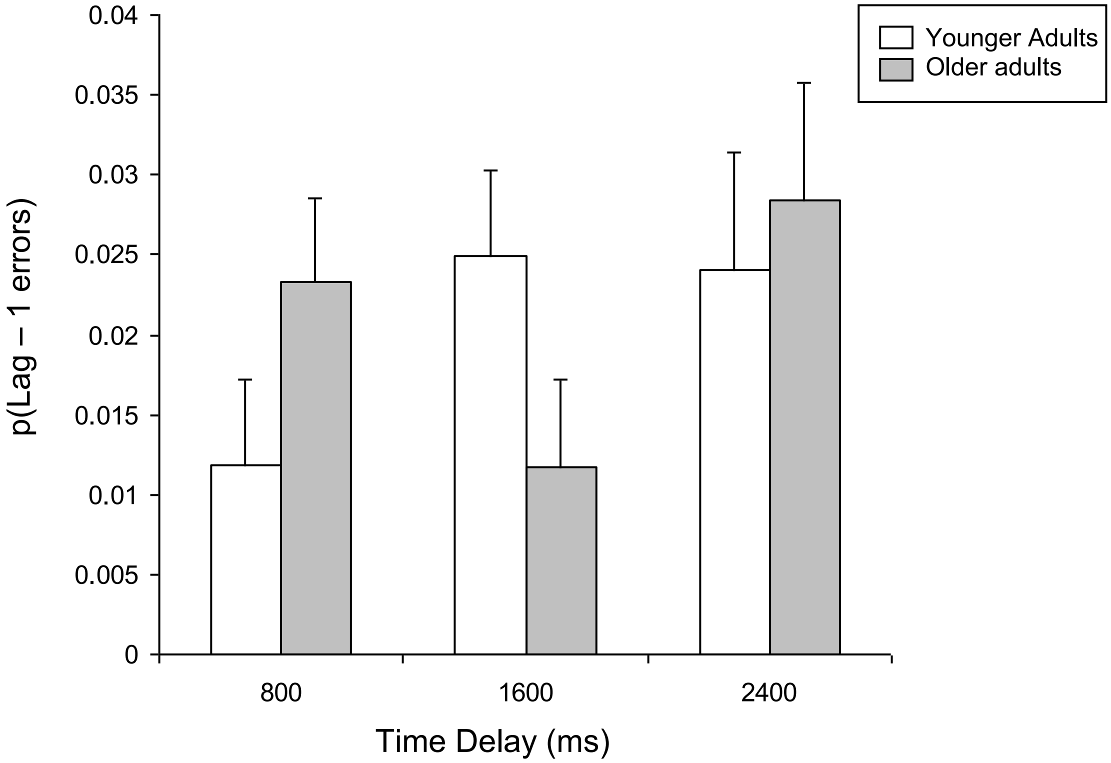

Figure 3.2. Intrusion error rates for Lag - 1 as a function of age group and time delay before the prior target repeated with adjustment for age differences in Digit Symbol scores. Error bars represent one standard error of the mean.

normative research. In this study, we did not observe age differences in inhibitory functioning over the time course examined. This result is inconsistent with more recent work suggesting a delay in inhibitory functioning in older adults (e.g., Gazzaley et al., 2008; Schlaghecken et al., 2011).

Although the results observed are consistent with other work suggesting the lack of inhibitory decline in older adults (e.g., see reviews in Burke, 1997; McDowd, 1997; Maylor, et al., 2005), our assessment of error rates potentially limits our findings. While this error approach has been successful in past research with the sequential paradigm used (e.g., Blair et al., 2011; Li et al., 2000, 2010), in the present study we restricted our examination of errors on prior items to the previously completed item (*n* - 1 repeat). This approach made our time course examination of inhibitory efficiency straightforward by allowing for stringent experimental control between response to an item and the time over when that item was re-presented as an *n* - 1 repeat. However, this approach yielded very low error rates, likely reflecting the high level of functioning in young and older adults examined, with an average of 16 years of education in our young and older sample.

The examination of errors has been successful in the sequential literature, as emphasized by Houghton et al. (1994) who stated that error data “have played a significant role in the development of models of serially ordered behaviour” (p. 366). However, there are drawbacks to this approach as evidenced by the low error rates in this study. This need to address challenges using error-based dependent measures was noted by Schwartz (2006). In her review of sequential tasks in neuropsychological populations (who are more error prone than cognitively intact individuals), Schwartz emphasized the need for alternative approaches (e.g., error induction techniques).

In sum, the present work represents an attempt to better understand the time course of inhibitory functioning with age, a potential confound in inhibition research (Maylor et al., 2005). However, no age-related changes were observed, possibly a result of low error rates obtained. Thus, a broader focus on other indices within the sequential action task (e.g., response latency) might be helpful to examine if and whether there are age-related changes in the time course of inhibitory functioning with age.

Chapter 4

In the previous study, we investigated whether there were changes in the time course of deletion-type inhibition with age by examining error data in a sequential paradigm. However, no age-related changes were observed. It is possible that the low-error rates observed reduced the likelihood of obtaining age effects. In this study, we aimed to further explore the time course of deletion-type inhibition in young and older adults by examining response latencies within a sequential task. This approach was deemed more appropriate given the frequent occurrence of correct responses in our sequential action paradigm, thus, potentially providing a richer data set to address inhibitory changes with age.

Time course of deletion-type inhibition in young and older adults using a sequential updating task

4.1 Abstract

In this study, we examined whether older adults had more difficulty engaging deletion-type inhibition relative to younger adults in a sequential updating paradigm. Older and younger adults performed a sequential task in which they monitored for a learned sequence of targets among trials of randomly ordered stimuli. We investigated the time course of deletion-type inhibition by manipulating the number of distractors (1 – 3), corresponding to variable time delays (1000 to 3000 ms), between targets and repeated presentations of targets (*n* - 1 repeats). Examination of reaction time distributions revealed deletion-type inhibition in the latter distractor condition for younger adults compared to older adults, especially when response

latencies were slow and likely unprepared. In addition, we obtained evidence suggesting that the sequential task used involved working memory updating processes. Together, these findings indicate that older adults have reduced ability to engage deletion-type inhibition compared to younger adults, beyond the effects of age-related general slowing, and emphasize the utility of investigating the time course of inhibitory functioning in the context of a high-level sequential updating paradigm.

4.2 Introduction

In the aging literature, a large body of research shows age-related decline in multiple areas of higher order cognition including working memory and reasoning ability (for meta-analyses see Bopp & Verhaeghen, 2005; Verhaeghen & Salthouse, 1997). Amongst proposed mediators of age-related cognitive decline (e.g., reduced processing speed, set shifting, task coordination, working memory updating), it has been suggested that older adults have reduced ability to inhibit irrelevant information from interfering with task performance (Hasher, Zacks, & May, 1999). However, mixed findings in this area (e.g., Burke & Osborne, 2007; Maylor, Schlaghecken, & Watson, 2005) call into question whether the inhibitory deficit account has been over-generalized and whether other factors may constrain the extent to which inhibitory deficits are observed in older adults. For instance, some researchers have suggested that only high-level (consciously controlled) inhibitory processes are susceptible to the effects of aging (Andrés, Guerrini, Phillips, & Perfect, 2008; Collette, Germain, Hogge, & Van der Linden, 2009; Kramer et al., 1994); however, age differences in low-level (automatically triggered) inhibitory processes have also been observed (e.g., Schlaghecken & Maylor, 2005). More recently, it has been proposed that the time point at which inhibitory functioning is examined may be instrumental in revealing age effects (Maylor et al., 2005). The purpose of the current study was to further investigate this notion in the context of a high-level sequential paradigm in which conscious control is required to update task relevant information.

The inhibition deficit hypothesis (Hasher & Zacks, 1988) posits that inhibitory control processes are less efficient in older adults, thereby allowing irrelevant information to influence task performance in multiple areas, including attention, memory, language, and motor control (Hasher et al., 1999; Zacks & Hasher, 1997). According to this account, older adults have deficits in multiple inhibition functions, including preventing *access* of irrelevant information to conscious awareness, *deleting* (suppressing) no-longer relevant information, and *restraining* the execution of prepotent but inappropriate responses. A large body of research is consistent with age-related decline in these areas (see reviews in Hasher, Lustig, & Zacks, 2007; Lustig, Hasher, & Zacks, 2007). However, contrary evidence has been found (e.g., Kramer et al., 1994), notably within inhibition functions (e.g., see Maylor et al., 2005 for contrary evidence within the deletion function), as well as within specific tasks, such as the Stroop task (Verhaeghen & De Meersman, 1998a), negative priming (Verhaeghen & De Meersman, 1998b; Gamboz, Russo, & Fox, 2002), and directed-forgetting paradigms (Sego, Golding, & Gottlob, 2006; Zacks, Radvansky, & Hasher, 1996).

Given inconsistencies in whether age-related decline in inhibition is observed, Maylor et al. (2005) noted that a drawback and possible confound in extant research may be the assessment of inhibitory functioning at a single time point (see also Schlaghecken & Maylor, 2005). Older adults may show deficits in engaging or maintaining inhibitory control over time; thus, differences in inhibition may depend on where in the time course age group comparisons are conducted. Thus far, research investigating age differences in the time course of inhibitory processes is limited and in some cases mixed (e.g. Hasher, Stoltzfus, Zacks, & Rypma, 1991; Li & Dupuis, 2008; Schlaghecken & Maylor, 2005).

For instance, in high-level intentional inhibitory processes that require conscious control to suppress irrelevant information, Gazzaley, Cooney, Rissman, and D'Esposito (2005) conducted a functional neuroimaging study in which stimuli of faces and scenes were to be remembered, ignored, or passively viewed. Although younger adults showed suppression of cortical activity when ignoring stimuli relative to passive viewing, older adults had similar activation in both conditions, suggesting a top-down deficit in suppressing irrelevant information with age. Follow up research using electroencephalography (EEG) with this paradigm (Gazzaley et al., 2008) showed that the suppression deficit in older adults was restricted to the early stages of visual processing (see Jost, Bryck, Vogel, & Mayr, 2010 for similar findings using EEG). Together, these studies suggest that high-level inhibitory processes to suppress irrelevant information are delayed in older adults.

In contrast to high-level inhibition findings, investigations of age effects in the time course of more automatically triggered low-level inhibitory processes have been inconsistent. For instance, negative priming effects (indicated by slowed responses to recently ignored stimuli) have been shown to be maintained as long as 1700 milliseconds (ms) in younger adults, but were absent in older adults across this time window (Stoltzfus, Hasher, Zacks, Ulivi, & Goldstein, 1993). However, controversy exists as to whether this paradigm involves inhibitory processes (MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003).

Recent research on low-level inhibitory processes in inhibition of return (Castel, Chasteen, Scialfa, & Pratt, 2003) and the masked prime paradigm (Maylor, Birak, & Schlaghecken, 2011; Schlaghecken, Birak, & Maylor, 2011) have revealed early-stage deficits as found in high-level inhibition research. For instance, in the masked prime paradigm, subliminally presented primes trigger performance costs when subsequently presented after short delays (100 to 200 ms) at the conscious level, an effect known as the negative compatibility effect (NCE). Importantly, NCEs, proposed to reflect a low-level inhibitory process (Schlaghecken, Bowman, & Eimer, 2006), have been found to be absent in older adults (Schlaghecken & Maylor, 2005). However, in recent time course work by Schlaghecken et al., robust NCEs were observed in older adults, but were delayed compared to younger adults, indicating intact but delayed low-level inhibition with age. Of note, this finding was observed when reaction time (RT) distributions were examined across variable time windows and inhibitory effects were examined on an individual level. While detailed examination of response distributions have informed our understanding of various cognitive processes (see review in Houghton & Grange, 2011), the examination for significant effects at an individual level (rather than a group level) may have caused spurious findings (see erratum in Schlaghecken, Birak, & Maylor, 2012b). However, alternative approaches converged to support their observations, thereby suggesting that older adults may have reduced ability to engage low-level inhibition in a timely manner compared to younger adults, beyond the effects of age-related general slowing.

Current Study

In this study, we aimed to further investigate the precise nature of inhibitory functioning with age by extending work on time course dynamics from the subliminal task-level to the conscious level. To this end, we examined whether similar difficulties engaging low-level (unintentional) inhibition in older adults could be found in a sequential updating task that requires conscious control. This was accomplished by examining younger and older adults performance on the Sequential Action Control Task (S-ACT task; Blair, Vadaga, Shuchat, & Li, 2011; Li, Blair, & Chow, 2010; Li, Lindenberger, Rünger, & Frensch, 2000).

In this task, participants monitor for a learned sequence of targets among trials of randomly ordered stimuli, responding only to targets while ignoring distractors (items out of sequence). As theories of sequential action generally stipulate that target representations are dampened/suppressed upon completion (Arbuthnott, 1995; Houghton & Tipper, 1996), performance costs on previously completed targets indexes inhibitory efficiency in the S-ACT paradigm. More specifically, slowed response latencies on previously completed targets index deletion-type inhibition, defined as the ability to suppress no-longer relevant information (Hasher & Zacks, 1988; Hasher et al., 1999). Using the S-ACT paradigm, we have observed reduced deletion-type inhibitory efficiency in older adults compared to younger adults (Blair et al., 2011; Li et al., 2000, 2010).

Thus, to further investigate age effects in the S-ACT paradigm, we examined the time course of deletion-type inhibition on prior targets (*n* - 1) that were presented again after a variable number of distractors (1 to 3), which corresponded to variable time delays (1000 to 3000 ms). Specifically, participants made Yes or No responses as items were individually presented, responding according to whether items were targets or distractors. Deletion-type inhibition was assessed by examining RT performance on repeated presentations of previous targets (*n* - 1 repeats) compared to a control condition across 1 to 3 intervening distractors. Response times were predicted to be slowed to *n* - 1 repeats compared to the control condition. As outlined in theories of sequential action (Arbuthnott, 1995; Houghton & Tipper, 1996), such performance costs when processing previously relevant information (*n* - 1 repeat) are the result of suppressive/inhibitory after-effects applied to the prior target, thereby facilitating forward movement in the sequence.

It should be noted that as a variable number of distractors were used to index the time course manipulation of deletion-type inhibition, results will not reveal a pure measure of time course dynamics of deletion-type inhibition in the sequential task used. However, we chose this distractor-filled approach to improve the ecological validity of the sequential paradigm employed, as targets and distractor items are often intermixed during sequential tasks. This approach was also chosen because brief time manipulations (< 1000 ms) may have proven to be too difficult for participants, especially older adults, given time needed to endogenously update sequential targets during the task. Further, given the alternate possibility that longer time windows (>1000 ms) may lead to task-irrelevant processing (e.g., mind wondering during 2000 to 3000 ms delays, especially in the younger group), we surmised that using distractor filled delays in which responses were required should maintain an optimal level of task engagement.

In light of inconsistent age effects in inhibitory functioning and the suggestion that older adults may have a different time course of inhibition compared to younger adults (Maylor et al., 2005), we made two predictions. First, we predicted that older adults would have difficulty engaging deletion-type inhibition as compared to younger adults, beyond age-related general slowing, in line with recent findings (Castel et al., 2003; Gazzaley et al., 2008; Schlaghecken et al., 2011). Second, as we aimed to examine time course effects in a task that involves conscious control (necessary for updating sequence targets), we predicted that performance indices within the S-ACT task should relate to measures of higher order abilities, notably measures of working memory performance.

4.3 Method

4.3.1 Participants

Forty three younger adults (*M* = 21.98, *SD* = 2.78) and thirty four older adults (*M* = 67.29, *SD* = 3.56) participated in this study. Excluded from the aforementioned were data from five older adults who did not complete the S-ACT task, and six younger adults and one older adult with slow reaction times and/or high error rates in this task (>3*SDs away from the group mean*). Younger adults were recruited from the Concordia University undergraduate participant pool in the Psychology department. Older adults were recruited through a participant pool established by the Adult Development and Aging laboratories at Concordia University and also through posters placed around the neighbourhood. Inclusion criteria for both younger and older adults included fluency in English, and absence of medical, psychological, or motor conditions that could influence their cognitive performance. Number of years of education was significantly greater for older adults (*M* = 16.34, *SD* = 2.75) than younger adults (*M* = 15.07, *SD* = 1.01), *t*(71) = 2.73, *p* = .008. The two groups were similar in general health status (older: *M* = 3.79, *SD* = 0.83; younger: *M* = 3.85, *SD* =

0.82), *t*(75) = 0.33, *p* > .05, with options 1 through 5 representing poor, fair, good, very good, and excellent, respectively.

4.3.2 Materials and Design

Background information was obtained using a demographic questionnaire, which included information on chronological age, years of education, and general health status. Measurement of inhibitory efficiency was based on data obtained from the S-ACT task (Blair et al., 2011; Li et al., 2000, 2010). Working memory was assessed with a modified version of the reading span task (Daneman & Carpenter, 1980), *n*-back task (Kirchner, 1958), and Letter-Number Sequencing task (Wechsler, 1997). Processing speed was measured with the Digit-Symbol Test (Wechsler, 1981).

S-ACT task (Li et al., 2000, 2010). The stimuli for this task consisted of six animal drawings: butterfly, cat, ladybug, zebra, bird, and elephant (Beaumont & Selley, 1990; Li et al., 2010; see Figure 4.1). Items were black and white and occupied a space of 11 cm x 11 cm in the center of the computer screen. The task was programmed using C-Sharp, and presented on a PC with a 17-inch monitor, using arrow keys (left and right) on the keyboard for responses. To counteract order effects, each participant received one of two different sequences; further, the first and second blocks of each sequence were presented in an alternating manner across participants.

Two blocks of 40 test trials each were presented to all participants, with eight practice trials given to young participants and nine to older participants. On each trial, 18 items were presented at a rate of 1000 milliseconds (ms) per item and consisted of six target items and 12 distractor items (items out of sequence), with a maximum of 4

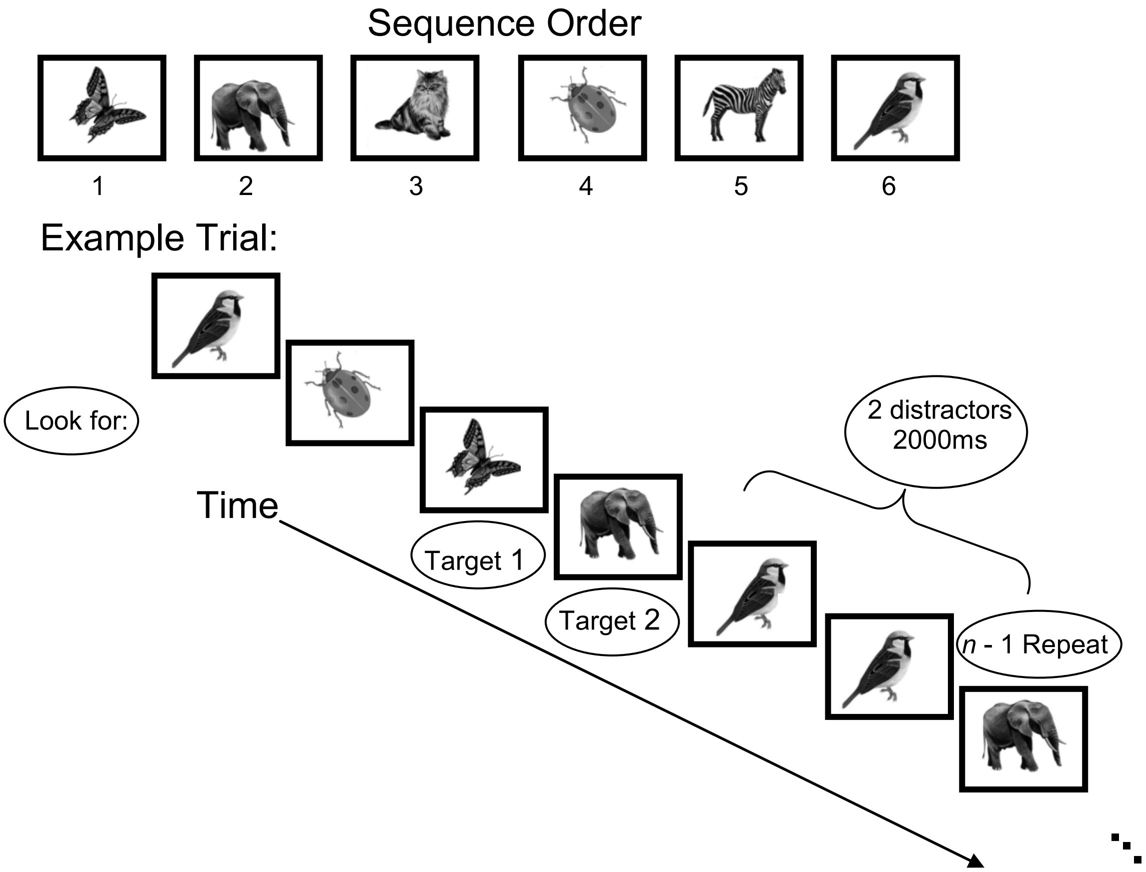

Figure 4.1. Stimuli for the sequential action control task and an example trial.

distractors between any two targets. Within the time limit, participants were required to make a “Yes” response to target items and a “No” response to distractor items. These choice responses were mapped on to either the left or right arrow key depending on participant preference.

To perform this task, participants memorized one of the two fixed sequences of six animals and monitored for each item in the memorized order as they appeared individually on a computer screen (see Figure 4.1 for one of the sequences used and an example trial). Thus, participants monitored for the presentation of Item 1 (e.g., butterfly in sequence 1) and responded by clicking “Yes” to this item when presented whereas they had to make a “No” response if any other item appeared. After responding to the first target item, participants monitored for the next target items in the order memorized, making “Yes” responses when they were presented while responding “No” to distractors (items out of sequence). After 18 items were presented in each trial, with the sixth target as the last item, a screen instructed participants that a new trial was going to begin; participants clicked the left/right arrow key when ready to begin the next trial. Error screens were presented for 1500 ms after incorrect responses or failures to respond within the 1000 ms time limit.

Performance indices included the following: (i) reaction times (RTs) on targets and distractors (“Yes”/”No” responses to targets and distractors); (ii) Lag errors, defined as incorrect responses to items ahead or before the present target (“Yes” to a distractor item); (iii) incorrect responses to target items (“No” response to target); and (iv) omission errors, defined as failure to respond to target or distractor items.

To examine the time course of deletion-type inhibition, target items were allowed to repeat within a trial. Between a target item (*n*) and the repeat of this item (*n* - 1 repeat), we placed a randomly determined distractor item. This distractor item was presented one to three consecutive times after the target (*n*) and before the *n* - 1 repeat. As each item was on screen for 1000 ms, the presentation of a distractor item one to three times allowed for a 1000 to 3000 ms delay between a target item (*n*) and repeat of this target (*n* - 1 repeat). This time delay manipulation between targets (*n*) and *n* - 1 repeats allowed for the examination of deletion-type inhibitory after-effects on *n* - 1 repeat items. In other words, if a target item becomes suppressed after being responded to (undergoes inhibition), responses to the repetition of this item within a short time (1000 to 3000 ms used here) should be slowed. To provide a control condition to compare RTs on *n* - 1 repeats, randomly selected Control distractors were presented after 1000 to 3000 ms delays following the presentation of target (*n*) items; thus, in these conditions, Control distractors were presented instead of *n* - 1 repeats. Thus, the manipulation conducted more specifically examines the time course of deletion-type inhibitory efficiency across differing numbers of distractors in the S-ACT task.

Within any of the 18-item trials, there were either (i) three randomly determined *n* - 1 repeats presented along with zero to one instance of a Control distractor or (ii) three randomly determined Control distractors presented with zero to one instance of an *n* - 1 repeat. The number of presentations of *n* - 1 repeats after one, two, and three distractors (i.e., 1000, 2000, 3000 ms delays) were randomly determined to be 47, 46, and 44 respectively; whereas presentations of Control distractors were randomly determined to be 46, 42, and 31, respectively.

An example trial would be: 1-2-5-5-**2**-3-6-6-*1*-4-2-2-2-**4**-5-2-**5**-6. Each digit represents the serial position of each sequence item. Bolded digits represent situations where *n* - 1 repeats were presented (items ‘2’, ‘4’, and ‘5’) after one to three distractors. The italicized digit (‘1’) represents a scenario where a Control distractor was presented after the distractor (‘6’) appeared two consecutive times.

To reduce the possibility that the task would become predictable following consecutive distractors (i.e., to expect an *n* - 1 repeat or Control distractor), we also included scenarios (27 opportunities) where instead of an *n* - 1 repeat or Control item, the next target item in the sequence was presented. Young (*M* = .06, *SD* = .06) and older adults (*M* = .04, *SD* = .04) did not differ in errors on these ‘catch’ trials, *t*(75) = .25, *p* > .05; thus, this index is not discussed in the rest of the manuscript.

Reading span task (Daneman & Carpenter, 1980). A computerized version of this task was presented (programmed with Superlab v. 4.7). Participants read sentences (8 to 12 words in length) presented individually in the middle of a computer screen and pressed one of two keys on the numeric pad of the keyboard (‘1’ and ‘3’) to indicate whether each sentence made semantic sense or not. After a set of sentences was presented (two to six), a blue screen appeared, at which point participants reported aloud the last word of each sentence in the order presented (final words). This procedure was carried out for 5 sets of sentences, starting with the lowest set (set size 2; two sentences sequentially presented) and increasing sequentially to the highest set size (set size 6; six sentences presented consecutively).

Participants were always given two trials of sentences at each set size. All participants advanced to the sixth set size regardless of whether they were able to recall the last words of sentences presented at lower set sizes. The experimenter recorded the number final words recalled after each set size was presented. An intrusion error score was also obtained from this measure that conceptually corresponded to deletion-type inhibition, specifically, difficulty suppressing previously relevant items in this task. This score included responses that were non-final words from the current trial, final or non-final words from the prior trial in the current set size, or final or non-final words from prior set sizes, all of which were once relevant for task performance (cf. Chiappe, Hasher, & Siegel, 2000).

N-back task (Kirchner, 1958). Participants were verbally presented with single digit numbers between one and nine (without consecutive repetition) and asked to repeat the number presented one step before (1-back) or two steps before (2-back). After receiving instructions, participants were given one practice trial, followed by two test trials of the 1-back task (11 items in length). Similar procedures were then repeated for the 2-back task (12 items in length). The total score was based on the total number of correct responses across all trials.

4.3.3 Procedure

Participants were individually tested in a quiet room. After participants read and signed the consent form, they completed the demographics questionnaire, followed by the S-ACT task. To perform this task, participants first memorized a fixed sequence of six animals. Next, they were instructed to monitor for each presentation of target items according to the order learned, clicking “Yes” for Item 1, then Item 2 through to Item 6, and "No" for items they were not looking for (distractors). After recalling items in the correct sequence order, participants completed a paper version of the sequential task, which required at least two successive accurate trial performances, before going on to practice and test trials on the computer. Participants were given a memory aid only for practice trials.

Halfway through the sequential task, participants completed the Digit-Symbol test and *n*-back task. Participants then completed the second half of the sequential task, and were asked for any specific strategies they used to complete the task. Subsequently, they completed the reading span task, Letter-Number Sequencing task, and other neuropsychological tests. Lastly, they were debriefed as to the purpose of the experiment and paid or given participation credits for their time. Each session lasted between 90 to 120 minutes.

4.4 Results

Results of independent samples *t*-tests indicated that younger adults outperformed older adults on the Digit-Symbol test, indices of the sequential task (average correct RT on targets, average correct RT on distractors, average Lag errors, and proportion of omissions), and working memory measures (reading span task, *n*-back task, and Letter-Number Sequencing test; see Table 4.1). Proportion of incorrect responses to targets (i.e., "No" responses on targets) did not differ between groups (young: $M = .05$, $SD = .03$; old: $M = .05$, $SD = .03$), $t(75) = 0.25$, $p > .05$. In addition, performance across block order and list sequence were comparable in response latency (RTs on targets and distractors) and errors (lags and omissions) for younger

Table 4.1

Correlations among variables controlling for age (top part of table) and descriptive statistics by age group (bottom part of table)

Variables	1	2	3	4	5	6	7	8
1. Mean RT to Targets	-							
2. Mean RT to Distractors	.85**	-						
3. Mean Lags	-.23*	-.15	-					
4. Proportion Omissions	.32**	.32**	.01	-				
5. N-back	-.24*	-.10	-.08	-.33**	-			
6. Letter-Number Sequencing	-.20	-.19	-.17	-.09	.15	-		
7. Reading Span[1]	-.03	.05	.02	.01	.15	.21	-	
8. Digit-Symbol Test[2]	-.16	-.15	-.14	-.26*	.34*	.16	.35*	-
Young Adults	469.3	443.72	.007	.007	36.12	13.14	20.6	66.12
	(47.31)	(57.08)	(.004)	(.01)	(3.79)	(5.75)	(4.71)	(10.28)
Older Adults	547.44	534.13	.011	.047	32.62	10.68	18.72	54.29

	(50.92)	(60.20)	(.006)	(.03)	(4.82)	(1.98)	(2.93)	(8.34)

Note. Values below correlation matrix reflect average scores per group; standard deviations are shown in parentheses. Significant age group differences were present in all background variables using independent samples t-tests, $ps < .05$.

RT = reaction time; ms = milliseconds

[1] Values shown represent total end-words recalled.

[2] Values shown reflect items correctly completed in 90 s.

$^{*}p < .05$, $^{**}p < .01$

adults, *ps* > .05, and older adults, *ps* > .05, and were therefore combined for each group in all analyses.

To examine the first hypothesis, namely that older adults should have more difficulty engaging deletion-type inhibition compared younger adults, when examined across distractors, we conducted an Age Group (young, old) x Distractor Number (1, 2, 3) x Trial Type (*n* - 1 repeat, control) mixed factorial analysis of covariance (ANCOVA) with age group as the between subjects factor and distractor number and trial type as within-subjects factors. Distractor number was operationalized by varying the number of distractors between targets (*n*) and *n* - 1 repeats or Control distractors. Digit Symbol scores served as the covariate. We obtained a significant main effect of age group, $F(1,74) = 26.89$, $p < .001$, $\eta_p^2 = .27$, due to slower RTs by older adults ($M = 526.20$, $SD = 53.66$) compared to younger adults ($M = 456.10$, $SD = 52.64$). No main effect was observed for trial type, $F(1,74) = 2.67$, $p = .11$, $\eta_p^2 = .04$, or distractor number, $F(2, 73) < 1$, $p =.98$, $\eta_p^2 = .001$. We obtained a significant Age Group x Trial Type interaction, $F(1,74) = 4.75$, $p = .03$, $\eta_p^2 = .06$, due to significantly faster responses in the *n* - 1 repeat condition compared to the control condition overall (across all distractors) in both groups, *ps* < .05, but which is more pronounced in older adults (*n* - 1 repeat: $M = 537.10$, $SD = 61.22$; control: $M = 553.94$, $SD = 58.25$) than younger adults (*n* - 1 repeat: $M = 466.39$, $SD = 60.07$; control: $M = 474.11$, $SD = 57.18$). No other interaction was significant including Age Group x Distractor Number, $F(2, 73) < 1$, $p = .66$, $\eta_p^2 = .01$; Trial Type x Distractor Number, $F(2, 73) < 1$, $p = .95$, $\eta_p^2 = .001$; and Age Group x Distractor Number x Trial Type, $F(2, 73) < 1$, $p = .76$, $\eta_p^2 = .01$ (See Figure 4.2; values shown are not adjusted for Digit Symbol performance). Thus, at this level of analysis, which emphasized one measure of central tendency for each trial type (repeat, control) at each distractor condition, neither younger nor older adults showed significant evidence of deletion-type inhibition.

In order to conduct a more detailed investigation of participants' S-ACT performance, we constructed cumulative distribution frequency (CDF) plots of participants' RT performance. This approach allowed for the examination of RT distributions for each trial type in the distractor conditions for the separate age groups. To construct CDFs for each trial type and distractor condition, we utilized the CDF-XL program provided in supplementary materials by Houghton and Grange (2011), which comprised the following steps. Firstly, in the one distractor condition, RTs were ranked ordered from fastest to slowest for each participant and for each trial type separately. Secondly, rankings for each trial type were divided into 10 bins (10 % bins; deciles). Lastly, mean RTs were calculated for each bin in each trial type and averaged across the separate age groups. This process was then repeated for the 2-distractor and 3-distractor conditions. The "binsize" (number of items per bin) for each condition (i.e., trial type) was determined in the following manner in the CDF-XL program: With a specified number of bins, Nbins, the number of responses, Nc, in a condition is divided by Nbins to yield the binsize for that condition, Binc. For example in the case of 40 responses partitioned into 10 bins, 4 responses will be included in each bin (Nc/Nbins = 40/10). However, if the value of Nc/Nbins is not a whole number, it is first made equal to its integer part, Binc = Int(Binc), with the result that Nbins × Binc < Nc. For example, suppose a condition contains 45 responses, (Nc = 45) and Nbins = 10. This means that Int(Nc/Nbins) = Int(4.5) = 4, and Nbins x Binc = 10 x 4 = 40. As a bin size of 4 throughout would leave 5 responses unused, the bin size is increased by 1 in this case such that Binc + 1 = 5, and the 9 remaining bins contain 4 responses each. Consequently the program drops 4 responses towards the slower end of the distribution where responses are highly variable and likely unreliable (note: this latter point is not explicitly noted in Grange & Houghton, 2011).

Thus, given that the number of the item presentations to respond to *n* - 1 repeats or controls were randomly determined to be between 31 and 47 (see Method Section for specific values), there was a maximum of 3.1 to 4.7 RTs provided per participant for each of the 10 bins. Specifically, for younger adults, the average number of trials in each of the 10 bins after 1, 2, and 3 distractors were 4.1, 4, and 3.7 in the *n* - 1 repeat condition and 4, 3.5, and 2.6 in the control condition, respectively. For older adults, the respective values following 1, 2, and 3 distractors were 4, 3.8, and 3.5 for the *n* - 1 repeat condition and 3.9, 3.3, and 2.4 for the control condition. Figures 4.3, 4.4, and 4.5 show CDFs across trial type for each distractor condition as a function of age group (values shown are not adjusted for Digit Symbol performance). It should be noted that slight differences between Figures 4.2 and figures representing CDFs (Figures 4.3, 4.4, and 4.5) are directly attributable to responses dropped towards the slower end of the distribution during the binning procedure, which were less than 5% in each age group.

We examined the pattern of performance across CDFs to conduct a more detailed examination of the first hypothesis. Thus, we conducted an Age Group

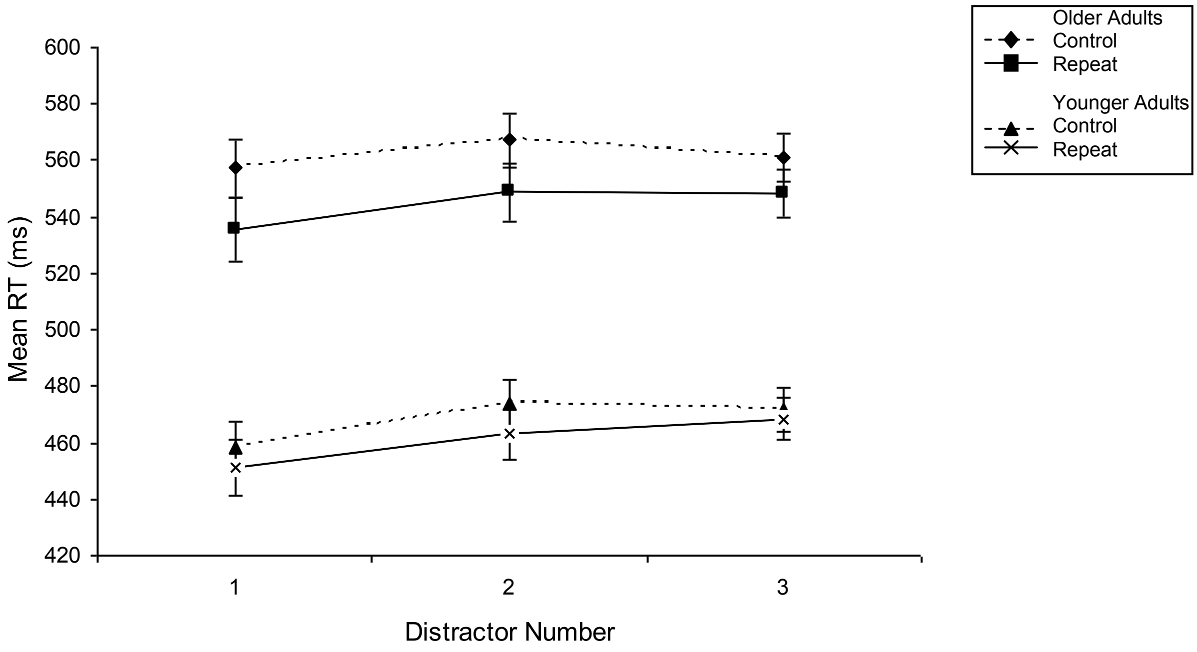

Figure 4.2. Mean RT performance in *n* - 1 repeat and control conditions as a function of age and distractor number without covariate adjustment. Error bars represent ± one standard error of the mean. ms = milliseconds.

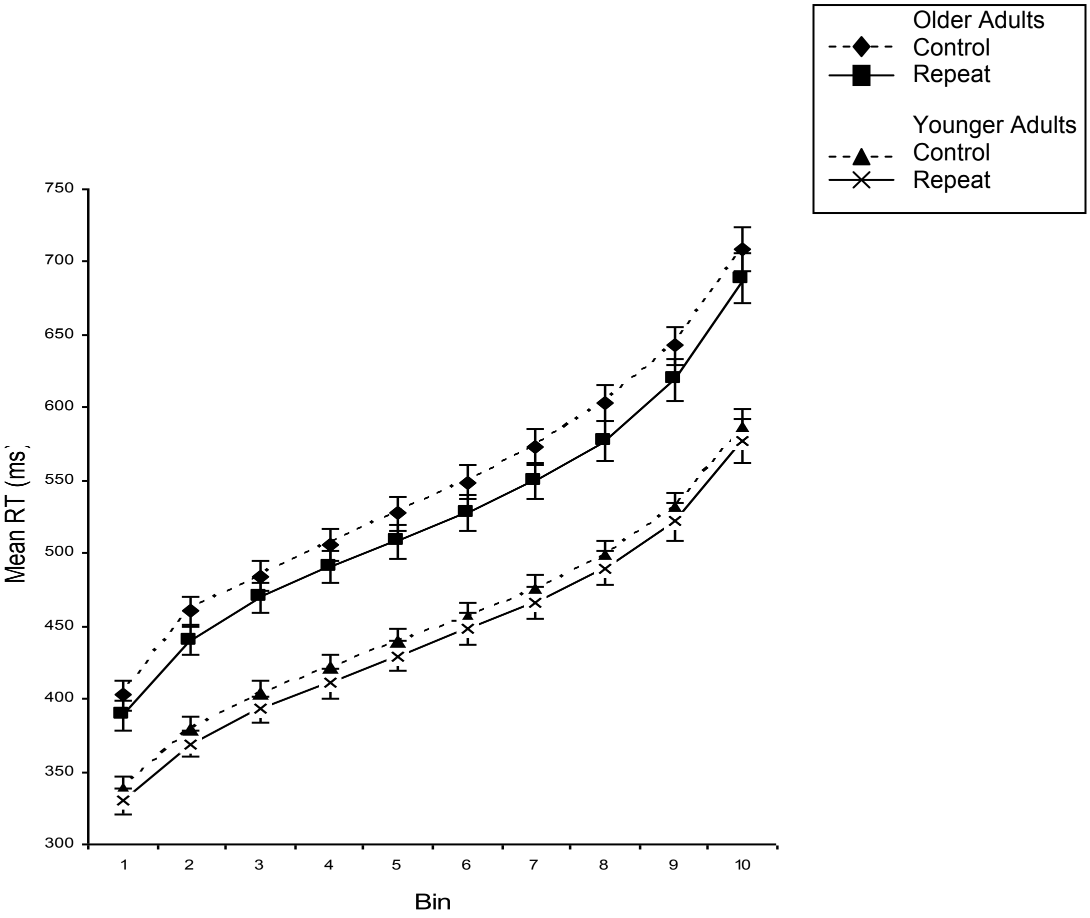

Figure 4.3. Cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 1-distractor condition without covariate adjustment. Error bars represent ± one standard error of the mean. ms = milliseconds.

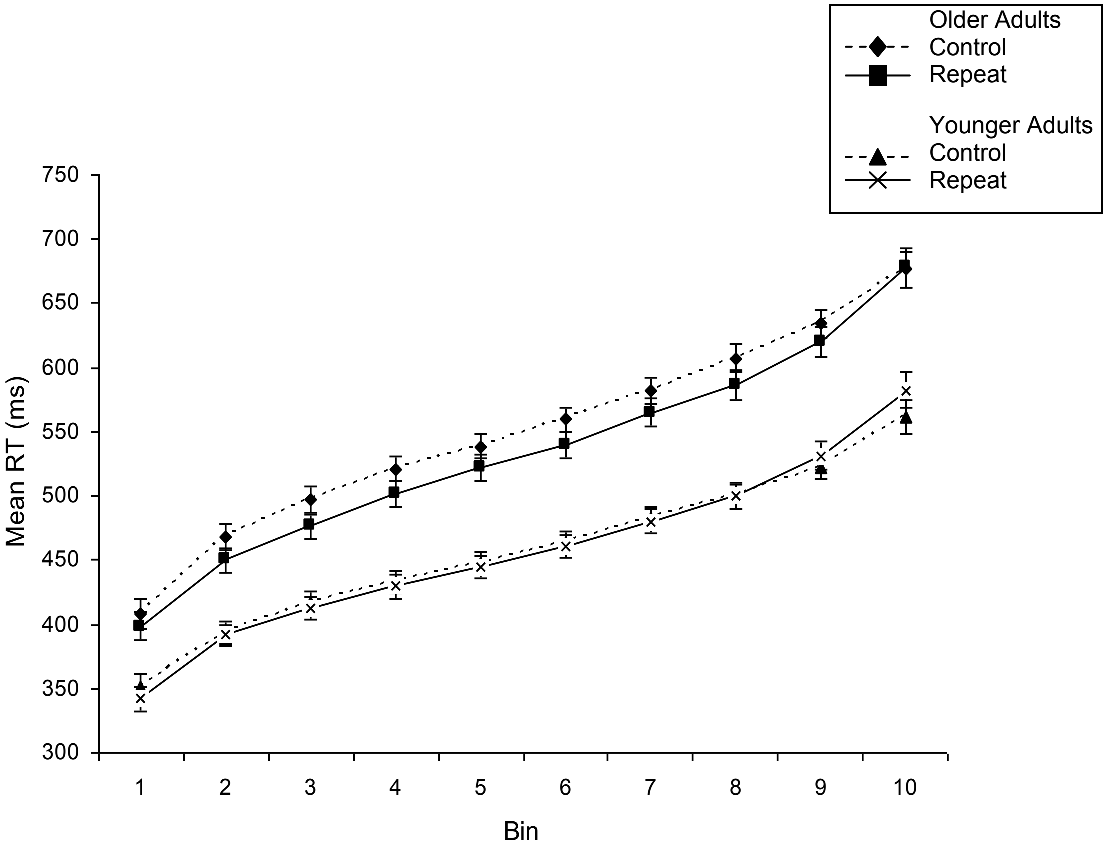

Figure 4.4. Cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 2-distractor condition without covariate adjustment. Error bars represent ± one standard error of the mean. ms = milliseconds.

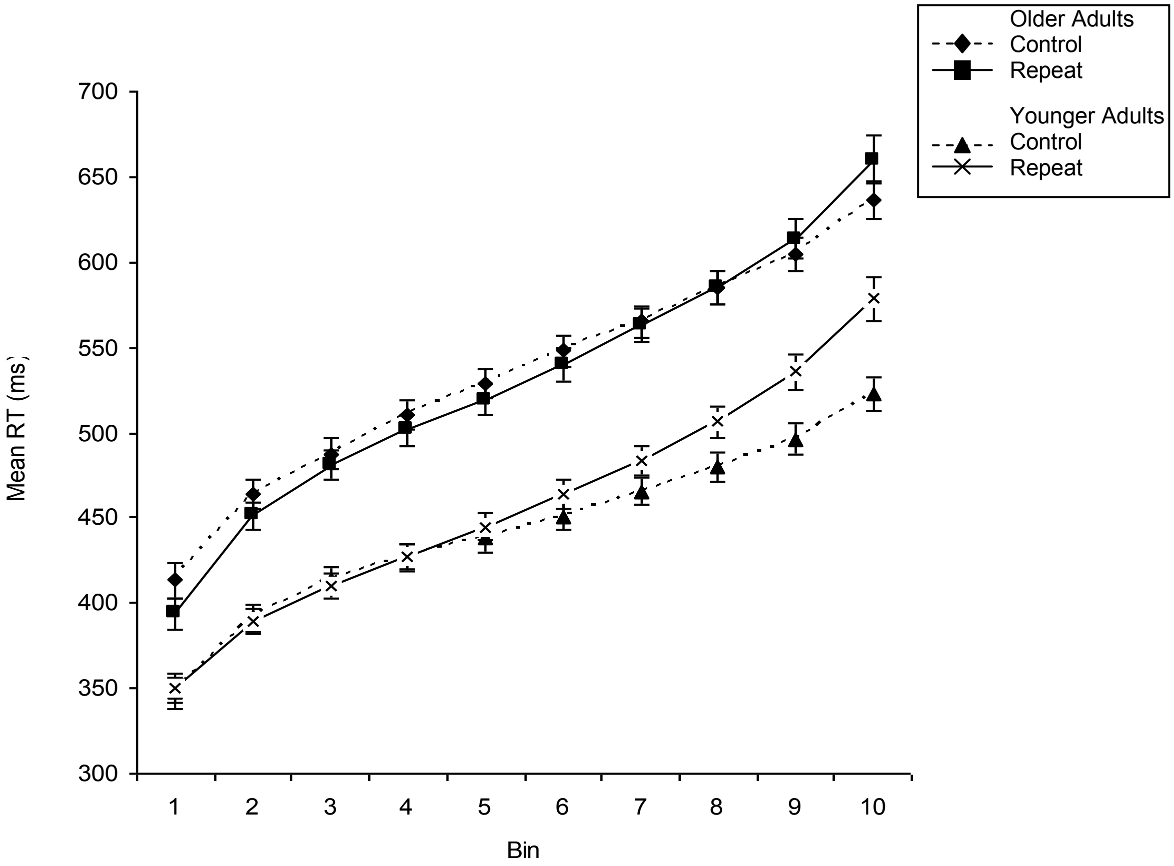

Figure 4.5. Cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 3-distractor condition without covariate adjustment. Error bars represent ± one standard error of the mean. ms = milliseconds.

(young, old) x Distractor Number (1, 2, 3) x Trial Type (*n* - 1 repeat, control) x Bin (1-10) mixed factorial ANCOVA with age group as the between subjects factor and distractor, trial type, and bin as within subjects factors. Digit symbol scores served as the covariate. Once again, the main effect of age group was significant, $F(1, 74) = 24.34$, $p < .001$, $\eta_p^2 = .25$, and no significant main effects were obtained for trial type, $F(1, 74) < 1$, $p = .88$, $\eta_p^2 < .001$, or distractor number, $F(2, 73) < 1$, $p = .83$, $\eta_p^2 = .01$. However, the main effect of bin was significant, $F(9, 66) = 13.94$, $p < .001$, $\eta_p^2 = .66$. These results were qualified by a significant Age Group x Trial Type interaction, $F(1, 74) = 8.72$, $p = .004$, $\eta_p^2 = .11$, as well as two 3-way interactions: Age Group x Trial Type x Bin, $F(9, 66) = 2.38$, $p = .02$, $\eta_p^2 = .25$; Distractor Number x Trial Type x Bin, $F(18, 57) = 1.89$, $p = .04$, $\eta_p^2 = .37$. No other 2- or 3-way interactions were significant: Age Group x Distractor Number, $F(2, 73) < 1$, $p = .87$, $\eta_p^2 = .004$; Age Group x Bin, $F(9, 66) = 1.56$, $p = .15$, $\eta_p^2 = .17$; Trial Type x Distractor Number, $F(2, 73) < 1$, $p = .41$, $\eta_p^2 = .02$; Age Group x Trial Type x Distractor Number, $F(2, 73) < 1$, $p = .59$, $\eta_p^2 = .01$; Age Group x Distractor Number x Bin, $F(18, 57) < 1$, $p = .61$, $\eta_p^2 = .22$.

Together, the results were qualified by a significant Age Group x Distractor Number x Trial Type x Bin interaction, $F(18, 57) = 1.81$, $p = .047$, $\eta_p^2 = .36$. To follow up on this interaction, we conducted separate Age Group x Trial type x Bin mixed factorial ANCOVAs on each distractor condition. No significant Age Group x Trial Type x Bin interactions were obtained for the 1-distractor, $F(9, 66) = 1.09$, $p = .39$, $\eta_p^2 = .13$, or 2-distractor conditions, $F(9, 66) = 1.70$, $p = .11$, $\eta_p^2 = .19$, or any other 2-way interactions for these conditions (Age Group x Trial Type, Age Group x

Bin, or Trial Type x Bin, *ps* > .05). However, for the 3-distractor condition, the Age Group x Trial Type x Bin interaction was significant, $F(9, 66) = 2.58$, $p = .01$, $\eta_p^2 = .261$. Bonferroni corrected post hoc analyses with covariate-adjusted means revealed significantly slower RTs from bins 6 to 10 in the *n* - 1 repeat condition compared the control condition for younger adults, *ps* < .005. For older adults, no significant difference was obtained across trial types in any bin, *ps* > .05.

Convergent findings were obtained when alternative analyses were conducted to account for baseline RT differences between age groups by log-transforming RTs in the *n* - 1 repeat and control conditions (Kray & Lindenberger, 2000). In the 3-distractor condition only, this approach revealed a marginally significant Age Group x Trial Type x Bin interaction, $F(9, 67) = 1.94$, $p = .06$, $\eta_p^2 = .21$. Bonferroni corrected post hoc contrasts revealed a similar pattern as the covariate adjusted results: significantly slower RTs from bins 6 to 10 in the *n* - 1 repeat condition compared the control condition for younger adults, *ps* < .005; for older adults, no significant difference was obtained across trial types in any bin, *ps* > .05 (Figures using log transformed data for each distractor condition and trial type can be found in Appendix A). It should be noted that although the overall ANOVA design without the covariate adjustment did not yield a significant 4-way interaction (Age Group x Distractor Number x Trial Type x Bin, $F(18, 58) = 1.27$, $p = .25$, $\eta_p^2 = .28$) in a similar omnibus ANOVA, the results of the 3-distractor condition were the same as the covariate adjusted design and the log transformed results.

Together these findings characterize increased performance costs on *n* - 1 repetitions (*vs.* controls items) for younger adults relative to older adults in the latter half of 3-distractor distribution (Figure 4.5), with consistently increasing costs on *n* – 1 repetitions beginning in earlier bins for younger adults as a group (*M*bin = 5) compared to older adults as a group (*M*bin = 8) (values identical with log or covariate adjusted bins).

As an additional analysis, we examined whether there was supportive evidence of deletion-type inhibition in the *n* - 1 repeat trial type in the 3-distractor condition, as suggested by the CDF analysis, especially for younger adults (Figure 4.5). Thus, we conducted correlation analyses between a deletion-type inhibition index in the 3-distractor condition of the S-ACT task and a measure of deletion-type inhibitory efficiency in the reading span task (intrusion errors; two younger adult outliers were removed, >2.5SD). The deletion-type inhibition index was created by computing raw RT difference scores between trial types in the 3-distractor condition (sum of bin RTs in the *n* - 1 repeat condition subtract sum of bin RTs in the control condition); positive values indicate slowed responses in the *n* - 1 repeat condition compared to the control condition. We obtained a significant correlation for younger adults, $r = -.36$, $p < .025$ (Bonferroni correction), indicating that increased performance costs in the *n* - 1 repeat condition correlated with lower intrusion errors in the reading span task; however, this correlation was not significant in the older group, $r = .18$, $p = .29$ (Figure 4.6). No significant correlations with intrusion errors were observed for either group when similar deletion-type inhibitory indices were created in the 1- and 2- distractor conditions, *ps* > .05. The pattern of correlation results was identical using log-transformed RT data. Lastly, we tested the second hypothesis that performance in the S-ACT task involves working memory processes

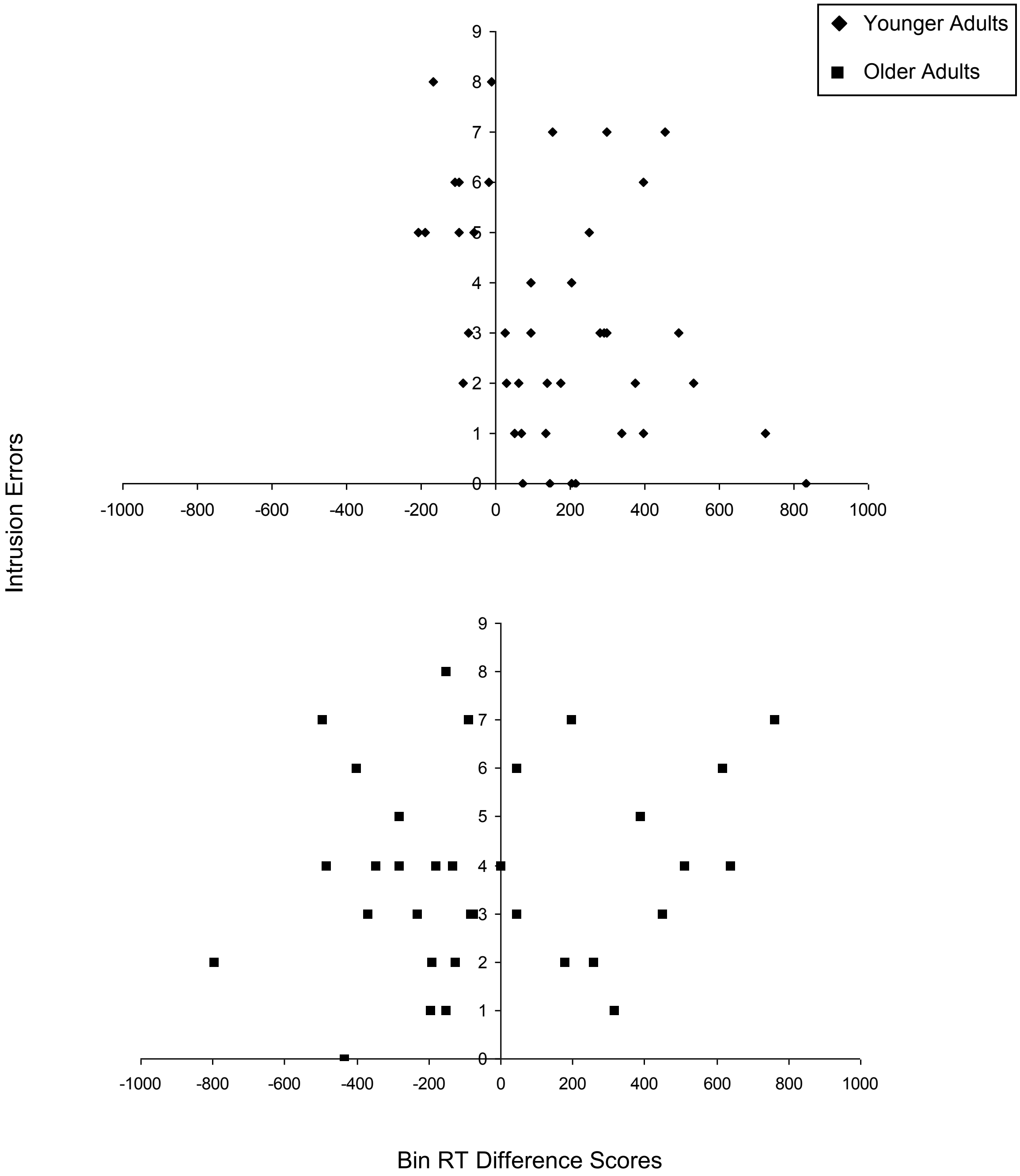

Figure 4.6. Correlations between deletion-type inhibition in the 3-distractor condition (sum of *n* - 1 bin RTs subtract sum of control bin RTs) and intrusion errors in the reading span task for younger adults (top panel) and older adults (bottom panel).

by examining correlations between performance indices in the sequential task with working memory measures. As shown in Table 4.1, average RT on targets and proportion of omissions correlated significantly, *ps* < .05, with *n*-back performance (Bonferroni corrections were not applied, given our apriori predictions regarding sequential performance indices and working memory performance). Correlations were not significant between working memory measures and the deletion-type inhibition index noted prior in the 3-distractor condition. In addition, a median split of the older adults' data based on working memory measures (*n*-back, Letter-Number Sequencing, and reading span performance) revealed no reliable differences in the deletion-type inhibition index (*ts* < 0*, ps* > .05).

4.5 Discussion

In this study, we examined whether older adults had more difficulty engaging deletion-type inhibition relative to younger adults using a sequential updating task in which conscious control was involved. To this end, we used a choice reaction time version of the S-ACT paradigm and employed a variable number of distractors (1 to 3), which represented variable time delays (1000 to 3000 ms), between targets (*n*) and repeated presentations of said targets (*n* - 1 repeats). This manipulation allowed us to examine time course dynamics of deletion-type inhibition, with the predictions that performance costs should be evident on *n* - 1 repeats, and that older adults should have more difficulty engaging deletion-type inhibition compared to younger adults. Standard analyses of central tendency indices for each distractor window revealed no evidence of deletion-type inhibition or age effects at specific distractor windows. Instead, both groups showed significant facilitation overall in the *n* - 1 repeat condition, which was more exaggerated in the older group. However, closer investigation of participants' performance by examining RT distributions revealed evidence of deletion-type inhibition at the latter window (third distractor), especially for younger adults. This finding was specific to the latter half of the distribution in the third distractor window and appeared virtually non-existent in the older group, indicating much reduced inhibitory efficiency in older adults. In addition, we obtained evidence suggesting that working memory updating processes are involved in the S-ACT paradigm due to correlations with the *n*-back task. Together, these findings indicate that older adults have reduced ability to engage deletion-type inhibition as compared to younger adults, and emphasize the utility of investigating the time course dynamics of inhibitory functioning in the context of a high-level sequential updating paradigm.

Research on the precise nature of inhibitory functioning and changes with age continue to be a controversial area (Burke, 1997; Burke & Osborne, 2007; Lustig, Hasher, & Zacks, 2007; McDowd, 1997). This work represents an additional effort to complement a small but growing body of research indicating reduced ability to engage deletion-type inhibition in a timely manner with age (Maylor et al., 2005). Below we address a number of observations in the present work, specifically the limited evidence of deletion-type inhibition observed overall. We subsequently discuss its specificity to the 3-distractor condition as likely representing a combination of contextual factors (target expectancy) and task preparation, before we return to discussing differing age effects observed.

The most noticeable observation in this study is the limited evidence of deletion-type inhibition across the majority of distractor conditions. This was indicated in the standard analysis, which emphasized central tendency indices at each distractor condition, as well as in the examination of response distributions, except for the latter distractor condition (3-distractor). This general reduction in deletion-type inhibition may be reflective of a number of factors. Different from our prior studies with this paradigm (Blair et al., 2011; Li et al., 2010), we decreased the number of targets from eight to six items in order to aid performance, as our dependent measure required highly accurate performances. This fewer number of targets easily falls at the lower end of the working memory capacity of young and older adults when using a chunking strategy (e.g. 2 3-item chunks; e.g. Allen & Coyne, 1989; Allen & Crozier, 1992; Cowan, 2001), an approach previously observed in this paradigm (Li et al., 2010). A fewer number of chunks (or items) to be suppressed sequentially throughout the task may reduce the extent to which deletion-type inhibition is engaged (see Koch, Philipp, & Gade, 2006; Schneider, 2007 for modulatory effects of chunking on inhibitory functioning; cf. Mayr, 2009). In addition, fewer sequence targets combined with the repetitive nature of the task (to monitor for the same target sequence) may have also resulted in little task-level interference from distracting information, further reducing the degree of deletion-type inhibition exerted to facilitate performance.

Consistent with this notion, inhibitory mechanisms are generally proposed to resolve conflict/interference in the cognitive system (see reviews in Arbuthnott, 1995; Koch, Gade, Schuch, & Philipp, 2010) and have been shown to vary with cognitive and task-level conflict/interference. For instance, backward inhibition (*n* - 2 repetition costs; Mayr & Keele, 2000), often evidenced by performance costs when returning to a task recently performed, has been shown to vary with between-task competition (Gade & Koch, 2005). Similarly, inhibition of return, typically observed by reduced ability to re-engage attention at previously attended locations, has been shown to depend on the attentional demands of a task (Klein, 2000).

Moreover, the generally limited evidence of deletion-type inhibition observed in this study may have also been a consequence of a distractor rather than a pure time course manipulation. Specifically, to minimize disruptive effects between targets and repetitions of said targets, the same distractor was presented twice consecutively in the 2-distractor condition and three times consecutively in the 3-distractor condition, before critical trials were presented (*n* - 1 repeat or controls). This approach likely created within runs effects (priming/biasing responses during successive presentations of the same distractor), potentially causing disruptive start up costs and consequent noisy performance on critical trials (see Rogers & Monsell, 1995, for similar within runs effects in task switching). Such within runs effects are supported by faster response latencies observed on each successive repeated distractor (*ps* < .05), before critical trials were presented, which evidence start up costs following consecutive distractors (*ps* < .05). Notably, such an issue is not relevant in a pure time course manipulation where time is ideally the only factor manipulated before critical trials are presented. However, the S-ACT paradigm was designed to further understand sequential processes relevant to everyday sequential performance with aging; thus, the approach used to manipulate the time course is considered more ecologically valid as task-irrelevant distractors are integral to sequential tasks, despite the disruptive effects they may cause during task performance (e.g., slowed and erroneous responses; Schwartz, 2006). This has been observed in younger adults under cognitive load (e.g., Giovannetti, Schwartz, & Buxbaum., 2007; Humphreys, Forde, & Francis, 2000), and possibly reflects difficulty that older adults might display from time to time during sequential performance.

Despite the absence of an empirical signature of deletion-type inhibition throughout much of the sequential task, it is important to note that the absence of evidence of inhibition does not necessarily indicate that inhibitory processes were not engaged in this task. This point was illustrated in recent work by Grange, Juvina, and Houghton (2012) on a similar type of low-level (unintentional) inhibition, namely backward inhibition (empirically represented by n - 2 repetition costs in task switching paradigms; Mayr & Keele, 2000). These authors developed a cognitive computational model to examine n - 2 repetition costs by varying the amount of inhibition, and observed similar n - 2 performance costs to extant human work when inhibition was involved in the model. Importantly, they observed that the absence of n - 2 repetition costs were only possible with a reduced amount of inhibition in the model, whereas, n - 2 repetition benefits only occurred with inhibition completely removed from the model; this latter finding is consistent with an activation only perspective (primed performance benefits afforded from recently performing the task).

Grange and colleagues' (2012) findings clearly have implications in task switching work and should be applied cautiously outside that context. However, similar to task switching paradigms, the present sequential paradigm also involves common characteristics: (1) the need to suppress previously relevant task sets (Arbuthnott, 1995; Humphreys, Forde, & Francis, 2000), which comprises the representation of task-relevant stimuli and responses and corresponding stimulus-response mappings (Kiesel et al., 2010); and (2) the need to sequentially update (switch) working memory contents to the next task/sequence element (i.e., target item/chunk; Li et al., 2010). To the extent that similar cognitive mechanisms are involved across paradigms, including inhibitory mechanisms to suppress prior information, Grange and Houghton's findings may have relevance for our observations. Specifically, null findings across RT distributions especially in early distractor windows (1- and 2- distractor) may not necessarily indicate the absence of deletion-type inhibition, but rather reduced levels of inhibition in both groups. Moreover, for older adults, the pattern of results obtained may indeed indicate a complete absence of deletion-type inhibition at specific time points. This is due to the significantly greater performance benefit observed overall on *n* - 1 repeat items for older adults (16 ms) than for younger adults (8 ms), a result that appeared to be specific to the earlier time windows (1- and 2-distractor conditions) as observed in the CDF plots (Figures 4.3 and 4.4). This benefit is consistent with Grange and Houghton's finding of a performance benefit when returning to a recently performed task with inhibition completely removed from the model.

It should be emphasized that speculations regarding the degree of deletion-type inhibition in the early time windows is based on exploratory analyses that went beyond central tendency indices at each distractor window, specifically by constructing CDF plots (for the utility of this approach in elucidating various cognitive processes, see reviews in Houghton & Grange, 2011; Ratcliff, 1979; see also De Jong, 2000; Grange & Houghton, 2011; Pratte, Rouder, Morey, & Feng, 2010). This approach allowed for a more detailed examination of deletion-type inhibition across distractors, and revealed performance costs in the *n* - 1 repeat condition compared to the control condition in the 3-distractor condition, particularly for younger adults. This pattern is consistent with a suppressive after-effect of a sequential inhibitory process applied to the most recent target (Arbuthnott, 1995; Houghton & Tipper, 1996). Further evidence that deletion-type inhibition was present in the 3-distractor condition was shown by correlations with intrusion errors in the reading span task, which also conceptually represents difficulty suppressing prior relevant information and is commonly employed as an inhibitory measure (Chiappe et al., 2000; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Lustig, May, & Hasher, 2001).

Potentially problematic for an inhibition account, however, is that the generally early facilitatory pattern on *n* - 1 repeats did not quickly change into a performance cost across much of the distractor manipulation, only appearing in the 3-distractor window. This late evidence of deletion-type inhibition indicates that specific triggering mechanisms might be operating in the 3-distractor condition that were not present in the earlier distractor conditions. Given reduced difficulty (task-level conflict/interference) as noted prior, a triggering mechanism specific to the 3-distractor condition may be the high expectancy that the next target will be presented. In other words, as zero to four distractors were presented between targets (the critical conditions being the fourth: *n* - 1 repeat or control), it is likely that participants quickly learned to expect the next target in the 3-distractor condition. Consequently, such high expectations to transition to the next target makes the 3-distractor condition the most sensitive condition for inhibitory links between the prior interfering target and the upcoming target to be strongly exerted. This is particularly owing to the strong sequential bond linking neighbouring targets (Li et al., 2010). Notably, such strong exertion of deletion-type inhibition might be expected at the zero or one distractor condition to quickly facilitate target transition; however, the possibility of additional distractors to be presented and the affordances of task-specific factors (few targets to remember, repetitiveness of task) may not have encouraged strong inhibitory suppression in these early conditions.

It should be pointed out that the percentage of times zero to four consecutive distractors were presented, prior to target presentation, was fairly similar across the task: randomly determined percentages being 21%, 15%, 24%, 22%, and 18%, respectively. However, during the course of a sequence, each presentation of an intervening distractor between targets necessarily decreases the probability that the next target will be presented. For instance, after a target is shown, the probability of the next target being presented is 1 in 5 (0, 1, 2, 3, or 4 distractors can be presented); following a target and one distractor, the probability of the next target is decreased to 1 in 4 (0, 1, 2, or 3 distractors can be presented). Using this logic, by the time the *n* - 1 repeat should be presented, following 3 distractors (hence the 3-distractor condition), the probability of the next target is 1 in 2, namely, either a critical item (*n* - 1 repeat/control) or the next target can be presented. Thus, such high expectancy regarding the next target in the 3-distractor condition makes this condition most apt for the cognitive system to exert deletion-type inhibitory influences on the prior target to ensure a smooth transition to the next target. This notion is also supported by re-examination of prior work (Blair et al., 2011), which revealed reduced deletion-type inhibition across increasing numbers of distractors (reduced inhibition on 3-distractor *vs*. 1-distractor, $p < .05$); however, this pattern reversed (enhanced inhibition) on the latter distractor before the expected target presentation (similar level of inhibition on 4-distractor *vs.* 1-distractor, $p > .05$), a pattern specific to difficulty suppressing prior as opposed to future irrelevant targets. Moreover, such contextual effects are not limited to this paradigm.

For instance, much of the research evidencing n - 2 repetition costs typically employ a 100% switch rate to a different task (see reviews in Koch et al., 2010; Mayr, 2007). Consequently, high certainty regarding a switch to a different task makes consistent exertion of inhibition beneficial to task performance. This may explain the robust observation of n - 2 repetition costs across varying stimulus types (e.g., letters, numbers, symbols), response modalities (e.g., manual, vocal) and task levels (e.g., perceptual tasks, language switching) (Koch et al., 2010). However, a flexible and adaptive cognitive system would be expected to modulate such an approach if switch expectancy is reduced, as such consistent exertion of inhibition is likely to be costly to performance when tasks repeat (Philipp & Koch, 2006). Consistent with this, Phillip and Koch recently observed that with a reduced switch rate, thus allowing for immediate repetitions of prior tasks, n - 2 repetition costs decreased to non-significant levels (see Arbuthnott & Woodward, 2002, for complementary findings). Given such adaptive control to contextual factors, in the present study adaptive control may have modulated the strength of inhibitory links across distractor conditions, thus, making the 3-distractor condition (with high expectancy regarding the next target), the most sensitive condition to observe deletion-type inhibition.

Additionally, expectancy factors may not be the only triggering condition to engage inhibitory influences in the third distractor window of the sequential task used. In particular, exertion of a low-level deletion-type inhibition may be especially triggered when participants are also not fully prepared for the highly expected upcoming target. Importantly, the ability to closely investigate task performance during prepared and unprepared states has been argued as one of the primary benefits of examining time course effects by partitioning response latencies (De Jong, 2000; Grange & Houghton, 2011; Grange et al., 2012; Houghton & Grange, 2011; Pratte et al., 2010; Ratcliff, 1979). As a consequence of intermittently reduced preparation, the cognitive system is most likely to exert inhibitory influences to maintain task-level performance at an optimal level. Thus, if the latter half of the 3-distractor distribution, which comprise slower responses, reflected moments of lack of preparation for the upcoming stimuli as argued in the literature (e.g., De Jong, 2000; Grange & Houghton, 2012), the results indicate that younger adults were able to engage deletion-type inhibition when most unprepared for the next target. Taken together, in the 3-distractor condition, a combination of high target expectancy and times (moments) of reduced task-specific preparation may have resulted in strengthening inhibitory links to the prior target while advancing to the next, especially for younger adults.

Alternatively, episodic retrieval of the target stimulus when presented again as an *n* - 1 repeat may be interpreted as inducing a response conflict that increases RTs on *n* - 1 repeats in the 3-distractor condition, i.e., “Yes” response on target (*n*) conflicting with “No” response on *n* - 1 repeat (MacLeod et al., 2003). By extension, this account would also predict performance cost early in the time course (early bins in the RT distribution) when Yes/No response mappings to the same stimulus item change between target (*n*) and *n* - 1 repeat presentation. However, Figures 3, 4 and 5 show performance facilitation on *n* - 1 repeats in the earliest bins. This early performance facilitation indicates that any conflict resulting from a change in response mappings to targets (*n*) and *n* - 1 repeats was resolved very early in the time course. In lieu of the combination of expectancy and preparatory factors noted above, a non-inhibitory account would suggest that high expectancy to transition to the next target would result in a conflict when a distractor is presented (*n* - 1 repeat / control), which would take time to resolve; thus, re-mapping of responses would be expected to be slowed (“Yes” for targets to change to “No” for distractors). Moreover, this conflict would be stronger for the *n* - 1 repeat condition, given its recent performance and sequential association with the prior target. As a result, the re-mapping process would be more difficult (slower) in the *n* - 1 repeat condition, especially during moments of reduced task preparation (latter half of the RT distribution). However, from this viewpoint, we would expect older adults to have more difficulty resolving this conflict, and hence, produce higher costs on *n* - 1 repeats, which was not observed. Further, given our findings of convergent associations with intrusion errors in the reading span task for younger adults, an often used measure of deletion-type inhibition (Chiappe et al., 2000; Palladino & De Beni, 1999), we favour an inhibitory account for our findings.

Assuming that contextual (expectancy) and preparatory factors were operating in the 3-distractor condition, the benefit of engaging deletion-type inhibition favoured younger adults over older adults. Notwithstanding, like younger adults, the pattern of results for older adults also indicated response slowing in the *n* - 1 condition relative to the control condition in the latter bins. However, this pattern appeared to be much weaker in older adults compared to younger adults, indicating reduced ability by older adults to engage deletion-type inhibition. It is also consistent with prior work (e.g., Schlaghecken et al., 2011), but extends it by our examination of a low-level inhibition (unintentional) process in a high-level task that requires updating sequential information.

Our goal, namely to extend aging research on inhibitory time course dynamics to a consciously controlled task, was supported by significant relations between performance indices in the S-ACT task and working memory performance. We found that greater working memory updating (*n*-back task) was related to better ability to advance to the next target (shorter target RTs and lower target omissions). These results suggest that high-level working memory updating processes in the *n*-back task were involved in the S-ACT paradigm, in line with the updating nature of the sequential task. The lack of significant correlations between the S-ACT task and other working memory measures (reading span and Letter-Number Sequencing tasks) likely reflects a greater emphasis on working memory capacity in these measures rather than sequential updating processes. It should also be noted that working memory performance was not associated with individual differences in an inhibitory index created in the 3-distractor condition (that assessed slowing on *n* - 1 repeats as compared to controls).

In contrast to the absence of an association between working memory performance and individual differences in the ability to efficiently engage inhibitory functioning in our data, EEG research by Gazzaley and colleagues (Gazzaley et al., 2008; Zanto, Hennigan, Östberg, Clapp, & Gazzaley, 2010) showed that delayed inhibitory functioning in older adults constrained working memory performance (see similar results in Jost et al., 2011 using a slightly different paradigm). The inconsistencies between these results and our work may lie in the nature of the inhibitory process examined: the present work involved an unintentional inhibitory process whereas the prior studies noted involved intentional inhibitory processes. For instance, in Gazzaley and colleagues' work, participants suppressed stimulus elements that they were instructed to ignore. In addition, the nature of our task (repeated presentations of a fixed sequence of a few target stimuli) likely reduced the overall need for high-level processes to mediate task performance. Taken together, the extent to which engagement of inhibitory processes constrain higher order cognition (e.g., working memory) likely depends on the nature of the inhibitory process and extent to which high-level processes are involved in task performance.

A detailed explanation of older adults' mixed performance on inhibition tasks likely depends on a number of factors including: working memory load involved in tasks used (e.g., McCabe, Robertson, & Smith, 2005); downstream effects of older adults' reduced processing speed (Salthouse, 1996); and nature of stimuli employed (e.g., stationary vs. moving stimuli, Watson & Maylor, 2002; target detection vs. colour discrimination, Langley, Fuentes, Vivas, & Saville, 2007). Our results suggest that the reduced ability in older adults to engage inhibition in a similar manner as younger adults may represent another potential moderator of age effects observed in the literature. This difficulty engaging inhibition in older adults is consistent with the inhibition deficit hypothesis (Hasher et al., 1999, 2007; Lustig et al., 2007); however, the inhibition deficit account will likely benefit from further specification of the nature of the inhibitory deficit in older adults. Our results as well as findings from recent time course studies suggest that aging might have be associated with changes in the time course dynamics of engaging inhibitory functions.

Further, such difficulty engaging inhibition in older adults is consistent with the load-shift hypothesis of aging (Velanova, Lustig, Jacoby, & Buckner, 2007). Conceptualized within a memory retrieval framework, in the load-shift hypothesis it is proposed that aging is associated with reduced executive resources thereby leading to inefficient filtering of information at early selection stages. Consequently, there is a shift towards increased reliance on frontally-mediated processes in the latter evaluative stages of retrieval. Thus, although aging has been associated with increased recruitment of frontal systems (e.g., see reviews in Cabeza, 2002; Reuter-Lorenz & Campbell, 2008), the load-shift hypothesis explicates the time course nature of this neurocognitive shift with aging. Conceptually related to this hypothesis is the increased reliance by older adults on late stage reactive control processes due to inefficient preparatory proactive control processes (Braver, Gray, & Burgess, 2007; Czernochowski, Nessler, & Friedman, 2010). Thus, in regard to the timely engagement of inhibitory processes with age, the load-shift hypothesis suggests that irrelevant information may be accessible early, possibly due to reduced executive control or reduced automatically triggered control with aging (Reuter-Lorenz & Campbell, 2008). As a result, there is a compensatory shift to more high-level (frontal) control later in the time course to mediate task performance.

In summary, we extended recent research on the time course of inhibitory functioning to a sequential updating paradigm that required conscious control, and observed that older adults had more difficulty engaging low-level deletion-type inhibition in a manner consistent with younger adults. The generally observed similarity with paradigms in which older adults have difficulty engaging high-level inhibitory processes might be indicative of a degree of commonality across levels of inhibitory control, potentially reflecting increased but inefficient frontal involvement with aging.

Chapter 5

General Discussion

In this thesis, I set out to better understand how inhibitory and working memory functioning change with age in the context of a sequential action paradigm. The approach taken was guided by (1) inhibition deficit accounts of aging in which reduced inhibitory functioning with age negatively impacts higher order abilities, and (2) the utility of better understanding cognitive mechanisms underlying sequential performance. I observed that age-related decline in deletion-type inhibition accounted for age differences in working memory components (Study 1). This approach represents a methodological and theoretical step forward in examining single factor theories of age-related decline in working memory functioning. In particular, the use of variance partitioning techniques demonstrated the relation between inhibitory functioning in the context of sequential performance and higher order abilities (working memory) at the componential level. In addition, this approach is consistent with conceptualizations of working memory as a system for simultaneous storage and processing operations, and observations that both storage and processing components make independent contributions to higher-order abilities. Moreover, given the observation of age-related decline in deletion-type inhibition, I undertook a process-level analysis with the aim of specifying the time course nature of this change (Study 2 and 3). In using this approach, older adults had difficulty engaging deletion-type inhibition relative to younger adults (Study 3). In light of inconsistent findings regarding inhibitory functioning with age, this finding suggests that it might be important to examine the time point at which inhibitory functions are engaged. Taken together, this work highlights the important role of inhibitory functioning with age in higher order cognition (working memory) and emphasizes the utility of examining age effects in the time course dynamics of cognitive functions in sequential tasks.

Below I outline the findings of the thesis in more detail and subsequently address implications of these findings and outstanding issues regarding inhibitory functioning in cognitive aging.

5.1 Summary of study findings

In Study 1, I examined the extent to which reduced deletion-type inhibition (suppression of no-longer-relevant information) with age accounted for age differences in working memory functioning, as measured by the reading span task (Daneman & Carpenter, 1980). Unlike much of the prior research, I examined inhibitory changes with respect to working memory components (processing and storage). In line with inhibition deficit accounts of aging (e.g., Dempster, 1992, Lustig et al., 2007), I observed that reduction in deletion-type inhibitory functioning with age accounted for a sizable proportion of age differences in working memory components, with significant findings in storage and marginal findings in processing components.

Given mixed findings regarding inhibitory changes with age, I further examined whether changes in the time at which older adults are able to engage deletion-type inhibition compared to younger adults might represent a potential moderator of age effects, beyond age-related general slowing (Study 2 and Study 3). In Study 2, I did not observe differences in the time course of deletion-type inhibition with age when I examined erroneous responses to the prior, no-longer-relevant, item (*n* - 1 repeat). However, the low error rates obtained may have reduced the sensitivity of this measure to detect time course changes. Thus, in Study 3 I broadened my view to examine response latencies in the sequential task. In particular, response latencies on *n* - 1 repeats were examined across a variable number of distracters (1 – 3), corresponding to variable time delays (1000 – 3000 ms), to assess changes in low-level (unintentional) deletion-type inhibition with age. Compared to younger adults, older adults had difficulty engaging deletion-type inhibition, beyond the effects of age-related general slowing. Notably, this result was observed by utilizing a fine-grained approach in which response distributions were examined. The general implications of these findings are discussed below.

5.2 Inhibition and age-related decline in higher order cognition

Areas of cognitive functioning that account for variation in working memory performance and robust evidence of age-related declines in such functions continue to be a rigorous endeavor in cognitive psychology. While most theories focus on the capacity/size of working memory with age, inhibitory accounts emphasize efficiency of working memory functioning by restricting contents to task-relevant information (e.g., Hasher et al., 2007). The extent to which inhibitory functions relate to cognitive performance, such as working memory functioning, has been proposed to vary with age, under cognitive load (e.g., in younger adults during divided attention), and within individuals (e.g., changes in circadian patterns across the day) (Hasher et al., 1999, 2007). The pattern of results across Study 1 and Study 3 also suggests that the inhibition-working memory relationship with age may be moderated by the level of inhibitory control involved.

In particular, in the present work deletion-type inhibitory efficiency in the S-ACT task showed significant relations with age differences in working memory performance, but only when assessed by error responses (Study 1); in contrast, response latency did not account for individual differences with age (Study 3). It was hypothesized that both measures assessed deletion-type inhibitory efficiency, as defined by the ability to suppress no-longer-relevant information (Hasher et al., 2007). In study 3, inhibitory control appeared to be a low-level, unintentional process, as indicated by slowed response latency to previously relevant target information. However, erroneous responses to previously relevant information in Study 1 may have represented a combination of inhibitory processes: (1) similar low-level inhibitory processes to suppress prior relevant information in working memory; as well as, (2) high-level inhibitory processes to suppress responding to information that persists in working memory and triggered by external cues (e.g., stimulus presentation). Such high-level inhibitory functions are compatible with behavioural inhibition as conceptualized by Harnishfeger (1995) and Nigg (2000) to suppress cued but inappropriate motor responses. Further, such behavioural inhibition may be responsible for suppressing responses triggered by bottom-up factors, such as familiarity of stimuli and physical and semantic relatedness of stimuli to present goals during sequential tasks (Humphreys, Forde, & Riddoch, 2001). These abilities are notably compromised in individuals with psychopathological disorders (Nigg, 2000), those with sequential performance problems, such as, action disorganization syndrome (Humphreys & Forde, 1998), and younger adults when executive resources are taxed (e.g., under divided attention; Giovannetti, Schwartz, & Buxbaum, 2007; Humphreys et al., 2000).

In contrast to such high-level inhibitory functions, low-level (automatic) inhibitory functions, as measured in Study 3, did not relate to working memory performance in older adults. Further, in additional analyses on Study 3, age differences in deletion-type inhibition (see Study 3 Results for this index in the 3-distractor window) did not account for age differences in any component of the reading span task (recall, processing time, accuracy, *ps* > .05). This is in contrast to results observed with erroneous responses to prior relevant targets in Study 1 (negative lag errors). This pattern suggests differing levels of engagement in high- and low-level inhibition functions in explaining age differences in working memory performance.

It should be pointed out that for younger adults only, the low-level deletion-type inhibition assessed in Study 3 did relate with intrusion errors in the reading span task, an inhibitory measure that has been shown to relate to working memory performance in various groups (e.g., individuals with reading disabilities; Chiappe et al., 2000; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998). This relationship was not observed for erroneous responses (negative lag errors) for older or young adults in Study 1 or Study 2 (*ps* > .05), despite conceptual similarities in the presumed engagement of inhibitory control to resist proactive interference. However, the relation with age and inhibitory processes in complex span intrusion errors remain unclear, given: (1) inconsistent findings regarding age effects (e.g., Borella et al., 2008; McCabe & Hartman, 2003; Schelstraete & Hupet, 2002); (2) potential moderating effects of increased cautiousness (conservatism; Botwinick, 1966) with age, which may influence response threshold during uncertain recall; and (3) the potential involvement of personality factors in these measures for older or younger adults (Friedman & Miyake, 2004). Moreover, research thus far is quite limited regarding the construct validity of various inhibitory functions that have been proposed (e.g., Hasher et al., 1999; Nigg, 2000) and measures that examine these functions (Friedman & Miyake, 2004; Shilling, Chetwynd, & Rabbitt, 2002). Notwithstanding, a possible explanation for the differing pattern of results obtained in the current work might be the level of specificity of the deletion-type inhibition examined. In particular, in Study 1 and Study 2, the measure of deletion-type inhibition represented a global ability to suppress prior information as erroneous responses obtained were combined across all prior targets (average negative lags), given low error rates obtained at specific lags (e.g., *n* - 1, - 2; see Figure 2.2). Whereas, in Study 3, the deletion-type inhibition measure used was based on RT performance costs to the recent target (*n* -1) at a specific time window (third distractor). This higher level of specificity achieved in Study 3 may have allowed for the inhibition measure to be more sensitive (lower variability by excluding performance across multiple prior targets), thereby allowing it to capture overlapping variance in another inhibition measure (intrusion errors in the reading span task). However, given limited extant work on common and divergent variance amongst inhibition measures, moderating effects regarding the level of specificity of measurement (e.g., specific item and time point of measurement) would have to be systematically examined in future work.

Taken together, the pattern of results across Study 1 and Study 3 suggest that age-related changes in working memory performance may be more likely to be influenced by high- as opposed to low- level inhibitory functions assessed in the S-ACT paradigm. However, at present, direct evidence to support this hypothesis is limited. An approach to investigating this notion might be to systematically examine inhibitory functions at multiple levels of control (e.g., intentional and unintentional inhibition) and assessing for differential relations in working memory functioning with age. For instance, this systematic approach might be executed within the same task, thereby controlling for stimulus and task characteristics, or by taking a latent variable approach, which has proven successful in examining relations among executive functions (e.g., Miyake et al., 2000; Salthouse et al., 2003). Although both approaches have been used to examine relations among inhibitory functions (e.g., Friedman & Miyake, 2004; Shilling et al., 2002; Verbruggen, Liefooghe, & Vandierendonck, 2004), work is still needed to examine differential relations with working memory functioning across the lifespan.

Moreover, inhibitory constraints on higher order cognition (e.g., working memory functioning) are also likely to be impacted by other cognitive and task-specific processes. For instance, Lustig et al. (2001) observed that reducing proactive interference in the reading span task by presenting set sizes from highest to lowest (descending format) reduced age differences; in contrast, the ascending format revealed robust age differences (see also Carretti, Mammarella, & Borella, 2011; May et al., 1999; Rowe, Hasher, & Turcotte, 2008, 2009, 2010). In addition, for older adults, only the ascending format, a procedure that is susceptible to proactive interference, and not the descending format, accounted for variation in prose recall performance (Lustig et al., 2001). As noted by the authors, combating proactive interference in complex span performance in the ascending condition, purportedly by applying inhibitory control, accounted for the predictive utility of complex span performance in prose recall in older adults. However, contrary findings were observed by Emery, Hale, and Myerson (2008) who manipulated the level of proactive interference in the operation span task by using items to be recalled from overlapping categories and intermittent activity-filled breaks. Emery et al. observed that the low proactive interference condition predicted higher order performance in older adults, namely reasoning ability. Discrepant findings across these studies might be related to the similarity of cognitive processes involved in complex span performance and the criterion being measured (e.g., set switching) or commonality in domains assessed (e.g., verbal proactive interference measure predicting verbal recall; Emery et al., 2008).

Similar to the inhibitory account of the working memory-higher order cognition link is the goal maintenance approach proposed by Engle and colleagues with respect to young adults (Engle, 2002; Kane, Conway, Hambrick, & Engle, 2007), and by Braver and West (2008) and others (e.g., McCabe, Robertson, & Smith, 2005) with respect to older adults. According to this view, the use of controlled attention to maintain task relevant goals in the face of interference accounts for inhibitory functioning, working memory performance, and the predictive power of working memory performance in higher order cognition (Redick, Heitz, & Engle, 2007). As outlined in the goal maintenance account of Braver and West, reduced attentional control to represent, maintain, and update goal-relevant information declines with aging, and is likely a result of age-related deterioration in prefrontal functioning (see also West, 1996).

Despite the common inhibition link in the goal maintenance (to combat interference) and inhibitory accounts of aging, recent arguments have been made for their differences. For instance, neuroimaging evidence (e.g., Grady, Springer, Hongwanishkul, McIntosh, & Winocur, 2006; Lustig et al., 2003; Persson, Lustig, Nelson, & Reuter-Lorenz, 2007) reveal intact activation in task-relevant areas in older adults but failure to reduce activity in task-irrelevant areas (see discussion in Lustig et al., 2007). In regard to task-irrelevant activity, older adults often show difficulty reducing activity in the 'default mode network" (Raichle et al., 2001) comprised of a number of brain regions (e.g., medial prefrontal cortex, posterior cingulated cortex, precuneus, anterior cingulate cortex, and parietal cortex). This network has been implicated in task-irrelevant processing due to the observation of increased activity during resting periods (task-free moments) and reduced/suppressed activity during task performance, particularly with increasing cognitive demands (Broyd et al., 2009; Hafkemeijer, van der Grond, & Rombouts, 2012). Further, neuroimaging and neurophysiological work by Gazzaley and colleagues (Gazzaley et al., 2008; Gazzaley, Cooney, Rissman, & D'Esposito, 2005) has shown that failure by older adults to 'ignore' stimulus information (suppress/down-regulate neural activity), as opposed to 'remember' (activate/enhance neural activity), was related to memory recall and working memory performance. Such evidence is strongly supportive of the relationship between inhibitory deficits and consequent effects on higher order functioning, and dovetails with other evidence at the behavioural level (e.g., Study 1).

5.3 Inhibition and aging

Despite evidence consistent with inhibition deficit accounts (Dempster, 1992; Hasher et al., 1999, 2007), mixed evidence (e.g., Kramer et al., 1994) continues to indicate the need to clarify the nature of inhibitory deficits with aging. Such mixed evidence is suggestive that inhibitory accounts may have been over-extended across multiple inhibitory functions and across multiple levels of processing. Suggestions of intact low-level inhibition with aging, as opposed to reduced high-level inhibition, (Andrés et al., 2008; Collette et al., 2009; Kramer et al., 1994) continue to be challenged by the evidence provided in this thesis (Study 3) as well as other work (e.g., Schlaghecken, Birak, & Maylor, 2012a). Moreover, the present work (Study 3) highlights an important factor to consider when investigating age-related changes in inhibitory control, namely the time point at which low-level (unintentional) inhibitory functions are engaged in young and older adults.

Other convergent evidence of age-related difficulty engaging inhibitory processes come from work on inhibition of return (Castel et al., 2003), the masked prime paradigm (Schlaghecken et al., 2011), and a selective attention measure recently employed by Yang and Hasher (2007). They observed that unlike younger adults, older adults had difficulty ignoring distracting pictures that overlapped target words (relevant for a semantic judgment task) at an early time point (50 ms). When given additional time (1000 ms), older adults' ability to suppress distracting information improved to the level of younger adults, suggesting reduced ability to implement inhibitory processes at an early stage. This interpretation is in line with suggestions by the authors that older adults have difficulty suppressing distracting information early, i.e., “older adults allow more irrelevant information to enter working memory at this presumably automatic activation phase” (Yang & Hasher, 2007, p. P232).

It should be emphasized that in regard to the present work (Study 3), the reduced ability of older adults to efficiently engage deletion-type inhibition was observed using a fine-grained approach that partitions response latencies to examine the entire distribution of responses. For younger adults, this approach revealed evidence of robust deletion-type inhibition, evidence not observed by only examining central tendency indices per condition. This response partitioning approach has been used effectively in a number of paradigms, including lexical decision making (Yap, Balota, Tse, & Besner, 2008), Stroop and Simon tasks (Pratte, Rouder, Morey, & Feng, 2010), and also task switching paradigms, as a means of examining switch costs and *n* - 2 repetition costs (Grange & Houghton, 2011; see Houghton & Grange, 2011, for a review). Further, this approach is especially appropriate when a single time window is examined, which makes it particularly useful in age-inhibition research as there is a general tendency to utilize a fixed inter-stimulus interval throughout tasks (see review in Maylor et al., 2005).

Together, the present work and work in other paradigms (e.g., masked prime paradigm, selective attention tasks) argue for more specificity regarding the nature of inhibitory deficiencies with age. Changes in the ability to efficiently engage low-level (automatically triggered) inhibition with age might provide such specificity. Such changes might be a consequence of the increasing need for much slower, resource intensive top-down control in low-level performance with age. Such interdependence across levels of performance has been observed in older adults between low-level inhibition within the masked prime paradigm and consciously controlled high-level inhibitory processes in the Simon task (Maylor et al., 2011). This overlap in high- and low- level processes is suggestive of increased frontal mediation of low-level performance with age (also see Li & Lindenberger, 2002, for a review of increased overlap in sensory, sensorimotor, and high-level abilities with age).

Altered neural recruitment to facilitate cognitive functioning is likely not restricted to optimizing weakened low-level processes, but may be representative of a general strategy shift with aging. This notion is reflected in the load shift hypothesis (Velanova, Lustig, Jacoby, & Buckner, 2007) and the proposition that older adults are more reliant on reactive control processes due to failed preparatory control with age (Braver, Gray, & Burgess, 2007). For instance, in the memory domain, Velanova et al. (2007) observed late and extended frontal activity in older adults under high cognitive demands during a memory retrieval task, suggesting inefficient use of early strategies to constrain retrieved items at early selection stages. Further, Persson et al. (2007) showed that older adults were slower to reduce default mode activity, associated with resting states or task-irrelevant processing, as task demands increased. These findings along with the present observations (Study 3) indicate reduced ability in older adults to efficiently engage cognitive processes within a time frame consistent with younger adults, which in turn, has downstream consequences for cognitive functioning with age (Gazzaley et al., 2008; Jost et al., 2011).

5.4 Limitations and future directions

Much of the research concerning sequential performance and cognitive aging have utilized real world tasks. For instance, in the neuropsychological literature, the Naturalistic Action Test (Schwartz, Buxbaum, Ferraro, Veramonti, & Segal, 2003) or modifications thereof (see review in Schwartz, 2006) are often used, as they allow for performance of real world tasks (e.g., making toast with butter and jelly). These approaches are advantageous for knowledge translation purposes as difficulty observed on these measures have clinical implications (e.g., diagnosis of an emerging dementing illness, intervention training with real world measures).

In contrast to such naturalistic paradigms, the sequential action paradigm used throughout this thesis is limited in its real world applications as it is a computer based task that utilizes arbitrary stimuli (animal pictures), which do not have a naturally embedded sequence (but see Levy-Bencheton, 2006, for the use of naturalistic picture stimuli in the S-ACT task). Further, the utility of our findings regarding age-related changes in inhibitory functioning is limited as this sequential paradigm has not been validated with more naturalistic paradigms (e.g., the Naturalistic Action Test), particularly with regard to inhibitory indices across tasks.

Despite the aforementioned shortcomings, the presently used sequential action paradigm comprised a number of embedded ecologically based principles (e.g., multiple sub-goals, visually and functionally similar distractors and targets, and time limitation). In addition, the ecological validity of laboratory based cognitive paradigms, not unlike the one used here, have revealed modest relations between executive functions (e.g., inhibition, task switching, working memory updating) and older adults' performance of ADLs (e.g., Vaughan & Giovanello, 2010).

Moreover, the advantage of this laboratory based approach is that it allows for a fine-grained examination of dependent measures, particularly, response latency at an individual stimulus level. This approach has proven useful for examining the time course of inhibitory efficiency as shown in Study 3. Further, examination of response latency in previous work revealed that young and older adults utilized similar chunking strategies across the sequence, albeit chunk retrieval was slower in older adults (Li et al., 2010). Such a decline in the efficiency of chunk retrieval with age has implications for how hierarchical schemata are conceptualized in computational models of sequential processing (e.g., Cooper et al., 2005). It should be noted that such fine-grained analytic approaches are limited when using more naturalistic tasks, which explains the reliance of such work on error data (Schwartz, 2006) or overly general response latency measures (e.g., task completion times).

Given the above noted advantages and disadvantages of divergent approaches to examining age-sensitive processes in sequential performance, much work remains to be done. In particular, future work with the presently used sequential action paradigm is necessary to further examine how inhibitory processes in this paradigm relate to other real world and cognitive-experimental measures of inhibition (e.g., n - 2 repetition costs in task switching paradigms, proactive interference in Brown-Peterson tasks). Such an approach is crucial to better specifying the nature of inhibitory functions tapped by the sequential action paradigm and how such changes underlie the ubiquitous decline in higher order cognition with age. Importantly, given the observed delay in the time course of inhibitory functioning in older adults, further work is needed in sequential tasks to specify the neural signature of this delay and its downstream consequences on higher order cognition (see Gazzaley et al., 2008, for recent evidence using a face-scene recognition paradigm). For such an endeavor, it might be helpful to combine a sequential action paradigm with an event-related potential approach, an apt method for charting time course effects, and a functional imaging approach to examine increased top-down involvement in older adults' performance (see Velanova et al., 2007, for such an approach using a word recognition task).

Further, given the present findings and those of others (e.g., Humphreys, Forde, & Francis, 2000; Schwartz, 2006) regarding the role of inhibitory functions in sequential performance, training inhibitory functions using a sequential paradigm such as the one used here might be helpful for older adults. As noted previously (see General Introduction), independence in ADLs represents a primary risk factor in determining institutional care. Thus, in view of the quickly growing population of older adults (Statistics Canada, 2007), training efforts to maintain or relearn ADLs is a necessary endeavor. For instance, using everyday sequential tasks, Giovannetti, Bettcher, et al. (2007) showed that grouping and sequentially displaying items in their order of use led to improved performance in older adults diagnosed with Alzheimer's disease. To complement such efforts in pathological as well as normative aging populations, paradigms such as the one used in this thesis could be utilized in a focused training approach. In particular, the present sequential paradigm could be employed to target underlying processes, such as inhibitory functioning, and examine the generalization of such training to naturalistic situations. To improve the ecological validity of this work, however, the present paradigm could be modified to include reward contingencies for accurate performance. Such an addition seems beneficial as everyday tasks often result in rewards upon completion (e.g., a tasty meal for dinner after accurately following a recipe).

5.5 Conclusion

The studies outlined in the present work both support inhibition deficit theories of aging in explaining higher order functioning (working memory) and highlight an avenue for further refinement in these theories. Further, while age-related changes in inhibitory functions constrain higher order functioning, additional specification of inhibitory changes might be related to when inhibitory functions are engaged. That older adults show substantially reduced ability to engage inhibitory functioning complements other time course work, and possibly reflects reduced engagement of cognitive control at early processing stages. However, more work is necessary to test this notion across multiple paradigms that have evidenced mixed findings in inhibitory control with age.

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APPENDIX A

Study 3 additional figures

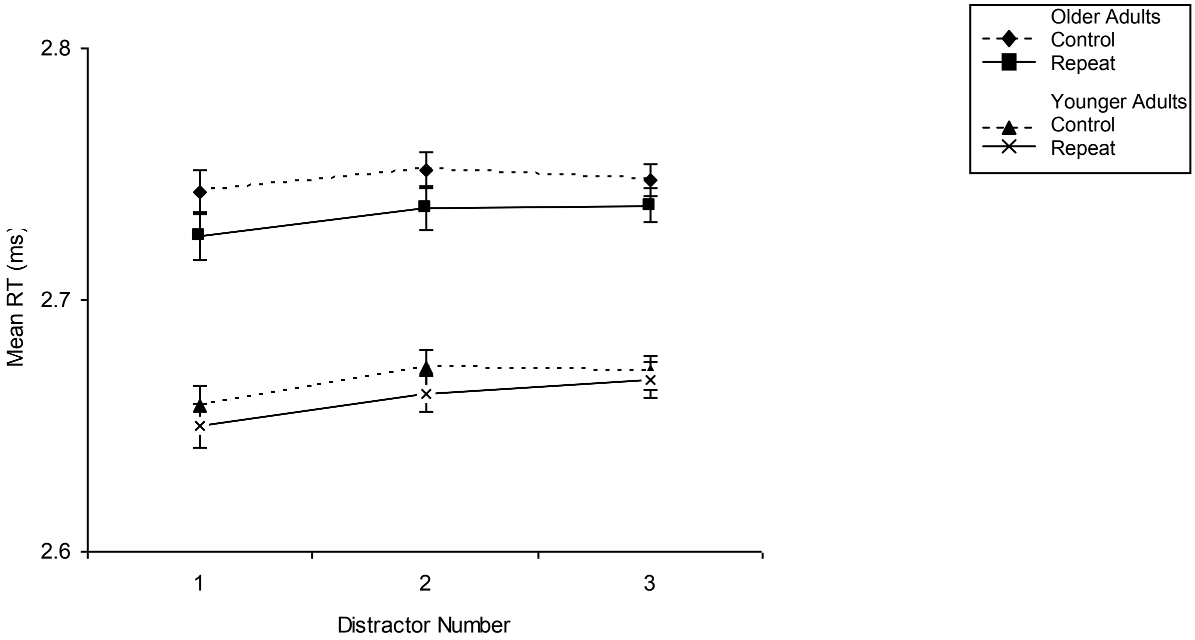

Figure 4.7. Log transformed mean RT performance in *n* - 1 repeat and control conditions as a function of age and distractor number. Error bars represent ± one standard error of the mean. ms = milliseconds.

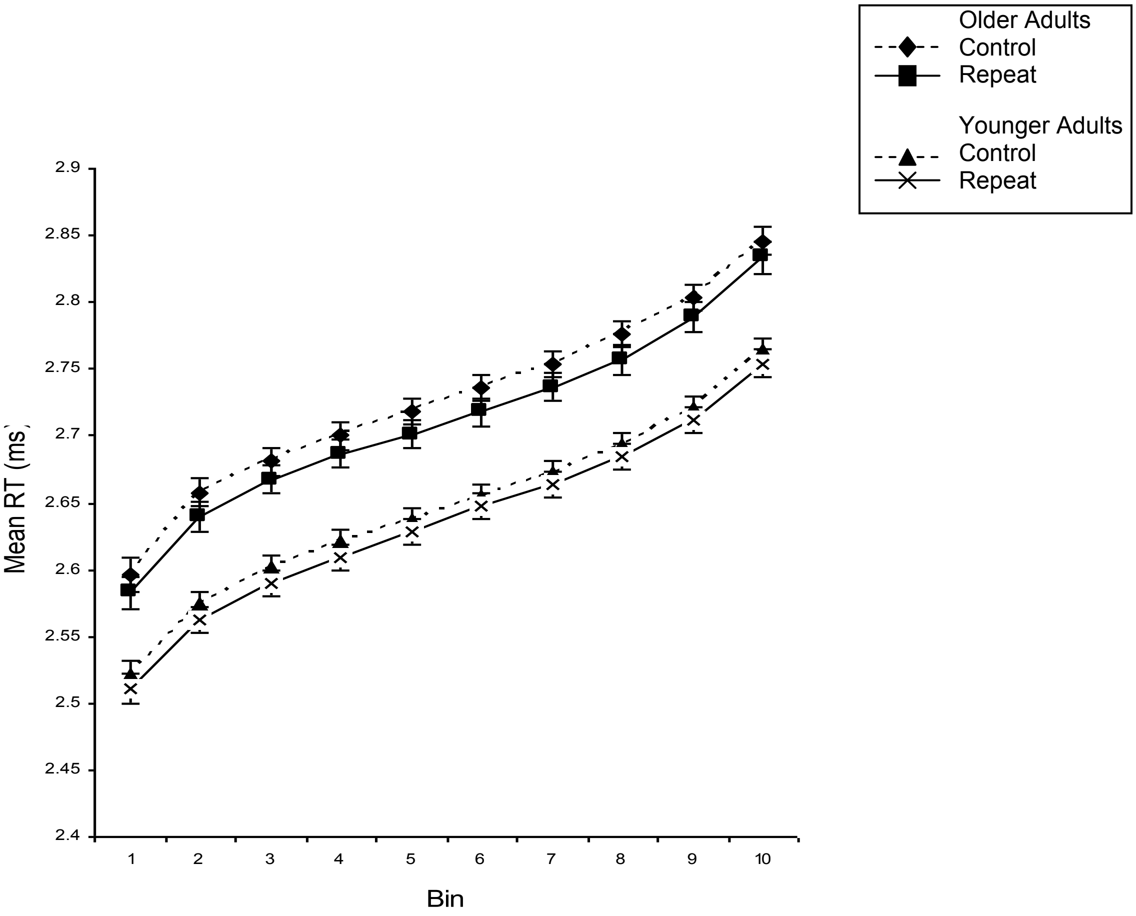

Figure 4.8. Log transformed cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 1-distractor condition. Error bars represent ± one standard error of the mean. ms = milliseconds.

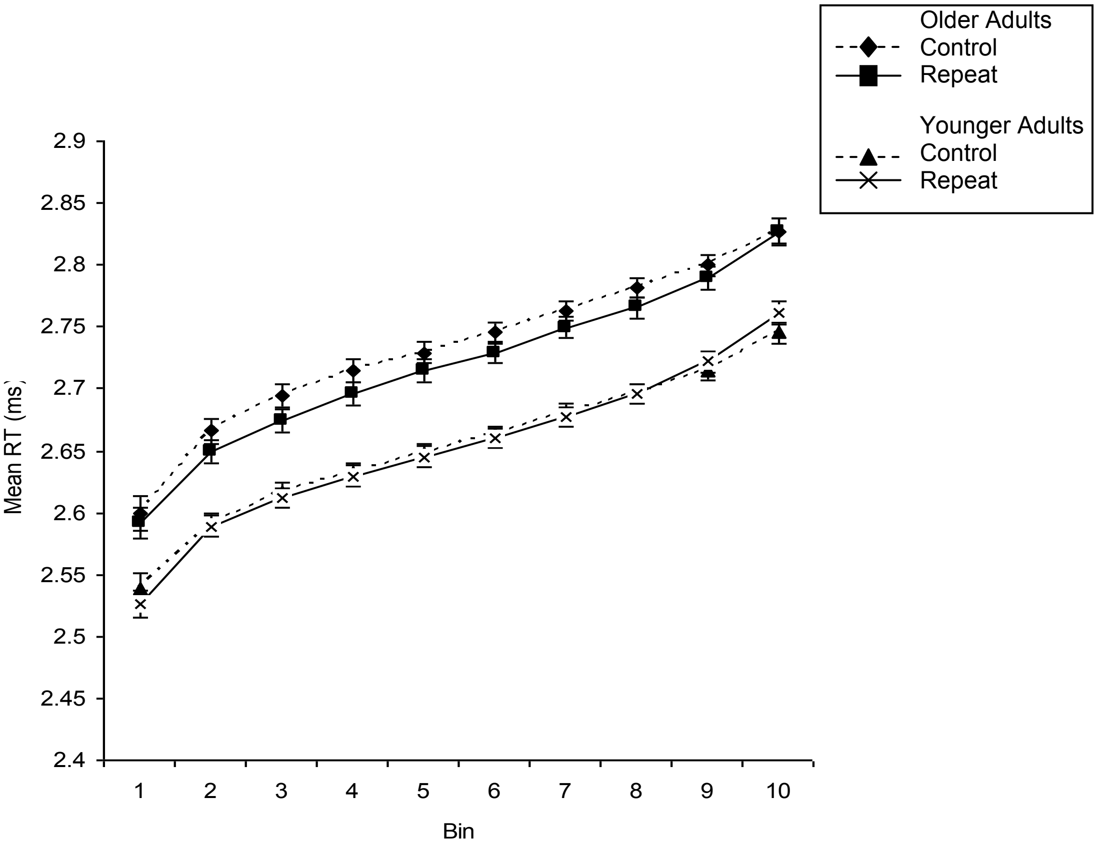

Figure 4.9. Log transformed cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 2-distractor condition. Error bars represent ± one standard error of the mean. ms = milliseconds.

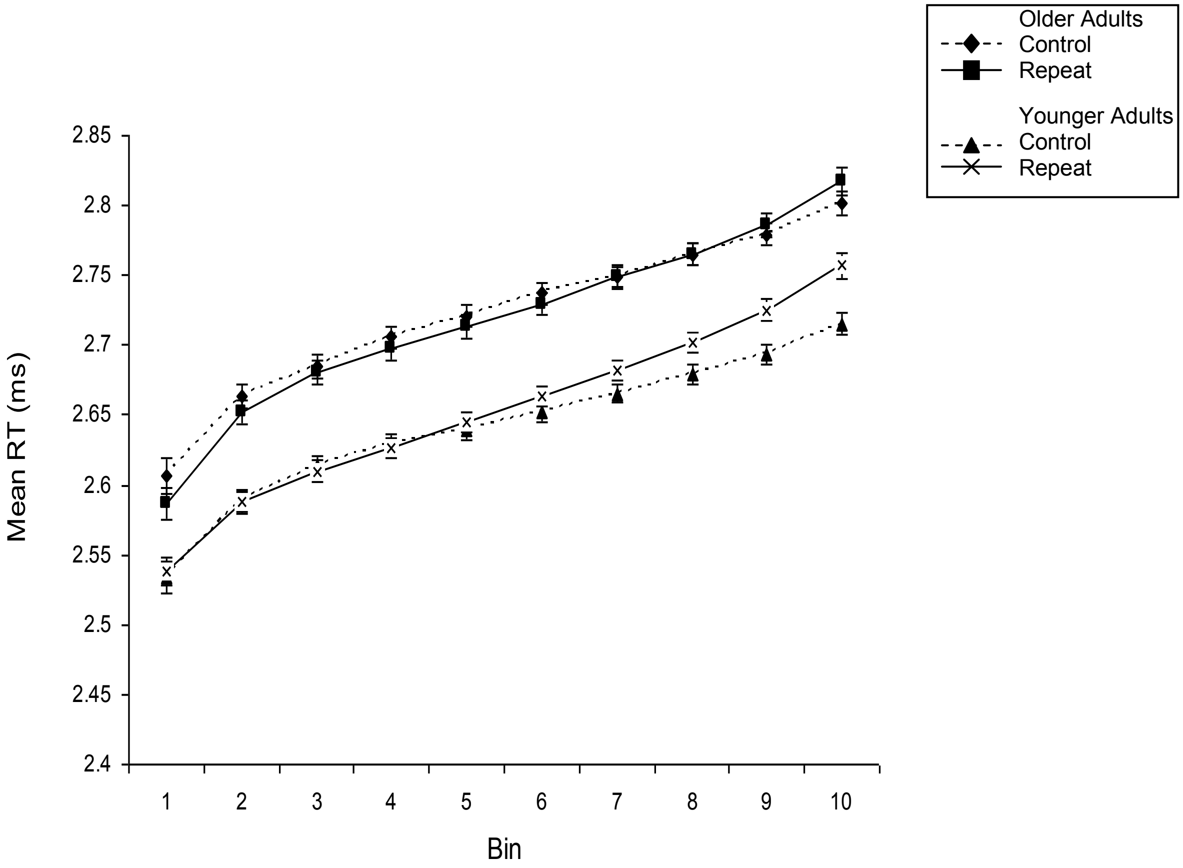

Figure 4.10. Log transformed cumulative distribution frequency plots for *n* - 1 repeat and control conditions as a function of age and time bin for the 3-distractor condition. Error bars represent ± one standard error of the mean. ms = milliseconds.

Appendix C

CONSENT TO PARTICIPATE IN SEQUENTIAL ACTION REGULATION AND WORKING MEMORY

This is to state that I agree to participate in a research study being conducted by Joni Shuchat and Mervin Blair (514-848-2424, ext. 2247 or karenlilab@gmail.com) under the supervision of Dr. Karen Li (514-848-2424, ext. 7542 or karen.li@concordia.ca) in the Psychology Department of Concordia University.

A. PURPOSE

I have been informed that the purpose of the research is to understand the effects of aging on the ability to regulate a sequence of actions, and on working memory.

B. PROCEDURES

The research will be conducted on the Loyola campus at Concordia University in the laboratory PY-017. Each participant will be asked to complete a series of background questionnaires, standard paper-and-pencil tests, and one computerized test of attention and memory. The computerized test will involve responding to visual images in a particular order using the mouse. The session will last 90 to 120 minutes. Each participant will receive 10 dollars an hour or 2 participant pool credits as compensation.

C. RISKS AND BENEFITS

The risks for this study are very low. The benefits of this study are to gain knowledge about the effects of aging on the ability to regulate a sequence of actions.

D. CONDITIONS OF PARTICIPATION

- I understand that I am free to withdraw my consent and discontinue my participation at anytime without negative consequences.
- I understand that my participation in this study is CONFIDENTIAL.
- I understand that the group results from this study may be published.

I HAVE CAREFULLY READ THE ABOVE AND UNDERSTAND THIS AGREEMENT. I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

NAME (please print):

____

SIGNATURE:

____

Please call me again for participation in other research YES ☐ NO ☐

If at any time you have questions about your rights as a research participant, please contact Adela Reid, Compliance Officer, Concordia University, at (514) 848-2424 ext. 7481 or by e-mail at areid@alcor.concordia.ca.

Appendix D

CONSENT TO PARTICIPATE IN SEQUENTIAL ACTION REGULATION AND WORKING MEMORY

This is to state that I agree to participate in a research study being conducted by Mervin Blair (514-848-2424, ext. 2247 or karenlilab@gmail.com under the supervision of Dr. Karen Li (514-848-2424, ext. 7542 or karen.li@concordia.ca) in the Psychology Department of Concordia University.

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I HAVE CAREFULLY READ THE ABOVE AND UNDERSTAND THIS AGREEMENT. I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

NAME (please print):
____

SIGNATURE:

____

Please call me again for participation in other research YES ☐ NO ☐

If at any time you have questions about your rights as a research participant, please contact Adela Reid, Compliance Officer, Concordia University, at (514) 848-2424 ext. 7481 or by e-mail at areid@alcor.concordia.ca.

CONTRIBUTIONS OF AUTHORS

This dissertation consists of 3 studies:

Study 1:

Blair, M., Vadaga, K.K., Shuchat, J., & Li, K.Z.H. (2011). The role of age and inhibitory efficiency in working memory processing and storage components. *Quarterly Journal of Experimental Psychology, 64* (6), 1157–1172.doi: 10.1080/17470218.2010.540670

Study 2:

Blair, M., & Li, K.Z.H. (2011). *Examination of the time course of deletion-type inhibition in young and older adults.* Unpublished manuscript.

Study 3:

Blair, M., Vadaga, K.K., Dalili, M., & Li, K.Z.H. (2012). *Time course of deletion-type inhibition in young and older adults using a sequential updating task.* In preparation.

Relative Contributions

Under the guidance of Dr. Li, I developed the goals and experimental designs for all studies reported. Additional feedback on the design of Study 3 was received from Dr. Virginia Penhune and Kiran Vadaga. The sequential tasks used in these studies were programmed by Alejandro Endo (Study 1), Ricco Boma (Study 2), and Luis DaCosta (Study 3). Random sequences for sequential tasks were created with Matlab programming by Alejandro Endo (Study 1 and 3) and Ricco Boma (Study 2). The working memory task in Study 1 and 3 was programmed with SuperLab by Joni

Shuchat and Kiran Vadaga. I recruited and tested the majority of participants for these studies. For Study 1, I also received recruitment, testing, and data entry assistance from Joni Shuchat and Kiran Vadaga. Michael Dalili provided data entry assistance for Study 3. I performed data cleaning, statistical analyses, interpretation, and preparation of all manuscripts. Data interpretation, conceptual contributions, and revision of all manuscripts were also provided by Dr. Li. Similar contributions were received from Joni Shuchat for Study 1, Kiran Vadaga for Study 1 and 3, and Michael Dalili for Study 3.