Task-set Inhibition And Aging: New Insights From The Dual Mechanisms Control Theory

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ABSTRACT

Task-Set Inhibition And Aging: New Insights From The Dual Mechanisms Of Control Theory

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With the increasing proportion of older adults in the population, the maintenance of autonomy in everyday functioning is of growing importance. To this end, cognitive aging researchers have identified executive functions, including attentional switching, inhibition, and updating, to be key factors in everyday functioning. A current model of cognitive control, Dual Mechanisms of Control theory (DMC; Braver, Gray, & Burgess, 2007) postulates two basic mechanisms. Proactive control involves goal maintenance and conflict resolution based upon preceding cue information, whereas reactive control resolves conflicts based upon immediate stimulus characteristics. The prior research indicates age-related variance in executive functions is related to age-related declines in proactive control. The overall aim of this dissertation is to examine DMC processes in one particular executive function, task switching, which is essential for efficient multi-tasking and entails task-set inhibition (TSI) to smoothly transition from one task to the next (Mayr & Keele, 2000; Mayr, 2001). Previous work suggests that TSI requires proactive control (Mayr, 2007), which declines with aging, yet the empirical support for age differences in TSI is mixed. Therefore, in Study 1, healthy young (n = 28) and older adults (n = 22) were compared on a task switching paradigm, in which TSI was assessed under high (flanker trials) and low (unflanked trials) reactive control task contexts. The results show age-equivalent TSI effects in low reactive control, but young adults showed larger TSI in high reactive control. In Study 2 (Expt. 1: $n_{\text{YA}} = 25$, $n_{\text{OA}} = 25$; Expt. 2: $n_{\text{YA}} = 25$, $n_{\text{OA}} = 25$), age-related TSI effects were examined across four conditions that varied along a proactive-reactive control continuum. A key aspect of this design was that the four task contexts were intermixed, thereby compelling participants to adopt a global control strategy that was either reactive (Expt. 1) or proactive (Expt. 2). In line with Study 1, the overall results of Study 2 indicate that TSI effects are observable in reactive control task contexts. Additionally, young and older adults showed differential modulation of the dual control processes to match the global task context. In Experiment 2 when the task context was more proactive, older adults exhibited more TSI than young adults. Taken together, these results suggest that age-related TSI effects are contingent on the age-related utilization of the dual control processes, which in turn are influenced by the global task context.

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CONTRIBUTIONS OF AUTHORS

Study 1

In collaboration with my supervisor, Dr. Karen Li, I conceptualized the research question, obtained ethics approval, designed the study protocol, trained research staff to test participants, conducted statistical analyses, and wrote the final manuscript. Dr. Li independently secured external funding from the Natural Sciences and Engineering Council of Canada (NSERC) and I was successful in obtaining a Vanier Canada Graduate Scholarship to support this research. Dr. Li provided extensive feedback on drafts of the manuscript and gave valuable conceptual input. The final manuscript represents a substantial combined effort from both authors.

Study 2

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TABLE OF CONTENTS

LIST OF FIGURES

Study 1

Study 2

LIST OF TABLES

Study 1

Study 2

CHAPTER 1

GENERAL INTRODUCTION

Scope of the Problem

The year 2016 is considered to be a landmark year in Canadian demographics, as for the first time ever, older adults have outnumbered children (Statistics Canada, 2016). By the year 2036, older adults are expected to comprise one quarter of the population. The economic, social, and health consequences of the aging population are predominantly determined by factors such as cognitive fitness, and the degree to which older adults are able to exercise autonomy in everyday functioning.

To this end, some of the overarching goals of cognitive aging research include, identification of basic cognitive mechanisms, or ‘cognitive primitives’ that are essential to everyday functioning; examining whether these basic mechanisms are susceptible to age-related declines; establishing the links between the basic mechanisms and the underlying neurobiology and anatomical brain regions; and development of cost effective interventions that can mitigate the effects of cognitive aging (Braver & West, 2008; Verhaeghen, Cerella, Bopp, & Basak, 2005).

In pursuit of these objectives, constructs bearing a strong resemblance to currently popular ideas of ‘executive functioning’ have dominated the cognitive aging landscape. Broadly defined, executive functions (EF) refer to a set of higher order cognitive processes that regulate attention, thought, and action (Wiebe & Karbach, 2018). Over the past three decades, reflecting the complexity in everyday functioning, many different EF have been proposed, including working memory updating and goal monitoring, cognitive flexibility and task switching, and response inhibition (e.g., Miyake et al. 2000). With respect to age-related changes in EF, the cumulative evidence from the behavioral research indicates that compared to young adults, older adults perform poorly on some laboratory tests of EF (e.g., global switch costs, working memory updating, response inhibition, but not others (e.g., local switch costs, task-set inhibition) (Li, Vadaga, Bruce, & Lai, 2018). In parallel, the neuroanatomical studies of brain aging show that EFs are primarily associated with white matter integrity and the functioning of frontal lobe that demonstrate more rapid volumetric decreases compared to other brain regions (West, 1996).

Among the many EFs postulated in the literature, task switching is considered to be the hallmark of cognitive control, as it entails conflicting attentional demands such as goal maintenance and cognitive flexibility (Goschke, 2000). To illustrate, in an everyday example, driving presents a complex environment in which many subtasks, such as speed monitoring, interpretation of abstract road signs, planning the best route etc., must be organized and deployed appropriately to arrive at one's destination safely. The question thus arises, how are humans able to optimize the conflicting attentional demands to ensure successful performance in multi-task environments? In the present series of experiments, I have examined the nature, function, and age effects of the hypothesized mechanism (i.e., Task-set inhibition; Mayr & Keele, 2000; Mayr, 2001) that is implicated in resolving the conflicting attentional demands in a multitask environments. To situate my work in this area, I will first provide a broad summary of EF and the aging research.

The Central Executive: A Historical Viewpoint

Prior to the contemporary conceptualization of EF, early information processing models of attention and memory (e.g., Atkinson & Shiffrin, 1968; Broadbent, 1958) outlined the role of 'immediate memory' (i.e., the amount of information that can be actively maintained at once) (for review, see Blakemanship, 1938) in overall cognition, and postulated that rehearsal mechanisms were the key determinant of successful encoding and retrieval of information. The first impetus for EF research was facilitated by empirical observations that early constructs such as immediate memory lacked theoretical precision to explain individual and age-related differences in complex cognition.

In the influential book, *Plans and the Structure of Behaviour* (Miller, Galanter, & Pribram, 1960), Miller et al. espoused a theory that could describe how knowledge translated into action, arguing that human beings are capable of forming and executing plans that could be retrieved, and activated into working memory (WM). Following Miller and colleagues' suggestions, Baddeley and Hitch (1974), in their seminal paper, proposed a multicomponent model of WM that entailed both storage and manipulation of information in the service of complex cognition. According to their model, the domain independent *central executive* is assumed to be the hub of WM, controlling the flow of information from and to its domain-specific storage buffers, namely the phonological loop and visuospatial sketchpad. Baddeley (1986) also proposed that Norman and Shallice's (1986; Shallice, 1988) *Supervisory Attentional*

System (SAS), originally constructed as a model of attentional control in healthy individuals, as well as neuropsychological patients with frontal lobe damage, may be a candidate model of the central executive. A recent formulation of the model (Baddeley, 2000) also includes a temporary multimodal storage component called the *episodic buffer*, which is capable of binding information from the subsidiary systems, and from long-term memory, into a unitary episodic representation.

The impact of Baddeley and Hitch's (1974) WM model was that the construct of 'central executive' gained theoretical traction, and provided researchers with a conceptual framework to develop WM measures, and begin investigating age-related changes in the central executive. The most widely used task to document age-related differences in WM is the 'complex span task' (e.g., reading span task; Daneman and Carpenter, 1980; counting span task; Case, Kurland, & Goldberg, 1982; operation span task; Turner & Engle, 1989), in which participants perform a processing task while remembering target items (e.g., the final words in a series of sentences) for later recall. The cumulative evidence indicates that compared to young adults, older adults perform poorly on complex span tasks (e.g., Chiappe, Hasher, & Siegel, 2000; Li, 1999; Lustig, May, & Hasher, 2001; Myerson, Hale, Rhee, & Jenkins, 1999). Importantly, complex span performance predicts age differences in higher order tasks such as language comprehension and episodic memory (e.g., Hess & Tate, 1992; Kwong See & Ryan, 1995).

Following these valuable empirical findings, cognitive aging researchers offered two divergent hypotheses to explain the observed age differences. One assumption was closely tied to the immediate memory construct and relates to older adults' reduced storage capacity for verbal material, both in the phonological loop and in the episodic buffer (Baddeley, 2000). This storage deficit hypothesis parsimoniously predicts the age differences in span measures, but fails to account for the age differences in complex cognition. A second assumption relates to the possible age-related declines in the 'central executive', which carries out a number of functions (Baddeley, 1996), including coordinating the simultaneous performance of multiple tasks (Baddeley & Hitch, 1974, 1994). The executive decline hypothesis parsimoniously predicts the age differences in complex cognition, but raises an important question: is the central executive a unitary construct?

It is worth noting that a few years prior to the development of the Baddeley and Hitch's (1974) WM model, Teuber (1972) in his review entitled *Unity and diversity of frontal lobe* *functions* and revisited by Duncan and his colleagues (Duncan, Johnson, Swales, & Freer, 1997) also raised a similar question—to what extent can different functions often attributed to the frontal lobes or to the central executive (or SAS) be considered unitary in the sense that they are reflections of the same underlying mechanism or ability?

However, the main impetus to question the unitary nature of the central executive comes from the neuropsychological tradition. It has been known for a long time that patients with damage to the frontal lobes, including the patient Phineas Gage, demonstrate severe deficits on well-defined cognitive tasks from neuropsychological test batteries (e.g., Wisconsin Card Sorting Test; WCST, Tower of Hanoi; TOH). However, importantly, some patients show poor performance on the WCST, but not on the TOH, whereas others show the opposite pattern, suggesting that the central executive may not be completely unitary (e.g., Godefroy, Cabaret, Petit-Chenal, Pruvo, & Rousseaux, 1999; Shallice, 1988). Another line of evidence against the unitary nature of the central executive comes from the individual differences studies, across different target populations, in which intercorrelations between different executive tasks, purportedly measuring the same construct, are low and not statistically significant (e.g., Burgess, 1997; Levin et al., 1996).

Taken together, Baddeley and Hitch's (1974) multicomponent WM model, Norman and Shallice's (1986; Shallice, 1988) SAS, and research on the frontal lobe functioning from the neuropsychological tradition, provided the necessary groundwork for EF research. The development of complex span tasks allowed researchers to measure declines in complex cognition, thus facilitating the proliferation of EF research into individual and age differences. However, neuropsychological and behavioral evidence from different target populations including older adults, question the unitary nature of the central executive.

The Diversity of Executive Functions and Cognitive Aging: A Contemporary Viewpoint

Among the many EFs proposed to reflect the complexity of everyday functioning, the most widely accepted EFs are, *shifting*, *updating*, and *response inhibition* (Miyake et al., 2000). The shifting function is related to the ability to switch attention between different sub-tasks or different elements of the same task, and it is traditionally measured by task switching methodology (e.g., Mayr, 2001; Meiran, 2010; Monsell, 2003) in which local and global switch costs are used as indices for cognitive declines. The local switch costs refer to the difference in response time (RT) between task switches and task repetitions in a mixed block trial (i.e., BBAB) and reflect executive process associated with the actual switching. The global switch costs refer to difference in RT between task switches in a mixed block trial (i.e., BBAB) and task repetitions in a single block trial (i.e., BBB) and reflect the costs associated with maintaining and scheduling two mental task sets. The cumulative behavioral evidence indicates that local switch costs are immune to aging, whereas older adults show larger global switch costs compared to young adults (Kray & Lindenberger, 2000). For example, using meta-analysis of 26 published studies Wasylyshyn, Verhaeghen, and Sliwinski (2011) showed that local switch costs are age-invariant, whereas global switch costs are age-sensitive which requires the simultaneous activation and maintenance of two mental task sets. These behavioral findings are well-supported by brain imaging studies in which a functional double dissociation in brain regions is observed between the global and local switch costs. For example, the global and local switch costs are associated with the age-sensitive frontal regions (e.g., right anterior prefrontal cortex) and non-frontal regions (e.g., right superior parietal cortex), respectively (Braver, Reynolds, & Donaldson, 2003).

The updating function is traditionally measured by complex span tasks, as described earlier. The span measures share features with dual tasks, requiring information storage in the context of simultaneous processing of other information. For example, in the reading span task (Daneman & Carpenter, 1980), participants read a series of short sentences for comprehension and then recall the sentence-ending words from the series. The sets vary in size (e.g., from two to six sentences) and the largest set-size that a participant can reliably understand and recall (all the items in that set) is commonly used as an index of WM capacity. The cumulative evidence from cross-sectional data and meta-analysis indicates that older adults show updating and WM capacity declines (e.g., Verhaeghen, 2014). These behavioral findings converge with neuroscientific findings in which WM-related brain regions such as dorsolateral prefrontal cortex show both structural and functional changes in older adults (e.g., Reuter-Lorenz & Sylvester, 2005).

The Inhibitory function is traditionally measured by ‘prepotent response’ tasks such as the Stroop task (Stroop, 1935), antisaccade task (Hallet, 1978), Stop signal task (Logan, 1994) and Hayling Sentence Completion task (Burgess & Shallice, 1997). All of these cognitive tasks share the common aim in measuring how well individuals are able to resist automatic and prepotent responses. For example, in the Stroop paradigm participants are required to indicate the ink color of words printed in incongruent ink colors (e.g., blue in green ink) and this performance is compared against the baseline condition (stating the color of neutral stimuli such as asterisks). The cumulative evidence from cross-sectional aging data is mixed. For example, in the antisaccade task (Hallet, 1978), in which participants are instructed to move their eyes in the opposite direction from the presented peripheral cue, older adults show robust age-related difficulties in suppressing their reflexive responses (Butler et al., 1999). However, in other prepotent response tasks such as the Stroop task, Go/No-go task, and Stop signal task, age-related differences are dependent on additional task demands (e.g., Williams et al., 1999).

An important indication that EFs play a major role in everyday functioning comes from experimental and intervention studies. For example, among all the EFs discussed previously, cognitive flexibility/switching have been significantly associated with activities of daily living (ADL; Katz, 1983) (Vaughan & Giovanello, 2010) and EF training has been implicated in improvements in ADLs (Rebok et al., 2014; Willis et al., 2006). Taken together, the fractionalization of EF into separable constructs provided an excellent opportunity for cognitive aging researchers to conduct a systematic investigation of age-related declines in complex cognition and its relation to everyday functioning. The cumulative evidence from cross-sectional data and meta-analyses points to age-related declines in some aspect of EF functions (e.g., global switch costs) but not others (e.g., local switch costs).

Executive Function Theories of Cognitive Aging

What are the basic mechanisms that can parsimoniously explain age-related declines in EFs? There are at least three EF theories of cognitive aging that attempt to answer the above question: Inhibitory Deficit hypothesis (Hasher, Lustig, & Zacks, 2007; Hasher, Zacks, & May, 1999), Executive Attention hypothesis (Engle & Kane, 2004; Kane et al., 2007), and the Dual Mechanisms Control theory (DMC; Braver, Gray, & Burgess, 2007).

Inhibitory Deficit hypothesis. According to the Inhibitory Deficit hypothesis (Hasher et al., 2007), Inhibition is the basic mechanism that predicts older adults' complex cognition. The construct of inhibition is conceptualized in three forms: Access, Deletion, and Restraint. In the early stages of the processing stream, the Access function prevents entry of goal-irrelevant information from entering WM. Once the goal-related information has been successfully processed, the Deletion function suppresses the no-longer-relevant information from WM. Finally, at the response level, the Restraint function prevents the execution of incorrect predominant responses and facilitates goal relevant responses. Within the context of age differences in the three EFs, the Access function is implicated in updating, the Deletion function is implicated in updating and switching, and Restraint function is implicated in response inhibition (Hasher et al., 2007).

For example, in complex span tasks (e.g., reading span task, Daneman & Carpenter, 1980), when the set size increases (e.g., from two to six sentences), there is a buildup of proactive interference (PI) on succeeding trials. Therefore, older adults' poor performance on complex spans tasks can be attributed to the failure of Deletion-type inhibition. Consistent with this interpretation, when the longest sets are given first to young and older adults, age differences in WM capacity are greatly reduced (May, Hasher, & Kane, 1999). Similarly, Deletion- type inhibition is also implicated in task switching paradigms in which the PI from the previous tasks are inhibited (i.e., Task-set inhibition: TSI). TSI is shown when observing increased reaction times (RTs) in the task-repetition trials (as in the third trial of an AB$\underline{A}$ sequence) compared to the task-alternation trials (as in the third trial of a CB$\underline{A}$ sequence) (Mayr, 2001). However, contrary to the inhibitory framework, TSI effects are age-invariant and are not related to task switching efficiency, such as local- and global switch costs (Mayr, 2001). Additionally, the recent evidence suggests that not all inhibitory functions are uniformly age-sensitive (Vadaga et al., 2015).

Executive Attention hypothesis. A similar EF theory to the Inhibitory Deficit Hypothesis is the Executive Attention account (Engle & Kane, 2004; Kane et al., 2007). According to this view, individual differences in Executive Attention account for the variation in tests of WMC and fluid intelligence. Executive Attention refers to one's ability to flexibly allocate attentional resources to goal related information while actively suppressing goal irrelevant information. According to the Executive Attention view, working memory is seen as an integrated memory and attentional system. Drawing from Cowan's (1995) model of working memory, the Executive Attention framework postulates that when goal-related representations from long-term memory are activated above threshold, only limited representations enter into conscious awareness while the remaining goal relevant information lies outside the focus of attention. Then, the role of Executive Attention is to recover and maintain the non-accessible goal relevant information against decay and interference. Thus, Executive Attention is assumed to control two separate mechanisms: activation of goal relevant information and suppression of irrelevant information.

Similar to Inhibitory Deficit hypothesis, the Executive Attention hypothesis conceptualises inhibition as a basic mechanism. By this model, age-related differences in complex cognition occur because of older adults' decline in both activation of goal relevant information and inhibition of irrelevant and no-longer relevant information. However, this is often not the case. For example, a number of findings suggest that older adults show preserved cognitive activation of goal-related information (see Hasher et al., 1999). In addition, contrary to the Executive Attention view, evidence from neuroimaging data suggests that older adults show greater or more distributed activation in response to goal-relevant information in both frontal and posterior regions (for a review, see Reuter-Lorenz & Lustig, 2005).

The Dual Mechanisms Control theory (DMC). The DMC framework (Braver, Gray, & Burgess, 2007) conceptualizes two basic mechanisms, namely 'proactive' and 'reactive' that influence complex cognition. In the proactive mode, goal-relevant information is actively maintained in WM in a sustained or anticipatory manner. Unlike other goal maintenance theories (e.g., Baddeley, 1986; Kane & Engle, 2002), in the DMC framework, proactive control encompasses active maintenance of *context* representations, which is defined as a subset of information within WM that governs how other goal representations are used (Braver, et al., 2007). The context representations are assumed to serve as a cue for attention, guide conflict resolution processes, and structure the encoding, maintenance, and retrieval of information in memory (Braver, Cohen, & Barch, 2002). It is assumed that proactive control, because of its reliance on context representations, biases attention, perception, and action systems in a goal-driven manner. This biasing function pre-empts conflicts by preventing any goal-irrelevant information from exceeding activation thresholds. Thus, proactive control is involved in goal maintenance in the form of sustained attention, and resolves conflicts pre-emptively (early correction) by using predictive information (e.g., valid task cues). Unlike proactive control, Braver's second process, reactive control, is engaged only in conflict resolution. In the reactive mode, when no task-relevant information is available beforehand, attentional control is recruited on a just-in-time basis after a high-interference event is detected. Therefore, the conflict resolution function of reactive control is stimulus driven and is invoked on trial-by-trial basis. Taken together, proactive and reactive control can be viewed as early selection and late correction mechanisms respectively (Braver et al., 2007), operating seamlessly as a 'unified control process' to achieve behavioral stability and flexibility in the face changing task demands.

With respect to age effects across these dual processes, the cumulative evidence from behavioral and neuroimaging studies, comprising tests of context processing, working memory, response inhibition, and task switching, indicate age-equivalence in reactive control and age-related differences favoring young adults in proactive control (Braver, Satpute, Rush, Racine, & Barch, 2005; Braver, Paxton, Locke, & Barch, 2009; Bugg, 2014; Vadaga et al., 2015)

To illustrate, Braver and colleagues (Braver et al., 2001; Braver et al., 2005) modified the classical Continuous Performance Task (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956), such that the cue (A or B) precedes the stimulus (X or Y) and the objective is to respond only to a subset of trials (AX trials). A key aspect of AX-CPT task is that AX trials occur 70% of the time, thus leading to a proactive task bias. On AY trials, biased proactive control is associated with more errors because the presentation of the A biases attention to respond, when one should in fact withhold a response. Consistent with age-related declines in proactive control, older adults make more omissions on AX trials than young adults (Braver et al., 2001). Conversely, the observed age advantage on AY trials suggests that young adults were overexerting proactive control (i.e., proactive bias), whereas older adults were relying on reactive control by not utilizing cue-related processes, possibly to offset age-related proactive declines (Braver et al., 2007).

The AX-CPT task provides preliminary support for the idea that young and older adults show a differential modulation of control processes in relation to task contingencies (i.e., valid versus invalid cues). That is, when the global task context is proactively biased (i.e., 70 % of AX trials), young and older adults may be using proactive and reactive control respectively, to optimize the trial-by-trial, local task demands, Accordingly, older adults show transient activity in the anterior prefrontal cortex (aPFC), which has been interpreted as signaling reactive control, to compensate for proactive declines (i.e., decreased sustained activity in the aPFC) (Jimura & Braver, 2009). Further, older adults' mode of control can become more proactive through strategy training, such as increasing the salience of predictive cues and focussed instruction (Braver et al., 2009; Paxton, Barch, Racine, & Braver, 2008). This demonstration suggests that older adults can flexibly recruit proactive or reactive control processes (Braver et al., 2009).

To further delineate the role of DMC theory in EF, in tests of response-inhibition, in which task instructions emphasize the selection of less frequent responses over pre-potent ones, the goal maintenance demands are high and the conflict resolution function must pre-emptively supress the competing responses. In tests such as the Stroop task (Davidson, Zacks, & Williams, 2003), antisaccade task (Butler et al., 1999), stop-signal task (Kramer et al., 1994), older adults show poorer performance compared to young adults as proactive demands increase. In tests of WM, goal maintenance and conflict resolution demands increase on successive trials. For example, in the reading span task (Daneman & Carpenter, 1980) participants memorise goal-related information for later recall (i.e., span scores) in the face of general interference (i.e., processing task). As participants recall more information from trial to trial, there is a buildup of PI, thus increasing the need for proactive control to maintain the currently relevant information and to resolve conflict that is created by the PI. Taken together, the age-related modulation of the dual processes forms the crux of the DMC theory in elucidating age-related executive declines.

In summary, the Inhibitory Deficit hypothesis conceptualizes different types of inhibition based on the nature of the irrelevant material. The Executive Attention framework (Engle & Kane, 2004; Kane et al., 2007), conceptualizes both goal maintenance and inhibition as crucial for complex cognition. However, the DMC framework postulates that goal maintenance is achieved by sustained proactive control and predicts that different inhibitory phenomena are an after-effect of both proactive and reactive control. All the above mentioned theories satisfactorily explain the age-related declines in updating, and response inhibition, however, only the DMC theory holds promise in explaining *the lack of age-related declines* in one particular executive function paradigm, task-set inhibition.

Task-set Inhibition: Nature, Function, and Age Effects

As mentioned earlier, task switching is considered to be the hallmark of cognitive control, as it entails two opposing attentional demands, namely “stability demands” (i.e., current task-set selection and maintenance), and “flexibility demands” (i.e., transition to new task representations). These opposing demands have been referred to as the *stability-flexibility dilemma* (Goschke, 2000). An important question to consider is how one is able to optimize the opposing attentional demands to ensure the successful performance in multi-task environments. A proposed underlying mechanism is Task-set inhibition (TSI), which refers to increased reaction times (RTs) in the task-repetition trials (as in the third trial of an AB$\underline{\text{A}}$ sequence) compared to the task-alternation trials (as in the third trial of a CB$\underline{\text{A}}$ sequence). This RT cost is also referred to as backward inhibition (Mayr & Keele, 2000; Mayr, 2001).

In the context of the stability-flexibility dilemma (Goschke, 2000), the hypothesised function of TSI is to ‘clear the slate’ by transiently supressing the proactive interference (PI) generated by the previous task sets (Mayr, 2007). This implies that TSI may be a necessary control process in task switching (e.g., Arbuthnott, 2005; Goschke, 2000; Masson et al., 2003; Mayr & Keele, 2000; Philipp, Kalinich, Koch, & Schubotz, 2008; Schuch & Koch, 2003) and a likely candidate for age-related decline, as inhibitory processes targeting PI are widely associated with age-related declines in working memory and episodic memory (e.g., Hasher et al., 2007). However, the evidence to date indicates that the magnitude of TSI is either age-equivalent or, in some cases, greater in older than younger adults (Mayr 2001; Lawo, Philipp, Schuch, & Koch, 2012; Li & Dupuis, 2008; Schuch, 2016). This raises an important question with respect to the functional utility of TSI, in the context of age-related EF declines (Mayr, 2007).

To disambiguate the mixed findings in the aging inhibition literature more broadly, it was recently proposed that the age-related declines in different inhibitory processes, including TSI, can be parsimoniously explained using DMC theory (Vadaga et al., 2015). In continuation of this work, in the current series of experiments, I have argued that in task-switching paradigms the immediate PI generated during task-alternation trials is supressed transiently by age-invariant reactive control.

The Current Research

In Study 1, I examined whether TSI effects are observable in reactive control task contexts. To this end, I developed a non-cueing task switching flanker paradigm and measured TSI in terms of N-2 repetition costs (low reactive control) and Lag -1 facilitation effects (high reactive control). The first goal of this study was to validate the theoretical assumption that both of these indices measure TSI. The second goal was to examine whether age-related differences in the magnitude of TSI vary as a function of increasing reactive control demands.

In Study 2, comprising two experiments, I examined the influence of global task context on age-related TSI. Accordingly, a task switching paradigm was used in which proactive and reactive control demands were varied from trial to trial. These local variations of proactive and reactive task demands were also influenced by the global task context, as driven by the ratio of valid and invalid cue-probe pairs within each block of trials. To this end, the age-related modulation of the DMC processes were examined in the context of joint influences of global (block-wise) context and local trial-wise demands in determining age-related TSI effects.

CHAPTER 2

STUDY 1

Task-set Inhibition and Age effects as a Function of Measurement

Abstract

Objectives. To examine 1) whether measurement of task-set inhibition (TSI; i.e., increased reaction times in task-repetition trials, ABA, compared to task-alternation trials, CBA) by two different indices (i.e., unflanked versus flanked trials) in the extant research capture the same underlying construct? 2) Whether young and older adults show differential TSI based on task context.

Methods. Word recognition task was used to measure TSI, where young (age: 18-35, *n* = 28) and older adults (age: 60-75, *n* = 22) responded to intermixed words from three categories appearing either singly or with flankers. The TSI effect was measured by comparing unflanked CBA versus ABA trials (N-2 repetition cost), and flanked Lag-2 versus Lag-1 trials (Lag-1 facilitation).

Results. 1) Robust negative correlation between N-2 repetition cost and Lag-1 facilitation, across both the age groups, 2) Age-related differences in TSI favouring young adults in the flanked condition.

Discussion. The findings suggest that the TSI effects measured under different task contexts show empirical convergence; however the differential age effects between flanked and unflanked trials indicate that the overall task context may determine the locus of age-related inhibitory effects.

Introduction

Task-set inhibition (TSI) refers to suppression of previously executed tasks, as measured by increased reaction times (RTs) in the task-repetition trials (as in the third trial of an AB<u>A</u> sequence) compared to the task-alternation trials (as in the third trial of a CB<u>A</u> sequence) (Mayr, 2001). This RT cost is also known as N-2 repetition cost. A variation of TSI is the Lag-1 facilitation, which is typically observed in sequential flanker tasks, in which the recently executed tasks when presented as flankers cause less interference in the current trial, compared to the less recently executed tasks (e.g., Lag -2) (Li & Dupuis, 2008; Hübner et al., 2003). Together, the N-2 repetition cost and Lag -1 facilitation are traditionally measured in task cueing paradigms; and these empirical effects are assumed to reflect an executive inhibitory process and therefore a likely candidate for age-related declines (Mayr, 2007). A limited number of studies have examined the age-related differences in TSI, and the findings from these studies indicate that the magnitude of TSI is either age-equivalent or, in some cases, greater in older than younger adults (e.g., Mayr, 200; Li & Dupuis, 2008).

In the current experiment, we examined two unresolved issues from the extant research. First, is there a negative association between N-2 repetition cost and the Lag -1 facilitation? If yes, then it would be the first study to validate the theoretical assumption that both these indices measure TSI. Second, do young and older adults show differential inhibition when measured by N-2 repetition cost and Lag -1 facilitation? If yes, then it would imply that the age-related TSI effects are contingent on task context (Vadaga & Li, under review).

To examine these issues, we used a word recognition task (WRT), where young and older adults responded to intermixed words from three categories (fruits, animals and clothing), appearing either singly or with flankers. The exemplars from the three categories (e.g., apple, lion, and belt) served as unique task sets without the need of a task cue. The TSI effect was measured by comparing unflanked CBA versus ABA trials, and flanked Lag-2 versus Lag-1 trials (Li & Dupuis, 2008; Hübner et al., 2003). We believe that with increased interference (flankers), the overall task demands are increased thereby testing the older adults' inhibitory process. If there are age-related TSI effects based on task context, then we predicted reduced TSI in older adults in the flanked condition.

Method

Participants

Twenty-eight young (64 % females and 34 % males, M_{age} = 24.42 years, *SD* = 4.46) and 22 older adults (68 % females and 32 % males, M_{age} = 67.02 years, *SD* = 4.13), were recruited were recruited from the Psychology Department at Concordia University, and the Montreal community via a student website and senior newspapers, respectively. Both age groups had comparable years of formal education (young: *M* = 15.55, *SD* = 2.66; older: *M* = 16.52, *SD* = 2.87), *t*(48) = -1.25, *p* = .24, *d* = -.36. Based on our intake questionnaires, participants were excluded if they reported any conditions that might impair perceptual abilities, concentration, or fine motor performance. Young adults were compensated with partial course credit, whereas older adults were compensated with a $20 honorarium.

Materials

To better describe the cognitive abilities of our sample, standard tests of psychomotor speed (WAIS-III Digit-Symbol Coding; Wechsler, 1981), task-switching (D-KEFS Trail Making Test; Delis, Kaplan, & Kramer, 2001), WM capacity (modified Reading Span Task; Daneman & Carpenter, 1980), and language abilities (Extended Range Vocabulary Test; ERVT Form V2; Educational Testing Service, 1976) were administered to the participants.

Word Recognition Task (WRT) used to measure TSI, in which the stimuli comprised of 21 words drawn from three different categories (i.e., fruits, animals, and clothing) with seven words in each category. Using Battig and Montague's (1969) word category norms, the stimuli for each category were matched for word length and frequency, and the development and the presentation of the stimuli was similar to Li and Dupuis's (2008) study. Each target word was presented either singly, or with flankers. In all the flanked trials, the participants were instructed to focus on the middle word and ignore the flanker words. They were further instructed to determine the category membership (i.e., fruit, animal or clothing) of the presented stimulus and make an appropriate key press response both quickly and accurately. The left, right, and middle arrow keys on the standard keyboard were assigned to the three categories, and the category-response mappings were counterbalanced across participants.

In the unflanked trials, the N-2 repetition cost was measured by comparing the mean RTs of category repetition (i.e., third A in AB$\underline{\text{A}}$) against the non-repetition control trials (i.e., A in CB$\underline{\text{A}}$). In the flanked trials, the Lag -1 facilitation was measured by comparing the mean RTs of

Lag-1 trials (i.e., the previously executed task set served as a flanker in the current trial) against the Lag-2 trials. If the recently executed category item is inhibited, then on the following trial when it is presented as a flanker, it should cause less interference compared to the control trial. Therefore, RTs on the Lag-1 inhibition trials were expected to be faster compared to the control trials. Fig. 1.1 illustrates one partial trial and includes examples of flanked, unflanked, CBA, ABA, Lag-2, and Lag -1 trials. The WRT overall consisted of 1600 trials, grouped in eight blocks. A practice block of 128 unanalyzed trials preceded the test trials. Flanked and unflanked trials were of equal proportion (500 trials each), and the critical inhibition trials and control trials were of equal proportion (250 trials each). In addition, the sequences of AB$\underline{A}$ and CB$\underline{A}$ were equally represented (500 trials each).

General Procedure

The participants were tested in the Adult Development and Aging Laboratory at Concordia University. A consent form and demographic questionnaire (age, years of education, general health status, and current medications) was given early in the session. Before the commencement of the WRT, the participants completed a stimulus familiarization procedure and 128 practice trials. A short break was provided after the completion of three blocks, during which the Digit-Symbol Substitution task and D-KEFS Trail Making Test were administered. After the completion of the WRT, the participants performed the Reading Span Task and the Extended Range Vocabulary Test after which they were debriefed and compensated. Each session lasted approximately 90 minutes.

Data Trimming and Outlier Analyses

In the WRT, the RTs from commission errors were excluded from the analysis. Since commission and omission errors were followed by an error screen, the RTs for items following an error screen were excluded from further analysis. The individual median RTs were trimmed at ± 3 SDs, computed on the basis of each individual's correct RT distributions. To examine the relative magnitude of age-related differences in TSI, the effect size (Cohen's D) was estimated by means of the formula $d = 2t/\sqrt{df}$. If any participant exceeded ± 3 SDs from the group mean on at least two background measures and on the WRT on either RTs or errors, such data were excluded from the main analyses. As such, one older adult's data were excluded from the analysis.

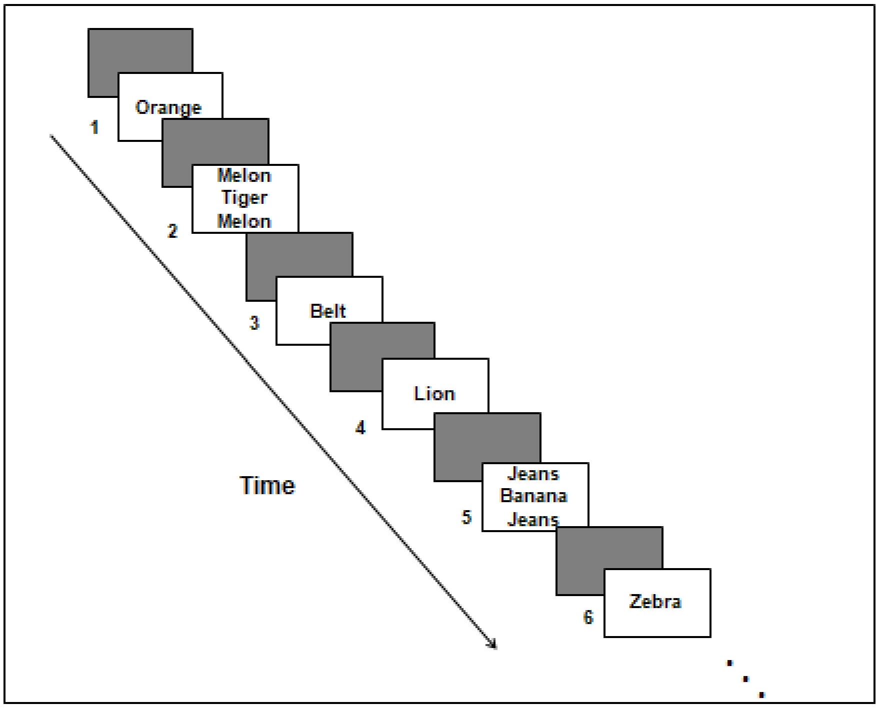


Figure 1.1. Word recognition task stimuli for one partial run. Flanked trials (items 2 & 5) are intermixed with unflanked trials (item 1, 3, 4, 5, 6). Items 2 and 5 are Lag -1 and Lag -2 trials respectively. Items 3 and 6 are CB<u>A</u> and AB<u>A</u> trials respectively. The blank screens and the stimulus trials were presented for 800 ms.

Results

The background measures and all the trial types on the WRT were approximately normally distributed with acceptable values of skewness and kurtosis of less than 3 and 10 respectively (Kline, 2009). Descriptive statistics for the background measures are shown in Table 1.1. As expected, age-related differences were observed in processing speed, WM, and task switching favoring the young group, whereas older adults' verbal knowledge was superior to that of young adults. Table 1.2 for adjusted and unadjusted median RTs and reliability estimates for all trial types in the WRT.

To validate the assumption that N-2 repetition cost (ABA vs. CBA) and the Lag-1 facilitation effect (lag-1 vs. lag -2) are both indices of the same inhibitory process, the difference scores between the unflanked (i.e., AB$\underline{\text{A-}}$ CB$\underline{\text{A}}$ trials) and flanked (i.e., Lag-1-Lag-2 trials) conditions were subjected to correlation analysis. As expected, both young and older adults showed negative correlations between the two measures: $r_{\mathrm{YA}}(27) = -.49$, $p = .01$, $r_{\mathrm{OA}}(22) = -.52$, $p = .01$. See Figure 1.2 for scatter plots.

With respect to overall error rates, both age groups showed high accuracy (>95%) with no significant differences between younger ($M = .05$, $SD = .03$) and older adults ($M = .03$, $SD = .03$), $t(43) = 1.53$, $p = .13$, $d = .46$. Given the near-ceiling accuracy rates, we turn to the analysis of RT data.

To investigate the hypothesis that young and older adults show differential inhibition across these indices, the mean RTs from WRT were subjected to 2 X 2 X 2 mixed factorial ANCOVA with Age Group as a between-subjects factor, Task Context (flanked vs. unflanked) and Trial Types (control vs. inhibition) as a within-subjects factors. The scores from the ERVT and the Digit Symbol Substitution test were added as covariates to control for language proficiency and general processing speed. The assumptions of ANCOVA (i.e., normality, homogeneity of variance) were verified by skewness and kurtosis of average RTs, and Levene's test of significance. No significant main effects of Task Context or Trial Type, or significant interactions with the covariates, were observed. There was a marginal effect of age group, $F(1, 39) = 3.9$, $p = .05$, $\eta^2 = .08$ and a significant interaction of age group, condition, and trial type, $F(2, 78) = 5.04$, $p = .04$, $\eta^2 = .08$.

Table 1.1

Means and Standard Deviations on the Background Measures by Age Group

Age Group	Processing Speed [a]*	Task Switching[b]	Working Memory[c]	Vocabulary [d]*
Young	83.46	0.43	23.17	06.12
	(14.91)	(0.13)	(4.48)	(4.70)
Older	67.04	0.48	20.73	16.28
	(11.23)	(0.20)	(3.46)	(4.93)

Note. Values reflect average score per group; standard deviations are shown in parentheses. [a] Wechsler Adult Intelligence Scale-Revised (WAIS-1V) Digit Symbol Substitution. The values reflect number of items completed in 120 seconds. [b] The values reflect proportional slowdown in the DKEFS Trail Making Test, from the control to the alternating condition. [c] The values reflect recall scores on the Reading span task. [d] Extended Range Vocabulary Test - Form V2. The values reflect correct items minus ¼ point deduction for errors. * Age group differences were statistically significant in independent-samples *t*-tests ($p < .05$)

Table 1.2

Descriptive statistics and reliability estimates for the Word Recognition task by age group

Age Group	Unflanked Trials		N-2 repetition cost	Flanked Trials		Lag -1 facilitation
	CBA[a]	ABA[a]		Lag -2[a]	Lag -1[a]	
			Adjusted Mean Reaction Time [a]			
Young	688 (86)	730 (95)	42	733 (95)	712 (89)	-21
Older	764 (91)	789 (101)	25	781 (101)	780 (94)	-1
			Unadjusted Mean Reaction Time [b]			
Young	680 (100)	716 (105)	36	715 (106)	702 (120)	-13
Older	770 (110)	809 (108)	39	802 (112)	790 (125)	-12
			Reliability Estimates [c]			
Young	0.92	0.99		0.98	0.99	
Older	0.96	0.99		0.99	0.99	

Note. [a] Mean reaction times in milliseconds after controlling for the language ability (ERVT) and the processing speed (Digit Symbol Test). [b] Mean reaction times in milliseconds without covariate adjustment. Standard deviations are in parentheses. [c] Reliability was calculated by adjusting split-half correlations with the Spearman-Brown formula. All the reliability estimates were statistically significant ($p < .05$).

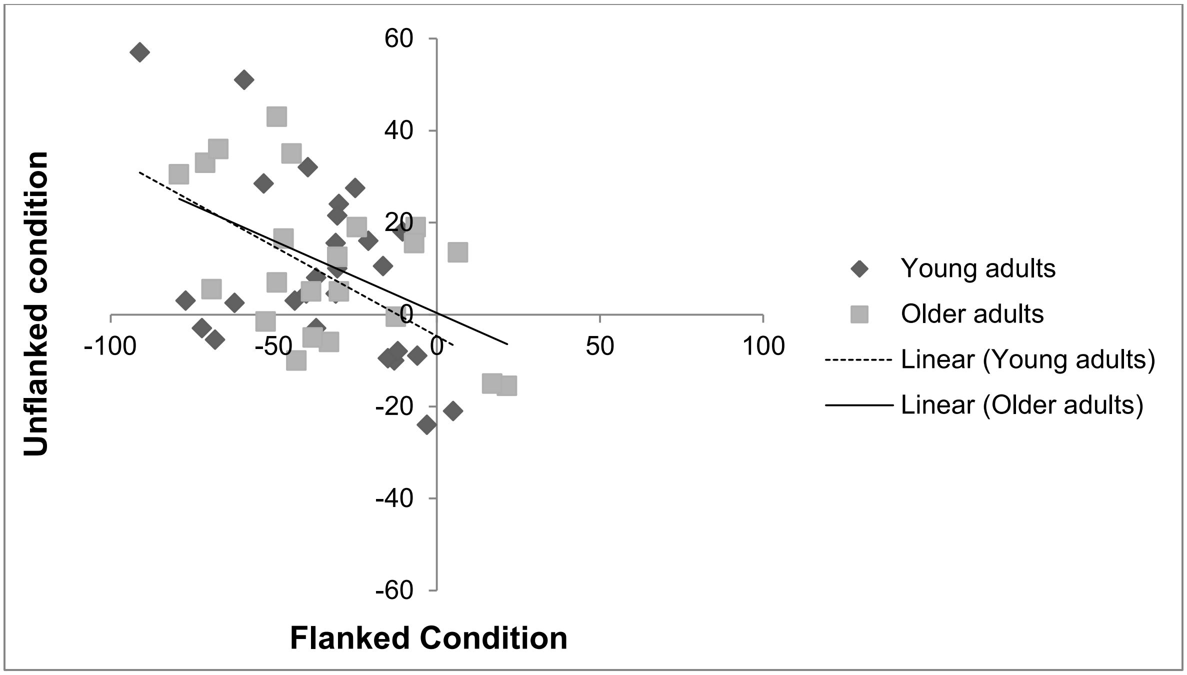


Figure 1.2. Correlation between unflanked and flanked conditions across both age groups. Unflanked condition = difference in RTs between AB<u>A</u> and CB<u>A</u> trials. Flanked condition = difference in RTs between Lag-1 and Lag -2 trials.

To decompose this 3-way interaction, we carried out Age Group (younger, older) x Trial Type (ABA, CBA, Lag-1, Lag -2) ANCOVAs separately for both unflanked and flanked conditions. In the unflanked condition, only a significant Trial Type effect was observed, $F(1, 47) = 6.7$, $p < .01$, $\eta^2 = .12$, indicating a comparable N-2 repetition cost for both age groups ($d = .28$). However, in the flanked condition, there was a significant Age Group by Trial Type interaction, $F(1, 47) = 4.8$, $p = .03$, $\eta^2 = .09$, indicating that young adults exhibited a larger Lag -1 facilitation, $t(27) = 2.4$, $p = .02$, compared to older adults $t(22) = .04$, $p = .8$, $d = -.51$.

Discussion

The first goal of the current experiment was to validate the theoretical assumption that the N-2 repetition cost and Lag-1 facilitation are both indices of the same inhibitory process. To that end, we measured N-2 repetition cost and Lag-1 facilitation by independent trials (i.e., flanked vs unflanked trials) in a mixed design. The results show a robust negative correlation between N-2 repetition cost and Lag-1 facilitation, across both the age groups. To our knowledge this is the first study to demonstrate such an association. The second goal of the current experiment was to investigate the age-related differences in TSI across both the indices. The results show age invariance in the N-2 repetition cost ($d = .28$) replicating previous research (Mayr, 2001), but *moderate* age-related differences favoring young adults in the Lag-1 facilitation ($d = -.51$). To our knowledge this is one of the very few studies to demonstrate TSI related age effects.

The empirical convergence between the N-2 repetition cost and Lag-1 facilitation indicate that the TSI effects are observable in varied task contexts; however the differential age effects between these two indices indicate that the overall task context may determine the locus of age-related inhibitory effects. For instance, it is likely that the N-2 repetition cost is a measurement of TSI at later time point (i.e., the presence of two intervening trials before the onset and the measurement of inhibition) compared to the Lag-1 comparison, in which the inhibition is measured one trial after its onset. It is possible, that compared to young adults, older adults are sluggish in initiating TSI. We are not keen on this interpretation as previous studies employing time course analyses of TSI have shown age invariance (e.g., Li & Dupuis, 2008). The second possibility is that the flanker trials invoke larger perceptual demands and interference, thereby compelling older adults to apportion limited capacity inhibitory process to flanker interference as well to proactive interference from the previous tasks. To test this interpretation holistically, a more fruitful approach would be to elicit TSI in varied task contexts, in which task conditions offer differing preparatory (e.g., valid and invalid task cues) and reactive (e.g., no task cue) demands and measure age-related differences in TSI as a function of global task context. In summary, the current experiment provides the first direct empirical evidence indicating that N-2 repetition cost and Lag -1 facilitation reflect common underlying mechanism, inhibition, but young and older adults differ on these two indices as result of overall task context.

CHAPTER 3

TRANSITION TO STUDY 2

In Study 1, I examined the age-related TSI effects in varied reactive control task contexts. To this end, I developed a non-cueing task switching flanker paradigm and measured TSI in terms of N-2 repetition costs and Lag -1 facilitation effects. The theoretical aims of this study were to validate that both these indices measure TSI, and examine whether young and older adults show age-equivalent TSI effects in both high (i.e., flanked trials) and low (i.e., unflanked trials) reactive control task contexts. Consistent with the first assumption, the correlational results indicate a negative association between N-2 repetition costs and the Lag -1 facilitation effects, across both the age groups. To my knowledge this is the first study to demonstrate such an association, thus bridging the gap between two traditional measurements of TSI. Another important finding from this study is that in the unflanked condition (i.e., ABA vs. CBA), both age groups showed robust TSI effects, replicating previous research (Mayr 2001; Lawo, Philipp, Schuch, & Koch, 2012; Schuch, 2016). However, in the flanked condition (i.e., Lag -1 vs. Lag -2 comparison) only young adults showed Lag -1 facilitation effects, indicating moderate age-related TSI advantage in favour of young adults (*d* = -.51). This is a novel finding, and is in opposition to the categorical predictions made from the DMC framework (i.e., age equivalence in reactive control), and indicates that young and older adults are utilizing reactive control differentially.

To elaborate, the empirical convergence between the N-2 repetition cost and Lag-1 facilitation strengthens the argument that the TSI effects are truly inhibitory in nature (Mayr 2007; Koch et al., 2010), and refutes other rival explanations postulated in the literature, such as perceptual priming and activation-based accounts that would predict the opposite results (i.e., Lag-1 costs, and N-2 facilitation effects). The observed negative correlations between both operationalisations of TSI, in both age groups, also indicate the ‘persistent’ nature of TSI across the task switching trials (Mayr, 2007). For instance, the N-2 repetition cost is a measurement of TSI at a later time point (i.e., the presence of two intervening trials before the measurement of inhibition). In comparison, the Lag-1 facilitation effect involves measuring the lasting effects of task set inhibition one trial after its onset. According to the time course hypothesis, one may assume that both young and older adults show a similar (peak) magnitude of TSI after two intervening trials, but compared to younger adults, older adults are sluggish in initiating TSI, as measured after one intervening trial. This interpretation is consistent with other research concerning the time course of inhibition (e.g., inhibition of return), in which older adults show a delayed onset of inhibition compared to younger adults (Castel, Chasteen, Scialfa, & Pratt, 2003). However, the very few studies that have examined the time course of TSI in young and older adults has demonstrated age-equivalent TSI effects across different delays (Li & Dupuis, 2008), arguing against the age-differential time course perspective. Thus, further experiments with a direct manipulation of cue-probe intervals in a TSI paradigm are warranted.

Within the DMC framework, it is assumed that the flanker trials would impose larger perceptual demands and interference, compared to the unflanked trials, thus invoking a higher degree of reactive control. Given the assumed age equivalency in reactive control, in a typical block design, the categorical predictions from the DMC framework would expect age equivalent TSI effects across both the reactive control task contexts. However, in a mixed design in which local task demands (i.e., high/low reactive control) vary with global task context (i.e., overall reactive bias), it is assumed that each age group should modulate the reactive control process differentially. To illustrate, in the traditional AX-CPT paradigm the global task context is proactively biased as result of differential proportion of cue-probe pairs (i.e., 70% A-X trials, and 10 % of AY, BX and BY trials). This proactive task bias, although facilitative in a majority of the trials (AX trials), also creates conflicts in cue-probe invalid trials (AY, BX and BY trials) thus impacting the overall performance on this task. According to the DMC framework, the age-related performance in this task is explained by the differential global control strategy employed by young (i.e., proactive control) and older (i.e., reactive control) adults. Given that young and older adults' default mode of control is proactive and reactive respectively, an optimal performance in the AX-CPT paradigm is achieved by down regulation of proactive control by young adults, thereby improving performance on AY trials, and upregulation of proactive control by older adults, thereby improving performance on AX trials.

Similarly, in the current WRT paradigm, the global task context is reactively biased, as a result of probe-based activation and flanker interference. However, this global reactive task bias is facilitative across both task contexts (i.e., flanked and unflanked trials) thus creating no local conflicts. Given that older adults' default mode of control is reactive control, from the DMC framework, the optimal performance in the WRT task is achieved by stable maintenance of reactive control by older adults, and upregulation of reactive control by young adults. Accordingly, one may attribute the observed age-related differences in TSI to a greater exertion (i.e., upregulation) of reactive control in response to the reactively biased global task context by young adults, compared to older adults. This interpretation is line with the idea that both young and older adults show flexibility in modulating the dual control processes in response to global task context (Braver et al., 2009; Paxton, et al., 2008). However, one clear limitation of Study 1 is that the TSI effects were only measured in reactive control task contexts, thus precluding the use of proactive control due to the absence of cues. That is, in the Study 1 design, it was not possible to examine both proactive and reactive control processes in predicting age differences in TSI.

In Study 2, with two experiments, I examined the influence of global task context on age-related differences in TSI. Accordingly, a task switching paradigm was used in which proactive and reactive control demands were varied from trial to trial. These local variations of proactive and reactive task demands were also influenced by the global task context, as driven by the ratio of valid and invalid cue-probe pairs within each block of trials. To this end, the age-related modulation of the DMC processes was examined in terms of the joint influences of global block-wise context and local trial-wise demands in determining age-related differences in TSI effects.

CHAPTER 4

STUDY 2

Age-Differential Effects of Global Context on Dual Mechanisms of Control During Task-set Inhibition

Abstract

A major challenge in cognitive aging research is to identify the basic cognitive mechanisms involved in executive functioning. In the current study, we used the Dual Mechanisms Control (DMC) theory to elucidate the ambiguous age-related findings in one particular executive function paradigm, task-set inhibition (TSI). The TSI effect refers to increased reaction times (RTs) in task-repetition trials compared to task-alternation trials. In Experiment 1, 25 young and 25 older adults performed a computerized math task, in which the valid and invalid task cues and probe trials varied in their proactive and reactive control demands along a continuum. The TSI effect was measured by comparing the third trial of the AB<u>A</u> and CB<u>A</u> sequences. TSI was observable in reactive control task contexts (i.e., probe based activation) and young adults downregulated proactive control to match the global task context. In Experiment 2, new samples of 25 young and 25 older adults performed a modified version of the math task, in which cue salience in one task condition was changed to better elicit proactive control. With this modification, older adults were able to modulate proactive control, and performed similarly to young adults in Experiment 1 in showing an age-related TSI advantage. Taken together, the results indicate that TSI effects are observable in reactive control task contexts. Importantly, these results are more consistent with a continuum perspective of DMC than a categorical viewpoint.

Introduction

Age-related declines have been demonstrated in a wide variety of cognitive domains (e.g., Kausler, 1991; Salthouse, 1991). Among the many cognitive functions known to decline in old age, executive functions such as working memory, inhibition, and switching, appear to decline more rapidly (Hasher, Lustig, & Zacks, 2007; Rabbitt, 1965). A major challenge in cognitive aging research is to identify the basic cognitive mechanisms involved in age-related executive declines (Verhaeghen, Cerella, Bopp, & Basak; 2005). One model, Braver's Dual Mechanisms of Control theory (DMC; Braver, Gray, & Burgess, 2007) postulates two basic control mechanisms, proactive and reactive control. According to the DMC framework, the age-related changes in these dual processes can explain age-related variance in executive functions. We have used the DMC theory to better understand the ambiguous age-related findings in one particular executive function paradigm, task-set inhibition (TSI).

Task-set Inhibition: Nature, Function, and Age Effects

In the task switching literature, task-set inhibition is viewed as a possible optimization process to resolve two opposing demands imposed on the attentional system, namely "stability demands" (i.e., current task-set selection and maintenance), and "flexibility demands" (i.e., transition to new task representations). These opposing demands have been referred to as the *stability-flexibility dilemma* (Goschke, 2000). In cued task switching paradigms, when task sets alternate, the N-2 repetition cost refers to increased reaction times (RTs) in the task-repetition trials (as in the third trial of an AB<u>A</u> sequence) compared to the task-alternation trials (as in the third trial of a CB<u>A</u> sequence). This RT cost is also referred to as backward inhibition (Mayr & Keele, 2000; Mayr, 2001). There is abundant empirical evidence to date showing N-2 repetition costs in simple perceptual tasks (Mayr, 2001), cognitive categorization tasks (Schuch & Koch, 2003), sequential action control tasks (Li & Dupuis, 2008), and language switching (Philipp, Gade, & Koch, 2007; Philipp & Koch, 2009). That task repetition is costly compared to task alternation is difficult to explain by rival hypotheses and appears to be a convincing demonstration of inhibition of previous task-sets (Koch, Gade, Schuch, & Phillip, 2010; Mayr, 2007). Hereafter, we refer to N-2 repetition cost as task-set inhibition (TSI).

In the context of the stability-flexibility dilemma (Goschke, 2000), the hypothesised function of TSI is to 'clear the slate' by transiently supressing the proactive interference (PI) generated by the previous task sets (Mayr, 2007). This implies that TSI may be a necessary control process in task switching (e.g., Arbuthnott, 2005; Goschke, 2000; Masson et al., 2003; Mayr & Keele, 2000; Philipp, Kalinich, Koch, & Schubotz, 2008; Schuch & Koch, 2003) and a likely candidate for age-related decline, as inhibitory processes targeting PI are widely associated with age-related declines in working memory and episodic memory (e.g., Hasher et al., 2007). However, the evidence to date indicates that the magnitude of TSI is either age-equivalent or, in some cases, greater in older than younger adults.

In the first study examining age-related differences in TSI, Mayr (2001) used a three task (colour- shape- size) cueing paradigm (Mayr & Keele, 2000) and found that older adults showed larger TSI effects compared to young adults. Additionally, this age-related TSI effect was unrelated to executive indices of switching efficiency, such as global set-selection costs (i.e., RT cost in task repetition in mixed block trials compared to single block trials) and local switch costs (i.e., RT cost in task alternation compared to task repetition in mixed block trials). Based on these surprising findings, Mayr (2001) proposed that TSI may reflect a low-level, automatic process triggered during task switching, and suggested a reappraisal of the functional role of TSI in the context of age differences. In a subsequent study, Li and Dupuis (2008) measured TSI by using a task-switching variant of the flanker paradigm (Hübner et al., 2003). Notably, the authors operationalized TSI as a facilitation effect, in which both young and older adults showed comparably reduced flanker interference effects when the flanker belonged to the previously executed task set. Similar age-equivalent TSI effects have been reported by Lawo and colleagues (Lawo, Philipp, Schuch, & Koch, 2012), who examined TSI by varying the cue-stimulus interval, and more recently, by Schuch (2016), who examined age-related TSI effects using a diffusion model (e.g., Ratcliffe, Smith, Brown, & Mckoon, 2016) and took into account the RT distributions of both correct and error responses. Together, these age-equivalent TSI findings seemingly contradict the assumption of age-related declines in inhibitory processes.

The Dual Mechanisms of Control Theory and Task-set Inhibition

To disambiguate the mixed findings in the aging inhibition literature more broadly, we (Vadaga, Blair, & Li, 2015) recently proposed that the age-related declines in different inhibitory processes, including TSI, can be parsimoniously explained using the Dual Mechanisms of Control theory (DMC; Braver et al., 2007). Within the DMC framework, two control mechanisms, proactive and reactive, are involved in conflict management. The proactive control mechanism utilizes predictive information (e.g., valid task cues, information held in working memory) to bias attention towards goal-related information in a sustained manner, thereby resolving task conflicts pre-emptively. For example, sustained proactive control resolves the buildup of PI across successive trials in working memory paradigms, wherein previous goal representations interfere with the current ones (Braver et al., 2007). In contrast, reactive control is initiated, transiently, by post-stimulus processing and resolves task conflicts on a trial-by-trial basis. For example, in task-switching paradigms the immediate PI generated during task-alternation trials is supressed transiently after the stimulus onset and response execution. Taken together, proactive and reactive control can be viewed as early selection and late correction mechanisms respectively (Braver et al., 2007), operating seamlessly as a ‘unified control process’ to achieve behavioral stability and flexibility in the face changing task demands.

With respect to age effects across these dual processes, the cumulative evidence from behavioral and neuroimaging studies, comprising tests of context processing, working memory, response inhibition, and task switching, indicate age-equivalence in reactive control; and age-related differences favoring young adults in proactive control (Braver, Satpute, Rush, Racine, & Barch, 2005; Braver, Paxton, Locke, & Barch, 2009; Bugg, 2014; Vadaga et al., 2015). From the DMC framework, a parsimonious way to explain the age-equivalent TSI effect is by conceptualizing TSI as an after-effect of reactive control. This view is consistent with the empirical work suggesting that TSI is a ubiquitous process in task-switching (Houghton, Pritchard, & Grange, 2009) and is initiated post-response (Schuch & Koch, 2003), but is not influenced by cue-based preparatory process (e.g., Gade & Koch, 2008). However, given that the TSI effect is invariably measured in valid cue-based paradigms, it is unclear whether TSI can be observed in task conditions where reliance on reactive control is crucial for task execution. The first aim of the present study was therefore to examine this possibility.

The Influence of Task Bias on the Dual Control Processes

A second issue to consider is the influence of task bias on the dual control processes. Conventionally, the dual control processes are measured by context processing tasks, in which the overall task contingencies elicit differential recruitment of proactive and reactive control between young and older adults. To illustrate, Braver and colleagues (Braver et al., 2001; Braver et al., 2005) modified the classical continuous performance task (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956), such that the cue (A or B) precedes the stimulus (X or Y) and the objective is to respond only to a subset of trials (AX trials). A key aspect of AX-CPT task is that AX trials occur 70% of the time, thus leading to a proactive task bias. On AY trials, biased proactive control is associated with more errors because the presentation of the A biases attention to respond, when one should in fact withhold a response. Consistent with age-related declines in proactive control, older adults make more omissions on AX trials than young adults (Braver et al., 2001). Conversely, the observed age advantage on AY trials suggests that young adults were overexerting proactive control (i.e., proactive bias), whereas older adults were relying on reactive control by not utilizing cue-related processes, possibly to offset age-related proactive declines (Braver et al., 2007).

The AX-CPT task provides preliminary support for the idea that young and older adults show a differential modulation of control processes in relation to task contingencies. Accordingly, older adults appear to rely on reactive control, as indexed by transient activity in the anterior prefrontal cortex (aPFC), to compensate for proactive declines (i.e., decreased sustained activity in the aPFC) (Jimura & Braver, 2009). Further, older adults' mode of control can become more proactive through strategy training, such as increasing the salience of predictive cues and focussed instruction (Braver et al., 2009; Paxton, Barch, Racine, & Braver, 2008). This demonstration suggests that older adults can flexibly recruit proactive or reactive control processes (Braver et al., 2009). In sum, the age-related modulation of the dual processes forms the crux of the DMC theory in elucidating age-related executive declines. Therefore, it is important to examine whether such age-related modulation of proactive and reactive control can shed light on the age-equivalent TSI findings found in the literature.

The Current Study

The main aim of the current study was to examine age-related differences in TSI as a function of varying proactive and reactive control demands on a continuum. The continuum idea is derived from the recent postulation that young and older adults shift differentially from one mode of control to the other (e.g., Paxton et al., 2008), suggesting that proactive and reactive control constitute two poles of a single dimension (Gonthier, Braver, & Bugg, 2016). To this end, we devised a task switching TSI paradigm comprising three task sets (i.e., Addition, Subtraction, and Multiplication) requiring 'yes' and 'no' responses to the presented math equations (See Fig 2.1). We used four distinct task contexts (Table 2.1) to reflect this continuum ranging from sole reliance on proactive control (Cue Only) to equal emphasis on proactive and

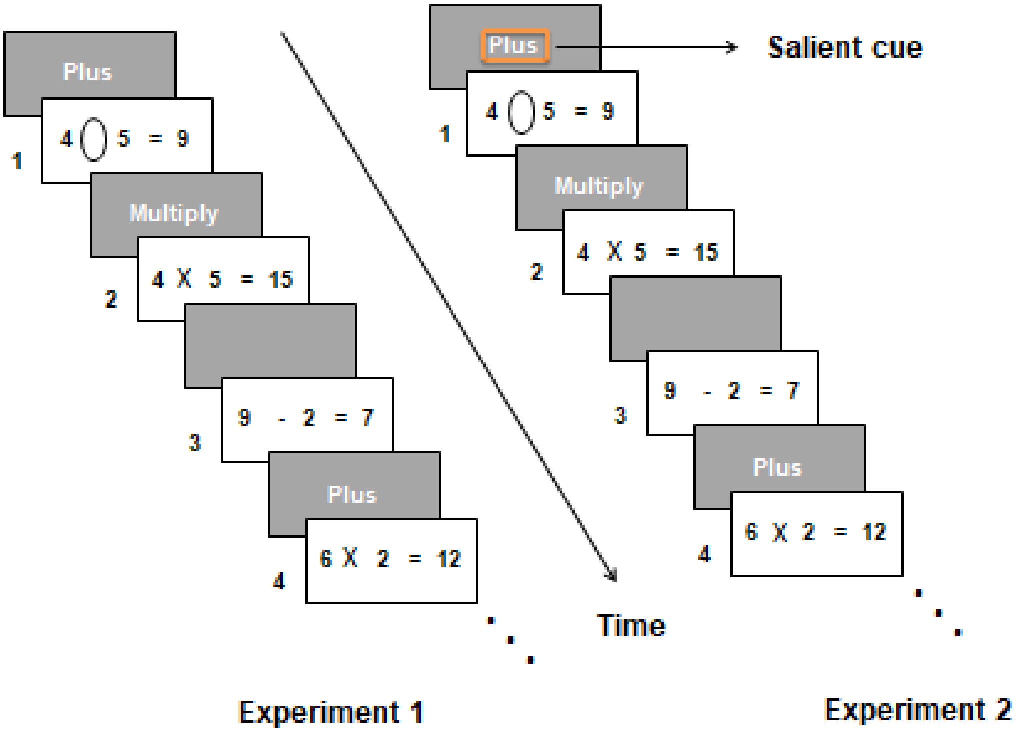


Figure 2.1. Computerized Math Task for one partial run. Items 1, 3 and 4 require 'yes' response and Item 2 requires 'no' response. Item 1 is 'Cue Only'. Item 2 is 'Cue + Operand. Item 3 is 'Operand Only' and CBA trial. Item 4 is 'Invalid Cue + Operand' and ABA trial. The cue duration was fixed at 2000 ms.

Table 2.1: Operationalization of Task Context and their Underlying Control Processes

Task Context			
Cue only	Cue + Operand	Invalid Cue + Operand	Operand only
Cue Stimulus Pairs			
ADD 6 4 = 10	ADD 6 + 4 = 10	ADD 6 X 4 = 24	6 - 4 = 2
Local Control Process			
Retention of cue-related information	Utilization of cue and probe-related information	Suppression of cue-related information, and probe activation	Probe activation
Proactive-Reactive Continuum			
High Proactive	Low Proactive	High Reactive	Low Reactive

reactive control (Cue + Operand), to high reliance on reactive control requiring suppression of cue information (Invalid Cue + Operand), and lastly, full reliance on reactive control (Operand Only). The simultaneous operation of the dual processes was either convergent (Cue + Operand) or divergent (Invalid Cue + Operand). Importantly, the latter condition should require a shift from a proactive to reactive mode of control.

Following Braver and colleagues' AX-CPT methodology (Braver et al., 2001; Braver et al., 2005), a key aspect of this design is that the four task contexts were randomly intermixed within each block of trials, thereby compelling young and older adults to adopt a global control strategy. To illustrate, the task comprised an equal proportion (.25) of four task contexts, ranging from sole proactive to reactive control, with equal frequency of cue-present (.75) and probe-present trials (.75). However, cues were valid on half the trials whereas, probes were valid on .75 of the trials, thus leading to an overall *reactive task bias*. From the recent formulation of the DMC framework (Braver et al., 2009; Paxton et al., 2008), young and older adults are assumed to adopt a *global* control strategy to match the overall task context. Accordingly, to achieve optimal performance across four task contexts, this should compel young adults to *downregulate* their default mode of control (i.e., proactive control), to offset the costs associated with invalid cue activation (i.e., analogous to 'AY' trials in the AX-CPT paradigm).

From the DMC framework, we conceptualize TSI as an automatic control process that is invoked, reactively post-response, to facilitate task flexibility. To this end, one may view TSI as a "flexibility cost" imposed in the form of increased RTs on task repetition trials (ABA) compared to non-repetition trials (CBA). Additionally, we conceptualize task-set activation (TSA) as reflective of proactive control. That is, when activated task-set information is sustained and then revisited (as in ABA), proactive control causes facilitation of performance rather than cost. Based on these assumptions, we made two condition specific predictions: First, if TSI is an automatic, low level control processes, then N-2 repetition costs should be solely observable in reactive control task contexts (i.e., Operand Only). Second, if the main function of proactive control is task-set selection, maintenance, and overriding of persistent TSI, then task contexts invoking proactive control should lead to N-2 benefits (i.e., Cue Only and Cue + Operand).

A conceptually important distinction between the *categorical* and the *continuum* viewpoints of the DMC theory can be made by examining age-differential outcomes within our design. That is, if global task context influences the age-related utilization of the dual control processes *categorically*, (Braver et al., 2001; Braver et al., 2005) then one would expect young adults to be at a relative disadvantage in the Invalid Cue + Operand condition (analogous to AY trials in the AX-CPT), compared to the Cue + Operand condition (analogous to AX trials in the AX-CPT). Conversely, older adults should be at a relative disadvantage in the proactive control task contexts (Cue Only, Cue + Operand). However, from the proactive-reactive continuum viewpoint (Vadaga et al., 2015), if the global task context influences the age-related modulation of the dual control processes overall, then young adults will downregulate proactive control across the continuum (Braver et al., 2009; Paxton et al., 2008) to match the reactively biased global task context. Therefore, one would predict either age equivalence in the Invalid Cue + Operand and Cue + Operand conditions or a relative advantage in favor of young adults. Conversely, given that the overall task context is in favour of older adults' default mode of control, older adults should be less flexible in their modulation of proactive control, and thus be more influenced by local condition-specific characteristics.

General Method

Overview

The current study was approved by Ethics Review Board of Concordia University. In the two experiments reported here, participants were given a background battery of neuropsychological tests to assess psychomotor speed, switching abilities, working memory capacity, and math ability. We used a computerized math task (CMT) to measure the TSI and TSA effect across the proactive-reactive continuum.

Background Neuropsychological Tests

To test psychomotor speed, participants were given the WAIS Digit-Symbol Substitution test (Wechsler, 1981), in which they copied the symbols corresponding to each of the randomly ordered digits, according to the key shown at the top of the worksheet. The dependent variable was the number of symbols substituted correctly within 120 seconds. To measure task switching abilities, the Trail Making test (TMT; Reitan & Wolfson, 1985) was used, during which the participants connected the numbers (1-25) in the control condition, and connected alternating numbers and letters (1A- 2B-…12L) in the task-alternation condition. The dependent variable was the proportional slowdown in the latter versus the former condition. The Reading Span Task (Daneman & Carpenter, 1980) was used to measure working memory capacity. The task was computerized and programmed with Superlab V. 4.7. The task comprised short sentences presented on a desktop monitor in Black, 22 point Times New Roman font on a white background. Sentences were presented one at a time, and participants were asked to read them out loud and make a key press response indicating whether they made sense or not. The task began with sets of two sentences, and after every two trials the set size increased by one sentence, up to six sentences per set. After the completion of each set, the participants were cued to recall the last word of each sentence in the order they were presented. The dependent variable was the total number of words recalled correctly (out of 20). The paper and pencil simple math task (SMT) was used to assess basic arithmetic proficiency. Participants completed 18 single digit math equations comprising addition, subtraction and multiplication. Overall completion time (s) was recorded.

Computerized Math Task (CMT). The stimuli for the CMT were simple equations composed of single digit numbers (1-9) and one of three operands (+, -, x). The equations were presented on a desktop monitor in white, 22 point Times New Roman font on a black background. SuperLab 4.5 software was used for stimulus presentation. In the CMT, the participants' objective was to determine the accuracy (yes or no) of the presented math equation by a key press response (left and right arrow keys on a standard keyboard). The math equations comprised single digit addition (e.g., 6 + 7 = 13), subtraction (e.g., 5 - 8 = -3), and multiplication (e.g., 4 x 5 = 25). The digit combinations within each math equation were randomly generated, then presented to all participants in a fixed order. Each equation was preceded by a task cue screen (i.e., the words PLUS, MINUS, MULTIPLY, or an empty box) with a cue-stimulus interval of 2000 ms. The stimulus duration varied with response times but did not exceed 2000 ms, after which the next trial would begin immediately.

Four task conditions were created to represent four points on the proactive-reactive continuum. In the first condition (Cue Only) the task cue was valid (e.g., PLUS) but the operand was absent in the subsequent trial (e.g., 4__6 = 10). In the second condition (Cue + Operand) the task cue was valid (e.g., PLUS) but not necessary as the task-set could be executed with the stimulus information itself (e.g., 4 + 6 = 10). In the third condition (Invalid Cue + Operand) the task cue was invalid (e.g., MINUS) and participants had to rely on the stimulus (e.g., 4 + 6 = 10) to execute the task. In the last condition, (Operand Only), the task cue was absent (i.e., empty box), and participants could only rely on the stimulus (e.g., 4 + 6 = 10).

The CMT consisted of 1200 trials, split into six blocks of 200 trials. Each block comprised all four task conditions and CBA and ABA sequences. Sequences of trials were pseudo-randomly constructed with the constraint that there could be no more than three consecutive “yes” or “no” responses. The order of blocks was counterbalanced across participants. A practice block of 100 unanalyzed trials preceded the test phase, with an option for repetition. Overall, all four conditions were equally represented (200 trials each) along with equal numbers of ABA and CBA trial sequences (100 trials for each condition). Following errors of omission or commission, feedback screens indicated that an error had occurred and oriented participants to the next item. Figure 1 illustrates one partial trial and includes examples of all four task contexts along with CBA and ABA sequences.

Procedure

The participants were tested individually in the Adult Development and Aging Laboratory at Concordia University. A consent form and demographic questionnaire (age, years of education, general health status, and current medications) were given early in the session. Participants were then familiarized with the CMT. A short break was provided after the first three test blocks, during which the Digit-Symbol Substitution task and Trail making test were administered. This was followed by three more blocks of the CMT, the Reading Span Task, and paper and pencil simple math task. Participants were then debriefed and compensated. Each session lasted approximately 150 minutes.

Analyses

In the CMT data, RTs for error trials, and two trials immediately following errors were excluded. Participants were classified as outliers if they exceeded more than 3 SDs on the CMT (RTs, errors) and at least one of the background neuropsychological measures. The RTs for ‘yes’ and ‘no’ responses were pooled across the conditions. To examine the relative magnitude of age-related differences in TSI, the effect size (Cohen’s D) was estimated by means of the formula $d = 2t/\sqrt{df}$.

Experiment 1

Method

Participants. Twenty-five young adults (72 % females and 28 % males, *M* = 24.42 years, *SD* = 4.46) were recruited from the Psychology participant pool at Concordia University, and 25 older adults (64 % females and 36 % males, *M* = 67.02, *SD* = 4.13) were recruited from the Montreal community via newspaper advertisements or from an existing participant database. Based on our intake questionnaires, participants were excluded if they reported any conditions that might impair their perceptual abilities, attention, or memory. Young adults received partial course credit as compensation and older adults received a $20 honorarium. Based on outlier analysis, data from one young adult and three older adults were excluded from the analysis.

Results and Discussion

Background measures. The background measures were normally distributed with acceptable values of skewness and kurtosis of less than 3 and 10, respectively (Kline, 2009). Descriptive statistics and group contrasts for the background measures are shown in Table 2.2. As expected, age-related differences favoring the young adults were observed on completion times on the WAIS Digit Symbol Substitution test. No age-related differences were observed in working memory or task switching, as measured by the Reading Span and Trail Making tests, respectively. Notably, older adults had faster completion times compared to younger adults on the background Math task.

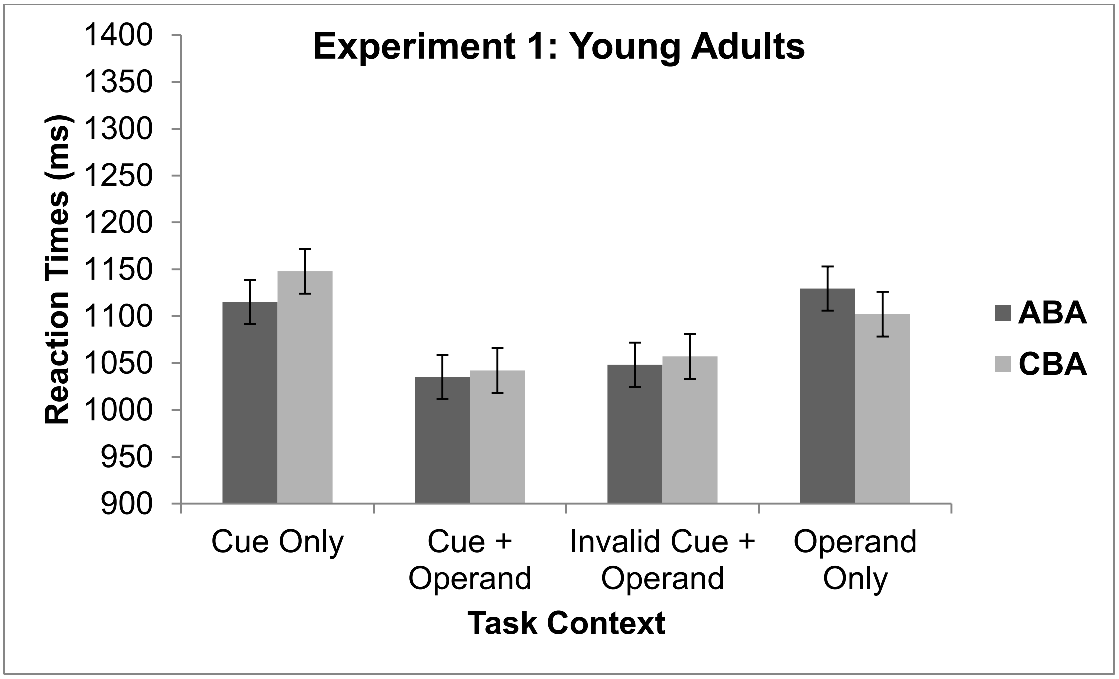
Computerized Math task (CMT). The mean RTs on the CMT were normally distributed with acceptable values of skewness and kurtosis. Figure 2.2 shows mean RTs for all trial types on the CMT across age groups. The reliability estimates for all the trial types on the CMT, as calculated by adjusting split-half correlations with the Spearman-Brown formula, were within the acceptable limits ranging from .74 to .95. With respect to overall error rates, both age groups showed moderate to high accuracy (> 90%) with no significant differences between younger ($M = .06$, $SD = .03$) and older adults ($M = .05$, $SD = .03$), $t(46) = 1.11$, $p = .13$, $d = -.33$ (Table 2.3). Additionally, bivariate correlations between RTs and error rates across both age groups ($r_{\mathrm{YA}}(23) = .06$, $p = .77$, $r_{\mathrm{OA}}(23) = .24$, $p = .28$) did not show any evidence of speed-accuracy trade off.

To test the first hypothesis that TSI can be observed in reactive control task contexts, the two reactive control task contexts were contrasted. Specifically, the mean RTs were subjected to a 2 x 2 x 2 mixed-factorial ANOVA with Age Group as a between-subjects factor, Reactive Control Task Context (Invalid Cue + Operand, Operand Only), and Trial Type (AB$\underline{\text{A}}$, CB$\underline{\text{A}}$) as the within-subjects factors. We assumed that the Invalid Cue + Operand condition required the most reactive control, as it entailed both probe-based activation, and suppression of invalid cue-related activation.

Table 2.2: Means and Standard Deviations on the Background Measures by Age Group

	Digit Symbol[a*]	Task Switching[b]	Working Memory[c]	Math ability[d*]
	Experiment 1			
Younger	84.33 (10.63)	2.23 (0.75)	10.58 (2.51)	38.55 (14.84)
Older	71.48 (10.29)	2.36 (0.61)	09.64 (2.70)	29.68 (8.64)
	Experiment 2			
Younger	81.32 (12.68)	2.40 (0.78)	10.20 (3.01)	40.10 (19.47)
Older	65.08 (12.20)	2.16 (0.64)	09.83 (2.54)	33.40 (10.12)

Note. Values reflect the average score per group; standard deviations are shown in parentheses. [a] Wechsler Adult Intelligence Scale-Revised (WAIS-IV) Digit Symbol Substitution. The values reflect number of items completed in 120 seconds. [b] The values reflect proportional slowdown in the Trial Making Test, from the control to the alternating condition. [c] The values reflect recall scores out of 20 on the Reading span task. [d] Simple Math Task. The values reflect completion times (sec) across 16 simple math equations. * Age group differences were statistically significant in independent-samples *t*-tests ($p < .05$).



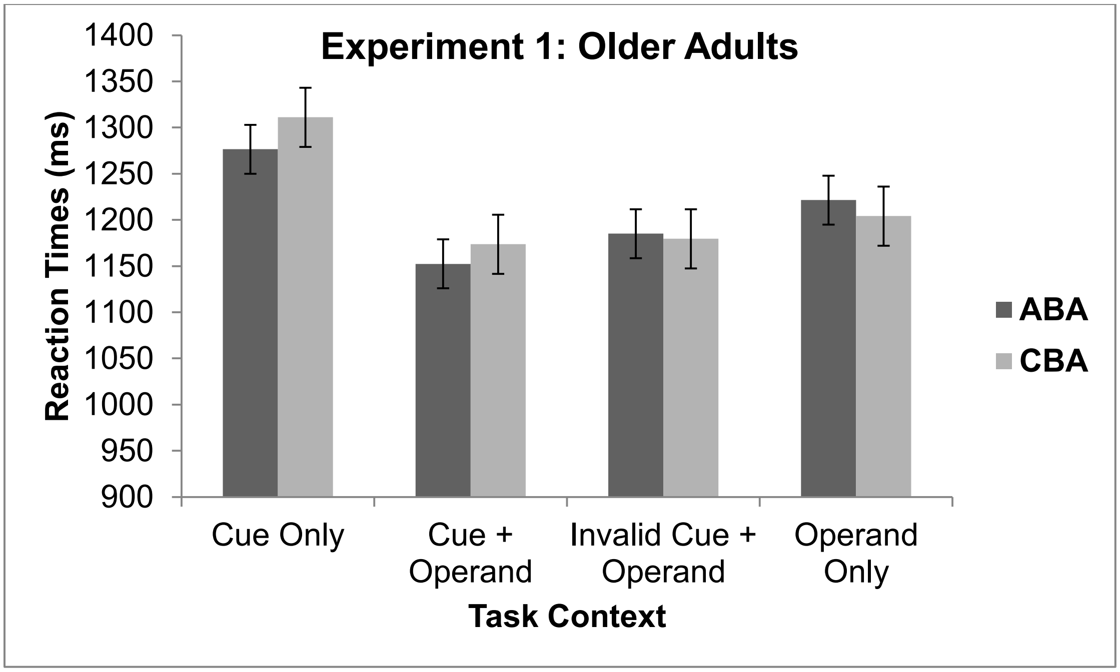


Figure 2.2. The graphs on the top and bottom depict young and older adults' mean reaction times (ms), calculated based on the individual median reaction times, on the Computerized Math Task (CMT) respectively. The error bars depict 1 Standard Error. ABA and CBA refer to triplet trials, and reaction times on the third trial of the sequence.

Table 2.3: Mean Error rates (%) and Standard Deviations on the Computerized Math Task (CMT) by Age Group

Task Contex	Cue only		Cue + Operand		Cue Invalid + Operand		Operand Only	
Trial Type	ABA	CBA	ABA	CBA	ABA	CBA	ABA	CBA
			Experiment 1					
Younger Adult	6%	8%	6%	6%	5%	5%	6%	7%
	(.09)	(.07)	(.07)	(.07)	(.09)	(.08)	(.08)	(.09)
Older Adults	5%	7%	5%	4%	3%	5%	5%	6%
	(.06)	(.06)	(.04)	(.03)	(.04)	(.05)	(.05)	(.03)
			Experiment 2					
Younger Adult	7%	9%	7%	7%	6%	8%	7%	7%
	(.09)	(.09)	(.09)	(.09)	(.09)	(.07)	(.09)	(.08)
Older Adults	6%	8%	5%	5%	5%	6%	6%	6%
	(.06)	(.06)	(.05)	(.05)	(.03)	(.04)	(.06)	(.06)

Note. Mean error rates (%) on the third trial of the sequence. Standard deviations are in parentheses.

Additionally, we assumed that TSI is a low level control process, therefore, we predicted smaller TSI effects in the Invalid Cue + Operand condition compared to the Operand Only condition. Based on the DMC framework, across both task contexts, we predicted age-equivalent TSI effects.

The ANOVA results indicate significant main effects of Task Context, $F(1, 44) = 38.11$, $p < .01$, $\eta^2 = .46$, indicating, unexpectedly, longer RTs in the Operand Only condition ($M = 1118$ ms, $SE = 17$) compared to the Invalid Cue + Operand condition ($M = 1164$ ms, $SE = 19$). There was significant main effect of trial type, $F(1, 41) = 5.3$, $p = .03$, $\eta^2 = .11$ indicating, as hypothesized, longer RTs in the AB$\underline{\text{A}}$ trials ($M = 1146$ ms, $SE = 17.6$) compared to the CB$\underline{\text{A}}$ trials ($M = 1136$ ms, $SE = 18$). There was also a significant main effect of Age Group, $F(1, 44) = 10.45$, $p < .01$, $\eta^2 = .19$, indicating longer RTs for older adults ($M = 1197$ ms, $SE = 25$) compared to young adults ($M = 1084$ ms, $SE = 25$). Further, two statistically significant two-way interactions were observed. First, Task Context interacted with Age Group, $F(1, 44) = 4.6$, $p = .04$, $\eta^2 = .10$, indicating that compared to older adults (30 ms difference, $t(22) = -1.14$, $p = .26$), young adults (60 ms difference, $t(22) = -2.62$, $p = .02$) had disproportionately longer RTs in the Operand Only condition ($d = -.75$). Second, Task Context interacted with Trial Type, $F(1, 44) = 5.93$, $p = .02$, $\eta^2 = .75$, indicating, as hypothesized, that the TSI effects were more pronounced in the Operand Only condition (AB$\underline{\text{A}}$, $M = 1175$ ms, $SE = 19$; CB$\underline{\text{A}}$, $M = 1153$ ms, $SE = 19$) relative to the Invalid Cue + Operand (AB$\underline{\text{A}}$, $M = 1116$ ms, $SE = 17$; CB$\underline{\text{A}}$, $M = 1118$ ms, $SE = 17$). There was no significant Trial Type X Age Group interaction, nor a significant 3-way interaction (ps $\geq .22$). Together, the results indicate that TSI effects are observable in low reactive control task contexts, and young and older adults show comparable TSI effects. Additionally, young adults show greater *costs* than older adults while transitioning from 'Invalid Cue + Operand' to 'Operand Only' task contexts.

To test the second hypothesis that Proactive Control overrides persistent TSI, the mean RTs were subjected to a 2 x 2 x 2 mixed-factorial ANOVA with Age Group as a between-subjects factor, Proactive Control Task Context (Cue Only, Cue + Operand), and Trial Type (AB$\underline{\text{A}}$, CB$\underline{\text{A}}$) as the within-subjects factors. We assumed that the Cue Only task context would recruit a larger degree of proactive control, as it entails additional WM demands to maintain the task cue in the absence of a math operand in the probe display. Therefore, we predicted longer RTs in this condition. Based on the continuum perspective, we expected age-equivalent TSA effects, whereas the categorical DMC perspective would predict young adults to show larger TSA effects than older adults in the Cue Only task context.

The ANOVA results indicate significant main effects of Task Context, $F(1, 44) = 112.30$, $p < .01$, $\eta^2 = .71$, indicating, expectedly, longer RTs in the Cue Only condition ($M = 1213$ ms, $SE = 20$) compared to the Cue + Operand condition ($M = 1101$ ms, $SE = 19$). There was also a significant main effect of Trial Type, $F(1, 44) = 24.68$, $p < .01$, $\eta^2 = .36$ indicating, as hypothesized, longer RTs in the CBA trials ($M = 1169$ ms, $SE = 18$) compared to the ABA trials ($M = 1145$ ms, $SE = 19$), consistent with TSA (and the absence of TSI). There was also a main effect of Age Group, $F(1, 44) = 15.11$, $p < .01$, $\eta^2 = .26$, indicating longer RTs for older adults ($M = 1228$ ms, $SE = 26$) compared to young adults ($M = 1085$ ms, $SE = 26$). Further, two marginally significant two-way interactions were observed. First, Task Context marginally interacted with Trial Type, $F(1, 44) = 3.80$, $p = .06$, $\eta^2 = .08$, indicating marginally higher TSA in the 'Cue Only' condition (34 ms) compared to the 'Cue + Operand' condition (13 ms). Second, Task Context marginally interacted with Age Group, $F(1, 44) = 3.27$, $p = .07$, $\eta^2 = .07$, indicating marginally longer RTs for older adults between Cue Only and Cue + Operand task contexts (131 ms difference, $t(22) = 4.71$, $p < .01$) compared to young adults (93 ms difference, $t(22) = 3.34$, $p < .01$), $d = .48$. Contrary to the *categorical* predictions from the DMC framework, the Trial type X Age Group interaction and 3-way interaction were non-significant (ps $\geq .44$). Together, the results indicate that TSA effects are observable in proactive control contexts, and young and older adults showed comparable TSA effects. Additionally, older adults showed marginal age-related costs while transitioning from 'Cue Only' to 'Cue + Operand' task contexts.

To test the final hypothesis that young and older adults differ in their ability to utilize the cue information and then ignore it when the probe information conflicts, the mean RTs were subjected to a 2 x 2 x 2 mixed-factorial ANOVA with Age Group as a between-subjects factor, Mixed Task Context (Cue + Operand, Invalid Cue + Operand), and Trial Type (ABA, CBA) as the within-subjects factors. Based on the *categorical* predictions made from the DMC framework, one would expect that both young and older adults should be equally able to respond in the Cue + Operand condition. Additionally, older adults should exhibit a TSA advantage and no evidence of TSI in the Invalid Cue + Operand condition if their tendency is not to use the cue information. Note that the efficient suppression of cue-related information in the Invalid Cue +

Operand condition leads to TSA. However, if young adults can *downregulate* proactive control, no age-related differences should be observed across the Mixed task contexts.

The ANOVA results revealed a significant main effect of Task Context, $F(1, 44) = 38.11$, $p < .01$, $\eta^2 = .46$, indicating expectedly longer RTs in the Invalid Cue + Operand condition ($M = 1118$ ms, $SE = 17$) compared to the Cue + Operand condition ($M = 1100$ ms, $SE = 18$). There was also a significant main effect of Age, $F(1, 44) = 12.80$, $p < .01$, indicating, longer RTs for older adults ($M = 1173$ ms, $SE = 25$) compared to younger adults ($M = 1046$ ms, $SE = 25$). There were no significant main effects of Trial Type ($p = .09$), nor 2-way or 3-way interactions ($ps \geq .14$). Together, the main effects and the lack of age-related interactions indicate that both young and older adults show comparable utilization and suppression of cue-related information. Additionally, the both age groups show comparable *costs* while transitioning between Cue + Operand and Invalid Cue + Operand task contexts.

Taken together, as hypothesized, the above results indicate, first, TSI effects are observable in reactive control task contexts (i.e., Operand Only). Second, proactive control (i.e., Cue Only, Cue + Operand) overrides TSI. Third, both age groups show comparable TSA and TSI effects (Figure 2.3). Shedding more light on the global control strategy employed by both age groups, young adults show higher costs while transitioning from Invalid + Cue to Operand Only task contexts (young = 60 ms; older adults = 30 ms) indicating age-differences in reactive control in favour of older adults. Whereas older adults show the opposite pattern, marginally higher costs while transitioning from Cue Only to Cue + Operand task contexts (young = 93 ms; older adults = 131 ms) indicating age-differences in proactive control in favour of young adults.

Somewhat ambiguous from the Experiment 1 results is a large slowdown in the Cue Only condition compared to other task contexts, especially in older adults. This might reflect an under-use of the cue information until it became necessary to recall in the absence of an operand. If so, the Cue Only condition might not be a clear assessment of high proactive control. To address this ambiguity, we capitalized on an important prediction from the DMC framework, that subtle variations in global task context should influence the relative use of the dual control processes. Therefore, in Experiment 2, our goal was to encourage the greater use of proactive control with a change in global task context, namely by making the cue information more salient in the Cue Only condition.

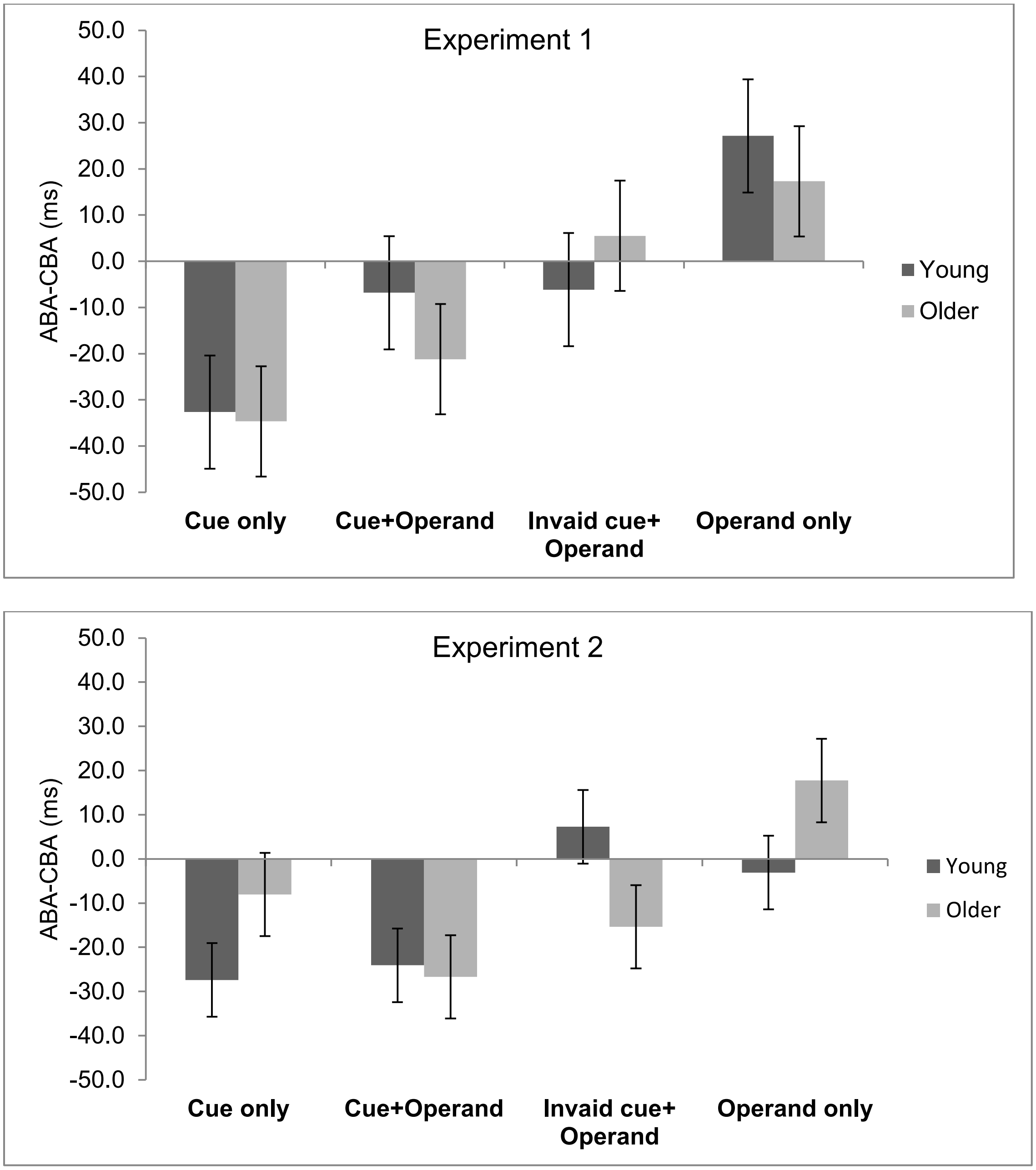


Figure 2.3. The graphs on the top and bottom depict task-set activation and task-set inhibition across both age groups in Experiment 1 and 2 respectively. The X-axis represents the task context. The Y-axis represents the difference score in milliseconds (with standard error) between the third trials of AB<u>A</u> and CB<u>A</u> sequences. Positive and negative values reflect task-set inhibition and task-set activation respectively.

Experiment 2

In Experiment 2, we increased the proactive control bias of the first condition (Cue Only) by increasing cue salience (Fig. 1 Panel 2). Our assumption was that the more salient cue in the first condition would alter the global task context to be more proactive, thus increasing the utilisation of cue-related processes across both age groups. Accordingly, from the continuum viewpoint, we hypothesized that both young and older adults would alter their global mode of control in light of the new task context. In line with the previous training studies for older adults (Braver et al., 2009), a salient cue in the Cue Only condition would necessitate a greater modulation of proactive control. Therefore, we predicted that older adults would show a *downregulation* of proactive control across the four task contexts, thus mimicking young adults' data from Experiment 1. Accordingly, we predicted that older adults' TSA and TSI should closely resemble those of younger adults, whereas young adults' data should closely resemble those of older adults in Experiment 1.

Method

Participants. A new sample of 25 young adults (52 % females and 48 % males*, M* = 22 years, *SD* = 3.2) was recruited from the Psychology participant pool at Concordia University, and 25 older adults (64 % females and 36 % males *M* = 68, *SD* = 4.1) were recruited from the Montreal community using the same inclusion and exclusion criteria. Young adults received partial course credit as compensation and older adults received a $20 honorarium. The data from one older adult and two younger adults were classified as outliers and excluded from further analysis.

Materials and Procedure. All materials and background measures were the same as in Experiment 1 with the exception of the small change to the cues presented in Cue Only trials of the CMT. The participants were told that if the cue appeared in a box, the subsequent equation would not contain an operand. We assumed that this would encourage the use of working memory in the Cue Only condition, thereby impacting the global control strategy across both age groups.

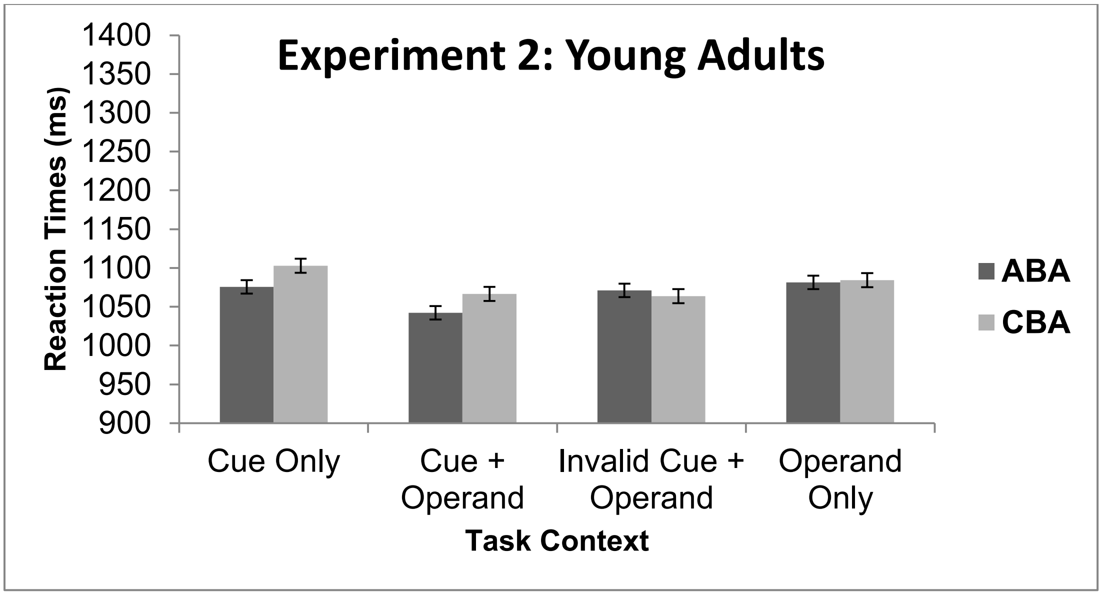
Results and Discussion

Background measures. The background measures were normally distributed with acceptable values of skewness and kurtosis. Descriptive statistics and group contrasts for the background measures are shown in Table 2.2. Replicating Experiment 1, age-related differences were observed on completion times on the WAIS Digit Symbol Substitution test (favoring the younger adults) and the background Math task (favoring the older adults). No age-related differences were observed in the other background measures.

Computerized Math task (CMT). The median RTs on the CMT were normally distributed and the split-half reliability estimates for all the trial types on the CMT were within the acceptable range (.85 to .97). With respect to overall error rates, both age groups showed moderate to high accuracy (> 90%) with no significant differences between young ($M = .07$, $SD = .04$) and older adults ($M = .06$, $SD = .06$), $t(44) = 1.50$, $p = .14$, $d = .45$. Additionally, bivariate correlations between RTs and error rates across both age groups ($r_{\mathrm{YA}}(25) =.16$, $p =.44$, $r_{\mathrm{OA}}(22) =.28$, $p = .20$) showed no evidence of speed-accuracy trade off. Figure 2.4 shows mean RTs for all trial types on the CMT.

To replicate the hypothesis that TSI can be observed in reactive control task contexts, the mean RTs were subjected to a 2 x 2 x 2 mixed-factorial ANOVA with Age Group as a between-subjects factor, Reactive Control Task Context (Invalid Cue + Operand, Operand Only), and Trial Type (AB<u>A</u>, CB<u>A</u>) as the within-subjects factors. The ANOVA results indicate significant main effects of Task Context, $F(1, 43) = 15.11$, $p < .01$, $\eta^2 = .46$, replicating Experiment 1 findings, and indicating longer RTs in the Operand Only condition ($M = 1203$ ms, $SE = 19$) compared to the Invalid Cue + Operand condition (M = 1175 ms, $SE = 17$). There was also a significant main effect of Age Group, $F(1, 43) = 41.65$, $p < .01$, $\eta^2 = .50$ indicating, longer RTs for older adults ($M = 1173$ ms, $SE = 25$) compared to younger adults ($M = 1046$ ms, $SE = 25$). There were no other significant main effects or 2-way interactions (ps $\geq .19$). However, there was significant 3-way interaction indicating that only older adults (older = 18 ms; younger = -3 ms) showed TSI effects in the Operand Only condition ($d = .70$).

To replicate the hypothesis that Proactive control overrides persistent TSI, the mean RTs were subjected to a 2 x 2 x 2 mixed-factorial ANOVA with Age Group as a between-subjects factor, Task Context (Cue Only, Cue + Operand), and Trial Type (AB<u>A</u>, CB<u>A</u>) as the within-subjects factors. The ANOVA results indicate significant main effects of Task Context, $F(1, 43) = 23.1$, $p < .01$, $\eta^2 = .35$, replicating Experiment 1 findings, in that RTs were longer in the Cue Only condition ($M = 1224$ ms, $SE = 17$ compared to the Cue + Operand condition ($M = 1170$ ms, $SE = 19$). There was also a significant main effect of Trial Type, $F(1, 43) = 14.23$, $p < .01$, $\eta^2 =$



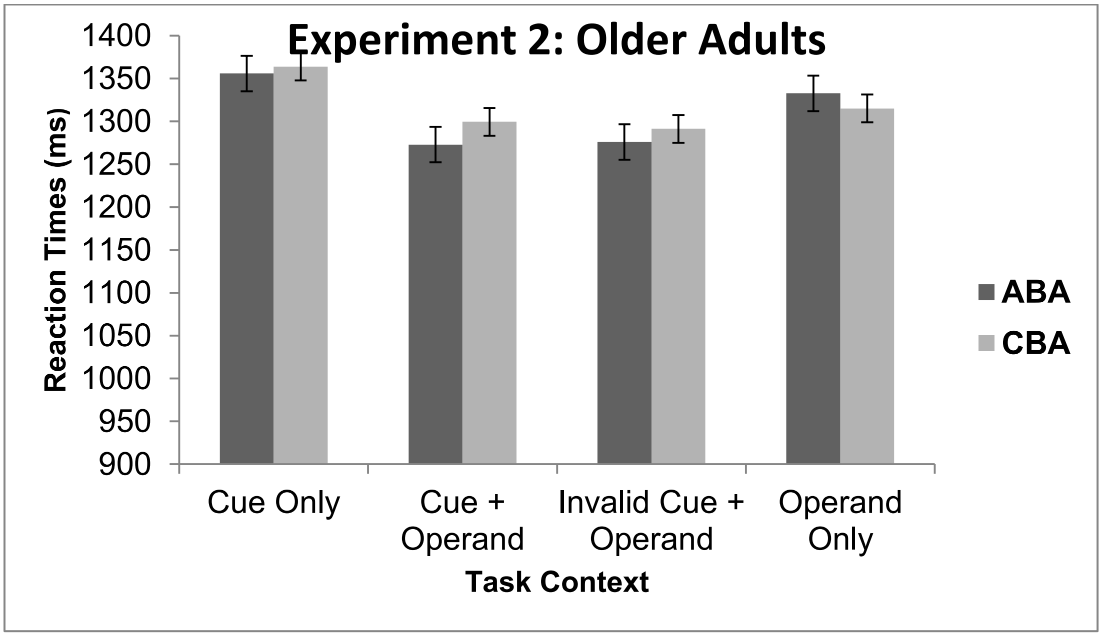


Figure 2.4. The graphs on the top and bottom depict young and older adults' mean reaction times (ms), calculated based on the individual median reaction times, on the Computerized Math Task (CMT) respectively. The error bars depict 1 Standard Error. ABA and CBA refer to triplet trials, and reaction times on the third trial of the sequence.

.25 replicating Experiment 1 findings, in that RTs were longer in the CBA trials (M = 1208 ms, SE = 18) compared to the ABA trials (M = 1187 ms, SE= 17).

There was also a significant main effect of Age Group, $F(1, 43) = 54.45$, $p < .01$, $\eta^2 = .56$, indicating longer RTs for older adults (M = 1332 ms, SE = 25) compared to younger adults (M = 1072 ms, SE= 24). There was no significant 3-way interaction (ps ≥ .23) indicating age-equivalence in recruiting proactive control and replicating Experiment 1 findings. Importantly, compared to Experiment 1 findings, a lack of significant 2-way interactions (Age Group X Task Context) indicates that both age groups show comparable transition costs between Cue Only and Cue + Operand conditions.

To test the final hypothesis whether young and older adults differ in their ability to utilize the cue information and then ignore it when the probe information conflicts, the mean RTs were subjected to a 2 x 2 x 2 mixed-factorial ANOVA with Age Group as a between-subjects factor, Mixed Task Context (Cue + Operand, Invalid Cue + Operand), and Trial Type (ABA, CBA) as the within-subjects factors.

The ANOVA results indicate significant main effects of Trial Type, $F(1, 43) = 5.7$, p =.02, $\eta^2 = .12$, indicating longer RTs in the CBA trials (M = 1165 ms, SE = 17) compared to the ABA trials (M = 1180 ms, SE= 17). There was also a significant main effect of Age Group, $F(1, 43) = 40.35$, $p < .01$, $\eta^2 = .48$, indicating longer RTs for older adults (M = 1284 ms, SE = 25) compared to younger adults (M = 1060 ms, SE= 24). However, compared to Experiment 1, there was no significant main effect of Task Context ($p = .40$). There was a significant two-way interaction of Task Context and Trial Type, $F(1, 43) = 5.73$, $p = .02$, $\eta^2 = .12$, indicating that the TSA effects were more pronounced in the Cue + Operand condition (25 ms) relative to the Invalid Cue + Operand condition (1 ms). There were no other significant 2-way or 3-way interactions (ps ≥ .20), indicating age-equivalence in cue utilization and cue suppression, replicating Experiment 1.

Together, the above results replicate the Experiment 1 findings in that proactive control overrides TSI. An important finding from Experiment 2 is that TSI effects were observable in reactive control task contexts only in older adults. Importantly, young and older adults showed comparable performance in utilizing cue-related processes (proactive control) as well as suppressing invalid cue-related information (reactive control).

General Discussion

The main aim of the current study was to reconcile the age-equivalent TSI findings in the extant literature with the predictions made from the DMC framework. The results from the two experiments unambiguously indicate that TSI effects are observable in reactive control contexts, and that proactive control overrides persistent TSI. A novel feature of the current study was to examine the age-related TSI effects in the context of a proactive-reactive continuum. Consistent with the continuum viewpoint, young and older adults appear to show flexibility in recruiting the dual control processes to match the global task context. Notably, when the global task context elicited more proactive control (i.e., increased cue salience in Expt. 2), the older adults' performance resembled that of the younger adults without the enhancement of cue salience (i.e., Expt. 1).

Task-set Inhibition and Proactive-Reactive Continuum

To resolve the ambiguity of age-related TSI effects found in the literature, we hypothesized that TSI may be a low-level process, and should be observable in reactive probe-based contexts. We have argued that traditional measurements of TSI in the literature have invariably used valid cue-based paradigms, thus masking the possible role of reactive control in TSI effects. Additionally, there are a handful studies that have examined TSI in probe-based contexts (e.g., Mayr & Keele, 2000; Hübner et al., 2003), and the results from these studies are difficult to interpret (Koch et al., 2010). To rectify the situation, we measured the TSI effects in four distinct task contexts that are assumed to reflect varying degrees (high, low) of proactive and reactive control demands.

According to the proactive-reactive continuum viewpoint, the dual control processes are assumed to operate seamlessly to resolve the *stability-flexibility dilemma* (Goschke, 2000). The function of reactive control is to suppress the proactive interference (PI) from previous task sets on a transient trial-to-trial basis, as reflected by N-2 repetition costs; whereas the functional role of proactive control is task activation and maintenance, and overriding persistent TSI. Consistent with these assumptions, the first important finding from both experiments is that the contrasts of high versus low reactive control unambiguously showed that TSI effects are observable in low reactive control contexts (i.e., operand only). The second important finding is that the contrasts of high versus low proactive control unambiguously showed TSA effects, indicating that proactive control overrides TSI. The latter finding is consistent with neuroimaging evidence in which lateral PFC activation (i.e., proactive control) was implicated in overcoming the residual inhibition from a recently performed task (Dreher & Berman, 2002). A novel finding from Experiment 2 is that with cue saliency manipulation, only older adults' show TSI effects in low reactive task contexts. Taken together, these findings support the emerging viewpoint in the literature (Koch, et al., 2010) that TSI may not be an executive inhibitory process targeting proactive interference (PI) from the previous task sets, but may reflect an automatic control process invoked reactively (Goschke, 2000). This interpretation also sheds light on the potential role of the dual control processes in resolving the stability-flexibility dilemma (Goschke, 2000).

Task-set Inhibition and Aging

The main impetus for the current study was to address the Mayr's (2007) original question regarding the functional role of TSI in the context of age differences. The Experiment 1 findings demonstrate age-equivalent TSI effects, replicating previous research. However, in Experiment 2, age-related TSI differences favoring older adults is a novel finding, and potentially sheds further light on the proactive-reactive continuum perspective.

According to the continuum view point, young and older adults are expected to modulate the dual control processes to match the global task context. To discern the modulation of the dual control process, one must examine the Age Group x Task Context interaction effects. To illustrate, the Age Group x Task Context interactions from Experiment 1 indicate that older adults had disproportionately longer RTs in the high proactive control (i.e., Cue Only) compared to low proactive control (i.e., Cue + Operand). Similarly, young adults show disproportionately longer RTs in the low reactive control (i.e., Operand Only) compared to high reactive control (i.e., Invalid Cue+ Operand). These age-related transition costs across the same control process (Young: reactive; Older: proactive) suggest that young and older adults were modulating their dual control processes differently. Furthermore, a visual inspection of the median RTs in Experiment 1 indicates that young adults showed comparable RTs between the extreme task contexts (high proactive and low reactive), whereas median RTs for older adults showed the longest RTs in the high proactive control condition, and comparable RTs across the other three task contexts.

Taken together, the pattern of results indicates two possibilities with respect to the modulation of the dual control processes. First, young adults may be using a *higher degree* of proactive of control as a global strategy, thereby impacting their RT performance on the low reactive control task context (Operand Only). Similarly, older adults may have underused the cue information until it became necessary, thereby using a *lower degree* of proactive control as a global control strategy (Cue Only). These interpretations are consistent with the categorical predictions made from the DMC framework and AX-CPT age-related findings.

The second possibility is that, compared to older adults, young adults were better able to downregulate proactive control to match the global task context, but were at a relative disadvantage while downregulating reactive control (i.e., in the Operand Only condition). The latter interpretation is consistent with a recent neurophysiological study (Staub, Doignon-Camus, Bacon, & Bonnefond, 2014) that examined ERP indices of dual control processes while performing a sustained attention Go/No-Go task. The behavioral and ERP indices indicate that older adults were able to sustain proactive control across time, whereas young adults exhibited downregulation of proactive control (Staub et al., 2014). Importantly, irrespective of the degree of proactive control exercised or modulated, both age groups in the Experiment 1 showed comparable TSI effects in the low reactive task context. This indicates that that TSI effects were less sensitive to the degrees of proactive control in Experiment 1.

In Experiment 2 we increased in the cue saliency in the high proactive task context, thereby compelling participants to alter their global control strategy. A key finding from Experiment 2 is that only older adults' showed TSI effects in the low reactive condition. The lack of significant Age Group x Task Context interactions and the similar pattern of RT data between young and older adults indicate that both age groups were modulating the dual control processes similarly. However, we note that compared to Experiment 1, older adults show disproportionally longer RTs in Experiment 2. Furthermore, a visual inspection of the age-related differences in TSA between experiments (Fig. 3) indicates a near reversal of age-related TSA effects across the high/low proactive control contexts. Given these patterns, it appears likely that with cue saliency effects in Experiment 2, young and older adults were downregulating reactive and proactive control respectively, to match the global task context, thus mirroring each other's RT distributions. Therefore, one can attribute the absence of TSI effects in young adults to greater downregulation of reactive control, or alternately, interpret the presence of TSI effects in older adults to age-equivalent downregulation of proactive control. Note that the lack of TSI in the low reactive control condition (i.e., Operand Only) indicates higher levels of probe-based activation. Taken together, the results from both experiments indicate that age-related differences in modulation of the dual control processes may be a key determinant of age-related differences in TSI.

These novel behavioral findings elucidate the role of the DMC framework within the TSI paradigm, and demonstrate the flexible nature of the dual processes across both age groups. Importantly, we replicate the previous strategy training studies (e.g., Braver, Paxton, Locke, & Barch, 2009) by demonstrating that increasing cue salience led older adults to exert proactive control. Additionally, the lack of age sensitivity to cue validity/invalidity is consistent with previous research (Giraudeau et al., 2016).

We acknowledge the possibility that our method of randomization of task contexts led to carry over effects, thus making the interpretation of age-related findings less clear. Additionally, the cue salience manipulation in Experiment 2 could have led to perceptual priming (e.g., Logan & Bundesen, 2003), thus confounding the validity of the proactive control exerted in the high proactive control (Cue Only) task context. Importantly, the modulation of the dual control processes is somewhat less parsimonious compared to the categorical predictions made from the DMC framework. Nevertheless, we believe that the randomization of the four task contexts compelled participants to adopt a global control strategy, which was expected to override carry over effects, as well as trial-specific proactive and reactive demands. Given that older adults showed overall longer RTs in Experiment 2 compared to Experiment 1, it is more likely that the cue salience manipulation led to higher exertion of proactive control, as perceptual cue priming interpretation would predict the opposite (i.e., older adults would be facilitated). To our knowledge, this is one of the very few studies that has examined the dual control processes from a continuum viewpoint. Future research is needed using other attentional paradigms to further generalize the continuum viewpoint.

CHAPTER 5

GENERAL DISCUSSION

Overview

The main aim of this dissertation is to clarify the nature, function, and age effects of task-set inhibition (TSI; Mayr & Keele, 2000; Mayr, 2001) based upon the Dual Mechanisms Control theory (DMC; Braver et al., 2007). As elaborated in the General Introduction, the major goals of cognitive aging research are to identify the core cognitive processes that are essential to everyday functioning, and examine whether these processes are susceptible to age-related declines. To this end, over the past three decades, the prominent cognitive aging theories in the field (e.g., Hasher et al., 2007; Kane et al., 2007) have attempted to conceptualize the core cognitive processes that modulate higher-order executive functions (EFs) such as working memory, task coordination, and response inhibition.

Despite many advances in understanding age-related EF declines, there is no consensus in the cognitive aging literature as to why older adults show no relative age declines in one EF construct, TSI which refers to increased RTs in the task repetition trials (i.e., AB<u>A</u>) compared to task alternation trials (i.e., CB<u>A</u>) (Mayr & Keele, 2000; Mayr, 2001). This is a particularly important research question, as TSI is assumed to promote task flexibility by resisting proactive interference (PI) invoked in a dynamic task context, thus resolving the stability-flexibility dilemma (Goschke, 2000). Additionally, age-related differences in inhibitory processes akin to TSI are implicated in age-related declines in episodic and working memory (e.g., Hasher et al., 2007).

To answer this research question, drawing from my previous research (Vadaga et al., 2015), I proposed that TSI could be fruitfully examined by using the DMC theory. I argued that lack of age-related TSI differences in the extant research can be parsimoniously resolved by conceptualizing TSI as a low level automatic inhibitory process (Houghton et al., 2009) which is age invariant. From the DMC framework, this implies that TSI may be an after effect of reactive control. However, a major impediment in validating this assumption is that the traditional measurement of TSI has invariably invoked proactive control, thus masking the potential role of reactive control in TSI.

Study Rationale and Summary of the Findings

To rectify the above mentioned limitation, in Study 1, I examined the age-related TSI effects in varied reactive control task contexts. To this end, I developed a non-cueing task switching flanker paradigm and measured TSI in terms of N-2 repetition costs and Lag -1 facilitation effects. The theoretical aims of this study were to validate that both these indices measure TSI, and examine whether young and older adults show age-equivalent TSI effects in both high and low reactive control task contexts. Consistent with the first assumption, the correlational results indicate a robust negative association between N-2 repetition costs and the Lag -1 facilitation effects, across both the age groups. To my knowledge this is the first study to demonstrate such an association, thus bridging the gap between two traditional measurements of TSI. Another important finding from this study is that in the unflanked condition (i.e., ABA vs. CBA) both age groups showed robust TSI effects, replicating previous research (Mayr 2001; Lawo, Philipp, Schuch, & Koch, 2012; Schuch, 2016). However, in the flanked condition (i.e., Lag -1 vs. Lag -2 comparison) only young adults showed robust Lag -1 facilitation effects, indicating an age-related TSI advantage in favour of young adults. This is a novel finding, and is in opposition to the categorical predictions made from the DMC framework (i.e., age equivalence in reactive control), and indicates that young and older adults are utilizing reactive control differentially.

To elaborate, the empirical convergence between the N-2 repetition cost and Lag-1 facilitation strengthens the argument that the TSI effects are truly inhibitory in nature (Mayr 2007; Koch et al., 2010), and refutes other rival explanations postulated in the literature, such as perceptual priming and activation-based accounts that would predict the opposite results (i.e., Lag-1 costs, and N-2 facilitation effects). The observed negative correlations between both operationalizations of TSI, in both age groups, also indicate the ‘persistent’ nature of TSI across the task switching trials (Mayr, 2007). For instance, N-2 repetition cost is a measurement of TSI at later time point (i.e., the presence of two intervening trials before the onset and the measurement of inhibition). In comparison, the Lag-1 facilitation effect involves measuring the inhibition one trial after its onset. According to the time course hypothesis, one may assume that both young and older adults show a similar (peak) magnitude of TSI after two intervening trials, but compared to young adults, older adults are sluggish in initiating TSI, as measured after one intervening trial. This interpretation is consistent with time course research on inhibition (e.g., inhibition of return), in which older adults show a delayed onset of inhibition (Castel, Chasteen, Scialfa, & Pratt, 2003). However, the very few studies that have examined the time course of TSI in young and older adults demonstrated age-equivalent TSI effects across different delays (Li & Dupuis, 2008), thus further experiments with a direct manipulation of cue-probe intervals may be warranted.

Within the DMC framework, it is assumed that the flanker trials would impose larger perceptual demands and interference, compared to the unflanked trials, thus invoking a higher degree of reactive control. Given the assumed age equivalency in reactive control, in a typical block design, the categorical predictions from the DMC framework would expect age equivalent TSI effects across both the reactive control task contexts. However, in mixed task contexts, in which local task demands (i.e., high/low reactive control) vary with global task context (i.e., overall reactive bias), it is assumed that each age group should modulate the reactive control process differentially. Accordingly, one may interpret age-related differences in TSI to higher exertion (i.e., upregulation) of reactive control in response to reactively biased global task context by young adults, compared to older adults. This interpretation is line with the idea that both young and older adults show flexibility in modulating the dual control processes in response to global task context (Braver et al., 2009; Paxton, et al., 2008). However, one clear limitation of Study 1 is that TSI effects were measured exclusively in reactive control task contexts, thus precluding the use of proactive control due to the absence of cues. This implied that in the Study 1 design, it was not possible to examine both proactive and reactive control processes in predicting age differences in TSI.

As mentioned earlier, the traditional measurement of TSI has invariably invoked proactive control. To illustrate, in the conventional task switching methodology, the presented stimulus (e.g., ‘6’) is either bivalent (i.e., odd/even or magnitude judgment) in two task situation, or trivalent in three task situations. Therefore, task selection must be executed based on prior information, in the form of valid task cues (e.g., cue-based paradigms), or information held in working memory (e.g., in *alternating runs paradigm*; Rogers & Monsell, 1995) thus inadvertently invoking proactive control. As such, any TSI effects observed in these paradigms are attributed to efficiency in proactive control (Mayr, 2007; for review see, Koch et al., 2010). An alternate approach is to measure TSI in both proactive and reactive control task contexts. In this attempt, a typical blocked design will test the DMC theory’s categorical predictions. In contrast, a mixed design allows one to examine how young and older adults are utilizing the dual control processes in relation to global task context. The latter approach is not only ecologically valid, but also sheds light on the interaction between the dual control processes.

To this end, in Study 2, comprising two similar experiments, I examined the age-related TSI effects across varied proactive and reactive control contexts (i.e., high proactive, low proactive, high reactive, and low reactive) thereby operationalizing the dual processes on a continuum. The continuum idea is derived from the assumption that proactive and reactive control constitute two opposite poles of a single control dimension differing in goal maintenance and conflict resolution demands (e.g., early- versus late- selection and correction, sustained versus transient control, voluntary versus automatic control, top-down versus bottom up processing) (Bugg, 2016; Gonthier, Braver, & Bugg, 2016). A key aspect of this design was that the four task contexts were equally represented to equate for the local trial-by-trial demands. However, the four task contexts were also intermixed, thereby compelling participants to adopt a global control strategy to match the global task context. Note that the global task context in Study 2, Experiment 1, was reactively biased as a result of the ratio of invalid cue-probe pairs, whereas in Experiment 2, the cues were made more salient in one task context (i.e., high proactive) to bias the global task context to be more proactive. Consistent with the hypothesis, that proactive and reactive control operate seamlessly to resolve the stability-flexibility dilemma by overriding and invoking TSI respectively, the overall results indicate N-2 repetition costs (i.e., TSI) in reactive control task contexts, replicating the Study 1 findings; and N-2 repetition benefits (i.e., task-set activation; TSA) in proactive control task contexts. These findings are in line with neuroimaging evidence in which lateral PFC activation (i.e., proactive control) was implicated in overcoming the residual inhibition from a recently performed task (Dreher & Berman, 2002).

The most important finding from Study 2 is that young and older adults were utilizing the dual control processes differently. For example, in Experiment 1, when the overall task context was reactively biased, young adults showed similar RTs across the mixed task contexts (i.e., Cue + Operand and Invalid Cue+ Operand), and relatively larger RTs in the *pure* task contexts (i.e., Cue only and Probe only). Shedding more light on the global control strategy employed by both age groups, Task Context X Age Group comparisons of high and low reactive control conditions indicate that compared to older adults, young adults showed disproportionately longer RTs in low reactive control (i.e., Probe only) relative to high reactive control (Invalid cue + Operand) (young = 60 ms; older adults = 30 ms) conditions. Whereas older adults show the opposite pattern: marginally longer RTs in high proactive (i.e., Cue only) relative to low proactive control (i.e., Cue + Operand) conditions (young = 93 ms; older adults = 131 ms), indicating age-differences in proactive control in favour of young adults.

This pattern of results indicates that young adults may have downregulated proactive control across the proactive-reactive continuum to match the reactively biased global task context, but were at a relative disadvantage while utilizing reactive control in the Operand Only condition. This interpretation is consistent with a recent neurophysiological study (Staub et al., 2014) that examined ERP indices of dual control processes while performing a sustained attention Go/No-Go task. The behavioral and ERP indices indicated that older adults were able to sustain proactive control across time, whereas young adults exhibited downregulation of proactive control (Staub et al., 2014). Conversely, In Experiment 2, when the global task context was altered to be more proactive, young and older adults exhibited comparable patterns of RTs across the four task contexts, thus mirroring each other's RT distributions. However, compared to Experiment 1, older adults showed disproportionately longer RTs overall in Experiment 2, suggesting a greater utilization of proactive control compared to Experiment 1. Furthermore, a visual inspection of the age-related differences in TSA between experiments (Fig. 2.3) indicates a near reversal of age-related TSA effects across the high/low proactive control contexts. Given these patterns, compared to Experiment 1, one can attribute the absence of TSI effects in young adults to greater utilization of reactive control in the low reactive control condition, thereby facilitating increased probe-based activation. Alternatively, one can interpret the presence of TSI effects in older adults to a greater utilization of proactive control, and equivalent utilization of reactive control compared to Experiment 1.

Taken together, the findings from Study 1 and Study 2 indicate that TSI may be a low level inhibitory process that is observable in reactive control task contexts. Additionally, age-related TSI effects are consistent with the differential utilization of the dual control processes in relation to global task context. Notably, when the overall task context was reactively biased, young adults appear to upregulate reactive control (i.e., Study 1) and possibly downregulate proactive control (i.e., Study 2, Experiment 1). However, in Study 2, Experiment 2, when the task cue was made more salient only in one condition (i.e., Cue only), older adults appears to utilize proactive control similarly to young adults. Overall, these findings provide converging support for the idea that young and older adults show flexibility in modulating dual control processes.

Study Limitations

Many of the conceptual issues raised in current research are confronted with some theoretical and methodological issues. First, although the construct of inhibition has been widely invoked to explain various empirical findings in attention and memory paradigms, there is no consensus in the cognitive and aging literature, as to whether the observed empirical effects are truly inhibitory in nature (MacLeod, 2007). Many non-inhibitory explanations have been proposed in the literature, including episodic retrieval (Neill & Mathis, 1998), sequential expectancies, cue/perceptual priming (e.g., Logan & Bundesen, 2003), among others to account for the broader inhibitory phenomena including TSI findings. To illustrate, according to the episodic retrieval view, participants routinely check their memory for relevant information that might help with current processing. Therefore in Study 1, when the recently executed task becomes distractor in the next trial (i.e., lag -1), the memory indicates that flanker information has to be responded to because of its fate in the previous trial, whereas the stimulus display (i.e., flanked trial) indicates ignoring of the flanker information. Resolving this conflict takes time that manifests as Lag -1cost. However, given that young adults show robust Lag -1 facilitation, it is unlikely that episodic retrieval view satisfactory explains the study 1 findings. Similarly, one could argue that the cue salience manipulation in Study 2, Experiment 2 could have led to perceptual priming, thus confounding the validity of the proactive control exerted in the high proactive control (Cue Only) task context. However, given that older adults showed overall longer RTs in Experiment 2 compared to Experiment 1, it is more likely that the cue salience manipulation led to a greater utilization of proactive control, as the perceptual cue priming interpretation would predict the opposite (i.e., older adults would be facilitated).

Second, the proactive-reactive continuum hypothesis is a nascent conceptualization, and is validated only in a handful of studies (e.g., Bugg, 2016; Gonthier et al., 2016). Additionally, the modulation of the dual control processes carry many more assumptions compared to the DMC theory’s categorical predictions. Therefore, in my view, a more comprehensive investigation is warranted using other test paradigms to validate the current findings. Third, at a measurement level, mixed designs carry a risk of carry-over effects from trial to trial, which might either inflate or obscure the age-related differences. Nevertheless, it should be noted that the randomization of the four task contexts compels participants to adopt a global control strategy, which was expected to override carry-over effects, as well as trial-specific proactive and reactive demands.

Theoretical Contributions and Future Research

Despite the above-mentioned limitations, the current research makes several novel contributions to the research on aging and cognitive control. To my knowledge this is first study to examine the nature, function and age-related variance in TSI based on the predictions made from the DMC framework. To this end, the current study makes some specific theoretical and methodological contributions to the TSI literature, DMC theory, and cognitive aging research.

First, the overall findings suggest that TSI is a ubiquitous inhibitory process in task switching, and is invoked reactively, to promote task flexibility. As such, any observed age-related TSI differences are not reflections of declines in inhibitory or executive processes per se, but rather indicate that young and older adults utilize the dual control processes differentially, which in turn is determined by the global task context. These interpretations parsimoniously resolve the age-related ambiguity in the TSI literature, and encourage researchers to use the DMC theory to examine other age-related discrepancies in the EF research.

Second, the present findings extend the DMC framework by operationalizing the dual control processes on a proactive-reactive continuum (Bugg, 2016; Gonthier et al., 2016). Compared to the DMC theory's categorical predictions concerning age effects (e.g., age constancy in reactive control, and age-related declines in proactive control), the continuum hypothesis offers a more nuanced approach in explaining age-related ambiguities in EF research. To illustrate, in the task switching literature, age-related declines are observed in global switch costs, but not local switch costs (Kray & Lindenberger, 2000). These age effects are often explained in terms of additional working demands (i.e., selection of two task sets in working memory) imposed in mixed block trails (e.g., <u>AA</u>BA), compared to pure block trials (<u>AA</u>AA) (Mayr, 2001). From the DMC framework, one may interpret the age-related differences in global switch costs to differential modulation of proactive control by young and older adults. That is, in the pure block trials, both age groups are exhibiting equivalent proactive control, but in the mixed block trials, older adults may be downregulating proactive control, to promote task flexibility.

Similarly, in a response inhibition paradigm, age differences are more apparent in mixed blocks (i.e., congruent versus incongruent trials) rather than on pure blocks (i.e., only incongruent) (MacLeod, 1991). According to the DMC framework, the mixed block creates a global task context that requires selective utilization of reactive (congruent trials) and proactive control (incongruent trials) processes. Age-related declines in mixed blocks, therefore, may be due to age-related differences in utilizing the dual control processes. At present these interpretations are speculative, therefore, further research is warranted to examine the influence of global task context in other EF paradigms.

Last, the current research also offers intervention researchers a methodological framework for the development of training protocols that emphasise the modulation of dual control processes by manipulating the global task context. Conventional cognitive training protocols, have utilized either *process-based training* approach (e.g., working memory training) in which cognitive control processes are practiced through different task conditions, or *strategy based training* approaches in which task instructions emphasise the strategy (e.g., inner speech, selective attention to cues, etc.) (Karbach & Verhaeghen, 2014). Based upon the established age-related differences in proactive control (e.g., Braver et al., 2005), training protocols could target this process. The current research (Study 2) offers a possible complement to training proactive control: That is, the increased cue salience appeared to elicit more of proactive control strategy in the older adults. Therefore, a blend of process- and strategy-based approaches may be a fruitful way to remedy age-related cognitive declines.

Conclusion

The current research resolves the age-related TSI ambiguities found in the extant literature by conceptualizing TSI as a low level inhibitory process that is invoked reactively. Additionally, the present work offers a novel way of conceptualizing and operationalizing the dual control processes on a continuum. In my view, the continuum framework has the potential to elucidate how young and older adults utilize the dual processes in optimizing local task demands in the face of global task context. Lastly, further understanding of age-related differences in the modulation of the dual control processes in other EF paradigms has the potential to develop training protocols that can remedy the age-related declines in everyday functioning.

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Appendix A

CONSENT TO PARTICIPATE IN THE TASK-SWITCHING STUDY

This is to state that I agree to participate in a research study being conducted by Kiran Vadaga and Candice Aflalo (514-848-2424, ext. 2247 or karentlilab@gmail.com) under the supervision of Dr. Karen Li (514-848-2424, ext. 7542 or karentlilab@gmail.com) in the Psychology Department of Concordia University.

A. PURPOSE

I have been informed that the purpose of the research is to understand **the cognitive processes involved in Task-Switching.**

B. PROCEDURE

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 background questionnaire. Participants will also complete a computerized test that involves responding to simple arithmetic problems by using the key press response. Also some participants will do a second computerized task that involves setting up a table and cooking a meal. The session will last around 1.5-2 hours. Each participant will receive 2.5 participation pool credits or $20 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 cognitive processes involved in Task-Switching.

D. CONDTIONS OF PARTICIPATION

- I understand that I am free to withdraw my consent and discontinue my participation at any time 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 of by e-mail at areid@alcor.concordia.ca

Appendix B

Debriefing Form

The purpose of this study is to examine age-related differences in task-switching.

During the testing session, you completed a consent form and a brief demographic questionnaire. Before beginning the computer task(s), you were asked to become familiar with simple arithmetic operations. The math computer task began with a series of practice trials and then the actual math computer task was completed. Lastly some participants completed an additional computer task in which they had set a table and cooked a meal.

We thank you for your participation and if you have any questions please feel free to contact Dr. Karen Li, faculty supervisor, at (514) 848-24-24 ext. 7542 or by email at karen.li@concordia.ca.

Suggested Readings:

Vadaga, K. K., Blair, M., & Li, K. Z. (2015). Age-Related Differences Uniform Across Different Inhibitory Functions? *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences,* gbv002.

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Appendix C

Simple Math Task

Please complete the following math operations as quickly and as accurately as you can

Addition

6 + 5 =

8 + 6 =

4 + 7 =

2 + 3 =

9 + 5 =

7 + 8 =

Subtraction

7 - 9 =

5 - 2 =

3 - 8 =

6 - 4 =

8 - 5 =

9 - 3 =

Multiplication

6 * 7 =

8 * 9 =

4 * 4 =

2 * 3 =

5 * 6 =

3 * 8 =

Appendix D

Extended Range vocabulary Test V3 Part I: ID # ________

1. cottontail
a) squirrel
b) poplar
c) boa
d) marshy plant
e) rabbit

2. marketable
a) partisan
b) jocular
c) marriageable
d) salable
e) essential

3. boggy
a) afraid
b) false
c) marshy
d) dense
e) black

4. gruesomeness
a) blackness
b) falseness
c) vindictiveness
d) drunkenness
e) ghastliness

5. loathing
a) diffidence
b) laziness
c) abhorrence
d) cleverness
e) comfort

6. bantam
a) fowl
b) ridicule
c) cripple
d) vegetable
e) ensign

7. evoke
a) wake up
b) surrender
c) reconnoiter
d) transcend
e) call forth

8. unobtrusive
a) unintelligent
b) epileptic
c) illogical
d) lineal
e) modest

9. terrain
a) ice cream
b) final test
c) tractor
d) area of ground
e) weight

10. capriciousness
a) stubbornness
b) courage
c) whimsicality
d) amazement
e) greediness

11. maelstrom
a) slander
b) whirlpool
c) enmity
d) armor
e) majolica

12. tentative
a) critical
b) conclusive
c) authentic
d) provisional
e) apprehensive

13. placate
a) rehabilitate
b) plagiarize
c) depredate
d) apprise
e) conciliate

14. surcease
a) enlightenment
b) cessation
c) inattention
d) censor
e) substitution

15. apathetic
a) wandering
b) impassive
c) hateful
d) prophetic
e) overflowing

16. paternoster
a) paternalism
b) patricide
c) malediction
d) benediction
e) prayer

17. opalescence
a) opulence
b) senescence
c) bankruptcy
d) iridescence
e) assiduity

18. lush
a) stupid
b) luxurious
c) hazy
d) putrid
e) languishing

19. curtailment
a) expenditure
b) abandonment
c) abridgment
d) improvement
e) forgery

20. perversity
a) adversity
b) perviousness
c) travesty
d) waywardness
e) gentility

21. calumnious
a) complimentary
b) analogous
c) slanderous
d) tempestuous
e) magnanimous

22. illiberality
a) bigotry
b) imbecility
c) illegibility
d) cautery
e) immaturity

23. clabber
a) rejoice
b) gossip
c) curdle
d) crow
e) hobble

24. sedulousness
a) diligence
b) credulousness
c) seduction
d) perilousness
e) frankness

Appendix E

Reading Span Sentences

Sets of two:

The house quickly got dressed and went to **work.**

I took a knapsack from my shovel and began removing **the earth.**

Sets of three:

The murky swamp slipped into the waters of the **crocodile.**

The castle sat nestled in the refrigerator above the tiny **village.**

It wasn't all her fault that her marriage was in **trouble.**

Sets of four:

They waited at the water's edge, the raft bobbing up and **down.**

I let the potato ring and ring, but still no **answer.**

The red wine looked like blood on the white **carpet.**

The children put on their closets and played in the **snow.**

Sets of five:

Three of the pillows were dead, and he was **next.**

My escape out of the telephone was blocked by a wire **fence.**

She turned around a sucked in a startled **breath.**

They ran until their lungs felt like they were going to **burst.**

The additional evidence helped the verdict to reach their **jury.**

As a full time university student, he studied **hard.**

The CN tower raced across the sail boat to the finish **line.**

Sets of six:

Trails are supposed to stay on the hikers, but they usually **don’t.**

He stormed out without giving me so much as a backward **glance.**

The paperclip was flaked white and red with **sunburn.**

Returning with an eagle, a branch breaks to land at its **nest.**

A television droned from the dark interior of the **apartment.**

They talked about what the world would be like after the **war.**