Chapter 7. Working memory, executive control and aging

Todd S. Braver and Robert West

Department of Psychology Campus Box 1125
Washington University
Saint Louis, MO 63139
tbraver@artsci.wustl.edu
Phone: 314-935-5143
Fax: 314-935-8790

Department of Psychology
Iowa State University
Ames, IA 50011
rwest@iastate.edu
Phone: 515-294-3950
Fax: 515-294-6424

To Appear In:
The Handbook of Aging and Cognition
Third Edition
Editors: Craik, F.I.M. and Salthouse, T.A.
Psychology Press

Introduction

Research on cognitive aging seems to have three primary goals. First, to determine the extent to which the diversity of observed behavioral changes that occur with advancing age can be potentially explained by a small set of fundamental cognitive mechanisms or "primitives". Second, to thoroughly and explicitly specify the nature of these mechanisms, potentially by drawing links to underlying neurobiology or to more formalized descriptions of how such underlying mechanisms might bring about observable behavioral changes. Finally, to use the knowledge gained in the pursuit of the first two goals to develop effective interventions that can minimize (or ideally, reverse) the effects of cognitive aging.

Studies of working memory and executive control in older adults provide a clear example of these three goals in action, and the potential tension that often arises between them. In particular, over the last decade there has been increasing interest in the role of working memory and executive control as fundamental causes of age-related cognitive change. However, at the same time this research has often been plagued by failures of specification. In particular, it has been difficult to define exactly which cognitive and behavioral processes fall under the purview of working memory and executive control, and thus should be affected by age-related declines in these domains. This definitional imprecision has led to controversy and confusion in the field, with researchers adopting different operational criteria for what constitutes a working memory or executive control task or measure, and with a mixture of results regarding the extent to which such measures either account for age-related variance or differentiate from other mechanistic constructs (e.g., processing speed).

In the current chapter, we review recent research in the area with a focus that is unashamedly influenced by our own theoretical perspective. Specifically, we describe an emerging theoretical framework, that in our view provides a productive middle-ground incorporating both: a) increased specificity in terms of the particular mechanisms of working memory and executive control affected by advancing age; and b) clear linkages to both underlying neurophysiology and to observable behavioral effects across a range of cognitive domains. Thus, our goal for the chapter is to lay out an explicit account of age-related changes in working memory and executive control that both clearly specifies what types of empirical phenomena should be explainable under this account as well as what classes of data should not fall within its purview. This theoretical account, which we refer to as *the goal maintenance account* will then serve as a reference point, from which to review and evaluate the recent literature on working memory and executive control in adults. Critically, we will aim to determine the extent to which this growing literature can be integrated under the goal maintenance account. In the final section, we discuss emerging trends and future research directions that may provide a better test of the theory, or point to ways in which it should be extended or refined. Before describing the goal maintenance theory, we begin by discussing first the historical trends and research approaches prominent in cognitive aging studies of working memory and executive control.

Historical trends in the study of working memory and executive function

The dominant theoretical influence on working memory (WM) research over the past two decades has been the model of Baddeley and colleagues (Baddeley, 1986, 2003). This model gained prominence by suggesting that short-term storage of information was utilized primarily in the service of complex cognitive tasks. Thus, the short-term storage system serves as a temporary workspace from which to keep task-relevant information in a highly accessible form for inspection and computation. This tight integration of the storage and processing components of the WM system provides functionality in higher cognitive domains, such as planning, problem-solving, and reasoning. At the same time, the Baddeley model postulates a structural distinction between the storage buffers and executive control components, which suggests that the two can be studied independently. The model potentially serves as an attractive basis for cognitive aging research, in that one might postulate age-related reductions in relatively circumscribed mechanisms – i.e., the function of the WM storage buffers – as a source for more global impairments in higher cognitive function. Thus, one research strategy is to determine how well reductions in WM storage capacity can account for more general age-related cognitive impairment (Salthouse, 1990). However, a problem with this strategy is that the tasks which seem to best tap into the function of WM storage buffers, the so-called simple or passive span measures (such as digit span), show minimal age-differences (Bopp & Verhaeghen, 2005; F. I. M. Craik, 1977; Zacks, Hasher, & Li, 2000)

An alternative strategy has been to examine age-differences, and their relationship to cognitive performance, with span tasks that require the coordination of short-term storage with the processing capacity of the executive controller. These so-called complex span tasks (such as reading span), do show robust and reliable age-differences (Babcock

& Salthouse, 1990; Bopp & Verhaeghen, 2005). More importantly, a great deal of research has provided evidence that at least some of the age-related deficits in different cognitive domains such as reasoning and language are mediated by performance on complex span tasks (J. T. Hartley, 1986; Light & Anderson, 1985; Salthouse, 2005a; Stine & Wingfield, 1990). Nevertheless, there have been many areas of contention and conflicting findings, such as the degree of reduction in span size, and the extent to which span effects, rather than other constructs such as processing speed, serve as the true mediator of age-related variance in these cognitive domains (Salthouse, 1994; Zacks et al., 2000).

A more serious problem concerns how age differences in complex span measures are interpreted in terms of WM theory. The most natural interpretation is that span effects reflect an age-related decline in WM capacity, that relates to the interaction of storage and control mechanisms. Yet, more recently the WM literature has been moving toward the view that individual and group differences in complex span measures primarily reflect executive processes rather than the storage capacity of the buffers. This view can be seen most clearly in the work of Engle and colleagues, who have suggested that complex WM span tasks correlate with performance in other cognitive domains because of the dependence of these tasks on control processes -- that they term "executive attention" -- rather than because of their demands on short-term storage capacity (R.W. Engle, 2002). Thus, under such a view, age deficits in complex WM span tasks may primarily reflect a decline in executive control abilities (e.g., management of proactive interference, as discussed below under Working Memory), rather than a decline in storage capacity per se. Moreover, a somewhat radical implication of this view is that it is unnecessary, and maybe even not preferable, to utilize WM span tasks at all when measuring age-related cognitive decline in executive control processes. Nevertheless, such age-related declines in executive control may be the main source of impaired performance among older adults in WM tasks.

The recent theoretical developments in WM research just discussed have also prompted a clear shift in the cognitive aging literature, in which there appears to be a greater emphasis on older adult performance in executive control tasks that have no obvious WM storage component, and conversely, in focusing primarily on the executive control components of WM tasks. The focus of the current review will reflect this emerging emphasis in the literature, by focusing on a range of domains of executive control that are enjoying new or renewed research attention. In addition to the variety of domains of executive control that are currently being studied in cognitive aging research, there are also a variety of research approaches being used. We next discuss these distinct research traditions in terms of their similarity and differences in analytic strategy and theoretical perspective.

Approaches to the study of Executive Function and Working Memory

Efforts to understand the effects of aging on executive functions and working memory and to identify the impact of these effects on other aspects of cognition have incorporated a variety of analytic strategies. Rather than trying to provide an exhaustive review of the diverse methodologies that have been applied in this domain of research, we have chosen to focus on three general approaches that have had the widest influence. These include *cross-sectional covariation* studies, wherein the central question is whether age-related variation in measures of executive function or working memory covaries with age-related change in other measures of cognition and functional status (Salthouse, Atkinson, & Berish, 2003); studies of *neurocognition,* that seek to define the functional anatomical or biochemical bases of age-related decline in executive functions or working memory (Cabeza, Nyberg, & Park, 2005); and studies utilizing *process analysis* that are designed to elucidate the cognitive processes that given rise to age-related decline on the performance of various measures of executive function or working memory (e.g.,Fristoe, Salthouse, & Woodard, 1997).

Studies incorporating the cross-sectional covariation approach have been designed to address two fundamentally different questions: 1) to what degree are age-related differences in various domains of cognition mediated by age-related declines in executive functions or working memory (Royall, Palmer, Chiodo, & Polk, 2004; Salthouse, Mitchell, Skovronek, & Babcock, 1989); and 2) what types of processes account for age-related differences in measures of executive function or working memory (Salthouse, 2005b). Early work related to the first question was designed to determine whether there was in fact a relationship between measures of executive function and measures of cognition (F. I. Craik, Morris, Morris, & Loewen, 1990; Parkin & Walter, 1992). Following these early findings, later work using mediated regression, growth curve analysis, and structural equation modeling has demonstrated that age-related declines in episodic memory, activities of daily living, and other measures are mediated by individual differences in executive functions (Royall et al., 2004; Salthouse et al., 2003; Troyer, Graves, & Cullum, 1994).

Probably the most influential proponent of the cross-sectional covariation approach has been Salthouse, who has addressed both of these questions using a variety of analytic methods, most recently including structural equation modeling (Salthouse, 2000; Salthouse et al., 2003). As Salthouse suggests, the strength of the cross-sectional covariation approach is that it typically involves psychometrically robust design features, such as the characterization of the relative amount of age-related variance captured by a particular construct (e.g., executive function) in relationship to other competing constructs (e.g., perceptual speed, reasoning), and the extent to which a particular construct can account for age-related variance even after controlling for other factors that are not of theoretical interest. The cross-sectional covariation approach may be limited by a typical reliance on multiple standardized psychometric measures that are potentially less sensitive indices of executive function constructs. Additionally, the approach is vulnerable to statistical mis-estimation due to the confounding effects of general (rather than covarying) population-level rates of age-related change (Hofer & Sliwinski, 2001). Finally, as discussed below, the psychometric-based measurement approach of individual difference analyses is somewhat in tension with the process-based approach, which aims to fractionate executive control measures into those which most selectively and sensitively index the constructs and mechanisms of age-related cognitive change (Salthouse, 2006).

The neurocognitive approach can be seen as evolving from two lines of scientific inquiry. The first is rooted in neuropsychology and is characterized by incorporation of experimental tasks widely used in the experimental neuropsychological literature (e.g., Wisconsin Card Sort (WCST), self-ordered pointing (SOPT), trail-making, verbal fluency, etc.) to determine what type of neuropsychological profile best characterizes the performance of older adults. Out of this work a fairly clear consensus has arisen that the effects of aging are somewhat greater on cognitive processes supported by the prefrontal cortex than on cognitive processes more heavily dependent on posterior cortex (A. A. Hartley, 1993; Moscovitch, 1992; R. L. West, 1996). More recent work has focused on further distinctions in cognitive aging that can be inferred from differing cognitive profiles associated with different types of frontal lesions (e.g., anterior vs. posterior, left vs. right, lateral vs. medial). For example, there has been some recent suggestion that older adults' cognitive deficits correspond better to a neuropsychological profile associated with lateral vs. medial frontal damage (MacPherson, Phillips, & Della Sala, 2002). A strength of this approach is that it enables a researcher to pick tasks on the basis of evidence that the tasks are dependent on the integrity of particular brain regions. On the other hand, one limitation is that many of the tasks in current usage have reasonably high sensitivity, but not great selectivity, such that behavioral impairments are associated with damage to a number of brain regions and systems. For instance, poor performance on the WCST, that is often associated with damage to the prefrontal cortex (Demakis, 2003; Stuss et al., 2000), is not always differentially diagnostic of frontal versus posterior pathology (S. W. Anderson, Damasio, Jones, & Tranel, 1991).

The second trend in neurocognitive research involves directly assaying the neurobiological effects of aging in the human brain using non-invasive methods. In this approach the goal is to determine the extent to which age-related neurobiological changes can be tightly linked to cognitive changes. One common method is to examine correlations between cognitive function and neuroanatomical or neurochemical markers that are sensitive to age. For example, anatomical brain imaging studies have demonstrated that declines in grey matter volume in prefrontal cortex are associated with cognitive impairments in tasks such as the WCST and Tower of Hanoi (Gunning-Dixon & Raz, 2003; Raz, Gunning-Dixon, Head, Dupuis, & Acker, 1998), while studies of neurochemical markers have demonstrated that dopamine receptor binding accounts for most of the age-related variance in tasks such as self-ordered pointing and trail-making (Backman & Farde, 2005).

Most recently, advances in functional brain imaging have made it possible to directly measure anatomically localized brain activation patterns in older adults that arise during the performance of cognitive tasks, rather than relying on more indirect correlational measures. For example, studies using functional MRI to examine the effects of aging on patterns of neural recruitment associated with working memory and executive functions have revealed some of the most provocative findings to emerge from the literature incorporating the neurocognitive approach (Cabeza, 2002; Reuter-Lorenz & Sylvester, 2005). One strength of this approach is that it has the potential for illuminating whether older adults show the same types of brain-behavior relationships observed in younger adults. Recent findings have suggested that they may not – instead demonstrating patterns of activation that may represent compensation for a reduced ability to meet the demands of cognitively challenging tasks, or alterations in cognitive strategy (Reuter-Lorenz & Sylvester, 2005; Rypma & D'Esposito, 2000).

The final research approach utilizes a cognitive task analysis as a means of more narrowly localizing the processes that give rise to age-related differences in paradigms wherein efficient task performance is determined by multiple factors. The WCST represents an excellent example of such a paradigm (Milner, 1963). In this task individuals are required to sort a series of cards into categories defined by the color, number, or form of stimuli presented on the cards based on a rule that must be abstracted from yes/no feedback that is provided by the experimenter following each sort. The pattern of age-related performance differences in the WCST occur in a variety of measures, and thus could be consistent with a number of interpretations regarding cognitive impairment, such as a decline in category abstraction, an increase in the tendency to perseverate on a category once it becomes irrelevant, or a decline in the ability to utilize feedback (Rhodes, 2004). The task analysis approach attempts to determine which explanation may best account for group differences in task performance, through modification of the basic paradigm. For example, this approach has been used very successfully in developmental studies of children performing variants of the WCST (Diamond, 1998; Jacques & Zelazo, 2001). Similarly, in work with older adults, Fristoe, Salthouse, and Woodard (1997) had individuals perform a modified WCST wherein they indicated with a verbal response what category was being applied on the current sort. This allowed the investigators to consider the consistency of participants' expressed intentions and actions, and to examine possible age-related differences in the use of feedback. The findings of this study revealed that the degree of consistency between intention and action was lower in older adults than in younger adults, and that older adults were less likely to maintain a category after positive reinforcement than were younger adults and more likely to maintain a category after negative reinforcement than were younger adults (Fristoe et al., 1997; Hartman, Bolton, & Fehnel, 2001).

Furthermore, 77% of the age-related variance in a composite index of task performance was accounted for by controlling for individual differences in feedback-usage.

The strength of the task analysis approach is that it provides a means of getting at the core cognitive processes in individual tasks that are associated with age-related decline, such that these processes might be shown to generalize across various different paradigms. Moreover, because this approach respects the maxim that "no task is process pure", researchers adopting it are prompted to search for more sophisticated ways to measure performance in a way that better isolates the process of interest. An example of such measurement approaches are recent trends to using process dissociation analysis and other mathematical modeling methods such as ex-Gaussian estimation of reaction time distributions, to provide better estimates of the cognitive process of interest (Jennings & Jacoby, 1993; Spieler, 2001). Weaknesses of the task analysis approach are that it may serve to identify processes that are quite task specific and therefore, fail to capture a significant portion of age-related variance in cognitive function. Furthermore, by typically focusing on single rather than multiple tasks (in contrast to the cross-sectional covariation approach) the process analysis approach makes it difficult to assess the convergent validity of the cognitive processes under study.

All three of the approaches to cognitive aging research – cross-sectional covariation, neurocognitive, and process analysis – have made invaluable contributions to our understanding of the nature and mechanisms of age-related change in working memory and executive control function. In the next section we describe a theoretical framework that we believe may further help to synthesize the growing literature in this domain, both in terms of what particular executive processes are expected to be impacted with advancing age, and conversely, what processes might be spared.

A theoretical framework for understanding age-related changes in executive control

The theoretical framework that has motivated much of our recent work, and around which we have structured this review, is known as the goal maintenance account. This account is based on a synthesis of findings arising from both young adult and aging research using the three research approaches described above. The first set of findings arises from process-based and individual differences research, that suggest that a common feature of many executive control tasks is that they rely on internal representations of task-set or behavioral goals. This is clearly the case in well-established paradigms such as the Stroop task, WCST and dual-task coordination. Moreover, individual differences studies have demonstrated that the links between working memory capacity, general fluid intelligence, and performance on a wide range of executive control tasks appears to be mediated by the construct of "executive attention", which is the component present in complex WM span tasks that is not mediated by short-term memory storage (R. W. Engle, Tuholski, Laughlin, & Conway, 1999; M.J. Kane & Engle, 2002). It is important to note that executive attention, as conceived by Engle, Kane and colleagues, is a latent construct rather than a specific observable measure of task performance. This conception is very consistent with the process analysis perspective since it suggests that core executive processes might not map in a straight-forward one-to-one way to particular measures of performance in executive task paradigms. Nevertheless, Engle, Kane, and colleagues suggest that the executive attention component is most strongly taxed in complex WM tasks when there is a high potential for proactive interference from previous trials (M. J. Kane & Engle, 2000). These interference effects can be best avoided by actively maintaining only goal-relevant information in WM. Thus, executive attention refers to the ability to actively maintain goals and to use goal-maintenance to suppress contextually-inappropriate response tendencies. Conversely, failures of executive attention can be thought of as instances of "goal neglect." (M. J. Kane & Engle, 2003).

This "goal neglect" view of executive control impairment is similar to the one arising out of the experimental literature on PFC function, in which damage to this brain region seems to commonly produce an executive control impairment, that is also well-characterized as goal neglect (Duncan, Emslie, Williams, Johnson, & Freer, 1996). Indeed, Duncan, like Engle and colleagues, has suggested that reduced efficacy of lateral PFC function is a common mechanism that underlies the increased tendency towards goal neglect in frontal patients and the less-severe goal neglect problems that are faced by healthy individuals with lower levels of general fluid intelligence (Duncan, 1995). The third perspective arises out of neuropsychologically and neurobiologically-based aging research, and as described in the previous section, emphasizes the similarity of neuropsychological profile between healthy older adults and patients with damage to the frontal lobes (A. A. Hartley, 1993; Moscovitch & Winocur, 1992; R. L. West, 1996). This neuropsychological similarity has been confirmed by a rapidly growing neurobiological literature demonstrating that aging is marked by preferential changes to prefrontal cortex structure and physiology (Cabeza et al., 2005). These changes involve reductions in gray and white matter volume, neuronal density, metabolic activity, and neurochemical modulation, particularly by the neurotransmitter dopamine (Raz, 2000).

The goal maintenance theory of PFC function nicely synthesizes these three perspectives on cognitive aging and executive control[1] (T. S. Braver & Barch, 2002; T. S. Braver, Cohen, & Barch, 2002). According to this theory, lateral PFC plays a critical role in control functions because of three inter-related properties of this region (T. S. Braver et al., 2002; Miller & Cohen, 2001): (1) the representational coding scheme of lateral PFC is one that conveys information about the prior temporal context and/or internal behavioral goals (i.e., the desired outcomes of action and perception); 2) these representations can be actively maintained over time in a highly accessible form (i.e., storage of information via sustained neuronal activity patterns); and 3) the output of this region is an activation signal that biases the flow of on-going processing in other brain regions, such as those responsible for perception, action selection, memory retrieval, and emotional evaluation. Additionally, in goal maintenance theory the neurotransmitter dopamine plays a key modulatory role over lateral PFC function by regulating the way that goal representations are maintained and updated. Specifically, dopamine activation may serve to regulate the access of afferent inputs to lateral PFC, thus serving the function of both insulating actively maintained goal information from the disruptive effects of noise during intervals when such information needs to be sustained, while at the same time allowing for appropriate updating of goal information when the situation dictates (T. S. Braver & Barch, 2002; T.S. Braver & Cohen, 2000).

---

[1] This framework is also known variously as the context processing (T. S. Braver et al., 2001) and guided activation theory (Miller & Cohen, 2001), but for purposes of this chapter we will refer to it as goal maintenance theory.

According to goal maintenance theory, a fundamental function of lateral PFC is to serve as a source of cognitive control, by exerting a top-down bias on posterior and subcortical brain systems engaged in task-specific processing based on actively maintained goal representations. The top-down biasing role of PFC is a critical one, that serves to modulate the outcome of competition for processing in local task-specific networks, similar to the well-established biased competition account of attentional control put forward by Desimone and Duncan (Desimone & Duncan, 1995). When there is a high degree of competition in task-specific pathways, active goal representations can serve as a critical attentional template that enables the most goal-relevant of different potential perceptual targets or dimensions to have priority in processing. Additionally, having an active goal representation regarding the desired targets of action is critical under situations when current internal states or environmental conditions are associated with dominant, but contextually inappropriate (i.e., goal-incongruent) action tendencies. The Stroop task provides an elegant example of both types of situation. In the Stroop there are both multiple perceptual dimensions that compete for attention (i.e., word and color) as well as a dominant, but inappropriate response tendency to read the name of the word. In such a situation, representations of task-context or behavioral goals can serve to appropriately bias the attention and response selection systems by enhancing color naming processes and suppressing and inhibiting word reading processes and the action tendencies associated with them.

Goal maintenance theory also provides a unique and unifying view of how lateral PFC function contributes to working memory. The theory diverges from the classic Baddeley model by suggesting that active maintenance is a critical, “embedded” characteristic of a cognitive control mechanism, rather than postulating a strict segregation of storage and control functions (although recent formulations of the Baddeley model have somewhat revised this view, e.g., Baddeley, 2003). Thus, lateral PFC representations can be viewed as the subset of representations within working memory that are specifically engaged in the service of cognitive control. In contrast, the theory also makes clear that activation of lateral PFC is not obligatory for maintenance of information in working memory tasks, as there may be other available mechanisms that can enable short-term storage, for example the phonological-articulatory rehearsal mechanisms typically ascribed to the phonological loop. Instead, the role of PFC-mediated goal representations in working memory tasks may be to help transform actively maintained representations into a plan for how to optimally prepare and respond to upcoming stimuli. For example, in a typical working memory task like the Sternberg item recognition paradigm (Sternberg, 1966), a goal representation may take the items "A, B" presented as a memory set, and transform this information into a representation of the form "if the probe item is A or B, press the target button, otherwise press the non-target button." By activating and then maintaining such goal representations over the delay interval the cognitive system can optimally prepare for the upcoming probe. Nevertheless, it is clear that whereas this process of goal representation can optimize performance in many working memory tasks, it is not necessary for reasonably successful performance. As such, the theory makes clear that the extent to which working memory tasks depend upon the efficacy of the lateral PFC function may be highly variable and dependent on many task factors.

Finally, goal maintenance theory also clarifies the relationship between attention, working memory and inhibition, and the role of lateral PFC in these domains. In particular, whereas performance in working memory tasks may be influenced by the degree to which the biasing effects of goal representations can be maintained over time, tasks requiring attentional or inhibitory control may depend upon goal representations to selectively enhance the processing of task-relevant perceptual dimensions and/or suppress the processing of task-irrelevant perceptual dimensions or action tendencies. Importantly, in situations of behavioral inhibition, the top-down biasing effects of goal representations may have a suppressive effect through indirect mechanisms. This is again in accord with biased competition theory (Desimone & Duncan, 1995), which suggests that there is local competition for representation at all levels of the pathway from sensation to action and that this local competition takes the form of mutually inhibitory interactions. Thus, a source of top-down excitatory bias arises from lateral PFC goal representations by altering the outcome of such competitions in favor of goal-relevant percepts and actions, even when goal-irrelevant competitors may have been otherwise dominant.

The goal maintenance account has been applied to the study of cognitive aging, by postulating that age-related declines in lateral PFC and dopamine function result in a specific impairment in the ability of older adults to actively represent and maintain goal information over time (T. S. Braver & Barch, 2002; T. S. Braver et al., 2001). Because of the role of such goal information in working memory, attention, and inhibition, an impairment in goal representation and maintenance is predicted to produce specific decrements in cognitive task situations that are most demanding of such goal maintenance functions. In particular, according to the goal maintenance account as described above, older adults should show the most difficulty under situations in which: a) goal representations need to be maintained over time in working memory, to bias task-appropriate responding; b) goal representations are needed as an attentional template to enhance processing of otherwise weak perceptual features or actions; and c) goal representations must be used as a top-down bias to suppress or inhibit otherwise dominant, but goal-incongruent perceptual features or dimension or response tendencies. As such, the model makes strong testable predictions regarding the nature of executive control and working memory impairments in cognitive aging. Nevertheless, a practical difficulty, which we will return to at the conclusion of the chapter, is that of determining, purely through task analysis, whether a particular executive control paradigm actually satisfies these conditions.

Over the last decade, research has accelerated in a number of relevant areas that provide a growing empirical database from which to evaluate the explanatory success of the goal maintenance account. In the following sections, we review and examine this database, focusing on the domains of working memory, strategic control of memory, response inhibition, task-management, and context processing. In the final section of the review, we discuss recent theoretical and empirical developments in understanding age-related changes in executive control function, focusing on recent attempts to further explicate and fractionate components and dimensions of executive control that are not within the primary scope of the standard goal maintenance account.

Working Memory

Study of the effects of aging on short-term and working memory has a rich tradition in the cognitive aging literature. A host of the salient findings in this area of inquiry have been expertly reviewed in previous editions of this Handbook (F. I. M. Craik & Jennings, 1992; Zacks et al., 2000). Investigations of the effects of aging on short-term storage have sought to determine whether age-related declines might be greater for primary or secondary memory and whether the effects of aging are greater on processing or storage aspects of working memory in the verbal or spatial domain. As described earlier, the outcomes of recent population-based and meta-analytic studies reveal that there are several unresolved issues related to these questions. In particular, the results of these studies call into question the degree to which deficits in short-term storage per se, as measured by passive span tasks (e.g., forward digit span) are a prominent feature of age-related working memory decline. Conversely, the working memory tasks that do show the most robust age differences are the complex span tasks, which require the integration of short-term storage with executive control processes (e.g., manipulation of stored content as in backward digit span, or coordination with other complex cognitive computations such as mental arithmetic in operation span; Bopp & Verhaeghen, 2005; Myerson, Emery, White, & Hale, 2003). Consequently, current research on aging in working memory has tended to focus on the executive control components of working memory tasks as a primary source of age differences.

We examine evidence from three lines of research that have emerged from the literature in the last several years that illustrate recent developments in our understanding of the effect of aging on working memory in terms of the role of executive processes. Importantly, many of the relevant findings are anticipated by goal maintenance theory.

These include: a) increased susceptibility to interference as a critical factor in understanding age-related differences in working memory (Lustig, May, & Hasher, 2001); b) age-related declines in the ability to control the focus of attention within working memory (Oberauer, 2001); and c) strong age-related memory impairments occurring in task condition that require the binding of arbitrary stimulus features together in working memory (Chalfonte & Johnson, 1996).

The idea that aging is associated with an increased susceptibility to proactive and retroactive interference has a long history in the cognitive aging literature, but has most recently been explored as an account of age-related declines in the efficiency of working memory (Bowles & Salthouse, 2003; Hasher, Chung, May, & Foong, 2002; Hedden & Park, 2001; Hedden & Park, 2003; C. P. May, Hasher, & Kane, 1999; Oberauer & Kliegl, 2001). The impact of increased susceptibility to proactive interference in older adults has been examined using a variety of methodologies. An elegant demonstration of the influence of proactive interference on age-related differences in working memory was reported in a study utilizing standard measures of simple and complex span (C. P. May, Hasher et al., 1999). The fundamental logic incorporated in the study was that there is typically a confound between memory load and proactive interference in the typical administration of span tasks since the total amount of information processed across the task increases with list length when testing begins with short list lengths and then moves to longer list lengths. To break this confound, May et al. (1999) administered the reading span and backward digit span tasks in descending order, thereby minimizing proactive interference at the longest list lengths. Across two experiments, ascending administration revealed the typical pattern of age-related differences; in contrast, descending administration served to eliminate age-related differences in these span tasks (Lustig et al., 2001; C. P. May, Zacks, Hasher, & Multhaup, 1999). In a replication of the original finding, Lustig et al. (2001) demonstrated that the relationship between working memory span and prose recall was eliminated in older adults, but not younger adults, with descending administration of list length. Other work reveals a potential neural locus for the age-related increase in the susceptibility to proactive interference in working memory(Jonides et al., 2000). In this study an increase in proactive interference was associated with a decline in the efficiency with which older adults recruited left lateral prefrontal cortex. Taken together these results are fully consistent with the idea that older adults' reduced ability to maintain goal representations in working memory leads to a greater vulnerability to proactive interference effects, and that such effects may strongly contribute to the observed age-related reductions in working memory capacity on complex span tasks.

Data from studies utilizing the cross-sectional covariation approach (McCabe & Hartman, 2003; Salthouse, 1992, 1994) might also provided indirect evidence for age-related increases in the influence of interference on working memory. For instance, one recent study found that age-related variance in reading span was accounted for by variance in speed of processing and simple word span (McCabe & Hartman, 2003). Based on the findings presented in the previous paragraph it could be assumed that proactive interference (unless properly controlled) represents one source of age-related variance in simple word span, thereby contributing to the relationship between reading span and word span (Lustig et al., 2001). The relationship between speed of processing and interference may be less obvious until one considers recent work demonstrating that an increased susceptibility to distraction contributes to age-related differences in commonly used measures of speed of processing (Lustig, Hasher, & Tonev, 2006). Given these findings, it seems possible that shared age-related variance in speed of processing, simple span, and complex span may arise from an increased susceptibility to interference and distraction (Hasher & Zacks, 1988). Nevertheless, the demonstration that susceptibility to interference and distraction/inhibition may reflect somewhat distinct constructs (Friedman & Miyake, 2004), suggests that further research is required in order to provide a full account of the influence of an age-related increase in susceptibility to interference on working memory.

The embedded process model of working memory (Cowan, 1988, 1995, 1999) has served as the backdrop for a number of studies examining the effects of aging in this domain in recent years. Within this model the contents of working memory represent both currently activated long-term memory representations as well as information that is in the more narrow focus of attention (Cowan, 1999). The focus of attention serves as a region of direct access that represents the information most relevant to the immediate processing demands of the current task (Oberauer, 2002). Whereas activated long-term memory is thought to be time-limited rather than capacity-limited, the focus of attention is thought to be severely capacity-limited (but not time-limited), and may have a capacity of only a single conceptual unit (Cowan, 1999; McElree, 2001). Thus, the conceptualization of the focus of attention in working memory as postulated by the embedded process model seems very close to the conceptualization of actively maintained goal representations within the goal maintenance account.

Recent studies have sought to characterize the effects of aging on component processes that are thought to underlie efficient working memory in the embedded process model. Various studies have demonstrated that aging is associated with a decline in efficiency with which individuals can refresh (Johnson, Mitchell, Raye, & Greene, 2004; Johnson, Reeder, Raye, & Mitchell, 2002) or update (Verhaeghen & Basak, 2005) the focus of attention in addition to an accelerated loss of accessibility to the contents of activated long-term memory (Verhaeghen & Basak, 2005). The most comprehensive investigation of the effects of aging within the context of the embedded process model is represented in a series of studies conducted by Oberauer and colleagues (Oberauer, 2001, 2005b; Oberauer, Demmrich, Mayr, & Kliegl, 2001). This line of research has revealed age-related equivalence in relation to a number of variables including the effect of variation in memory load within the activated portion of long-term memory (Oberauer et al., 2001), the time required to remove information from the focus of attention (Oberauer, 2001), and the time required move information form activated long-term memory back into the focus of attention (Oberauer, 2005b). In contrast, other processes reveal quite dramatic age-related differences. Older adults required a much greater amount of time to access information in the activated portion of long-term memory than do younger adults, and also show a diminished likelihood of successfully switching information into the focus of attention (Oberauer et al., 2001; Verhaeghen, Cerella, Bopp, & Basak, 2005). The influence of recently activated but task irrelevant information also appears to be greater for older than younger adults. For instance, older adults require significantly more time to reject a lure from a task irrelevant memory set in short-term recognition paradigms (e.g., the Sternberg task) than do younger adults (Oberauer, 2001, 2005a).

Together, the findings of this line of research demonstrate that the effects of aging can be localized to a limited set of processes thought to underlie the efficient operation of working memory within the context of the embedded process model rather than there being a general or pervasive effect of aging on working memory processes. Specifically, these deficits may relate to the ability to utilize the focus of attention when required, and to utilize this mechanism as a means of suppressing interference from activated items outside the focus. Likewise, the goal maintenance account suggests that aging will primarily affect working memory processes dependent upon active goal representation and maintenance and the utilization of such mechanisms in an attentional and inhibitory fashion, rather than basic short-term storage per se.

The binding deficit hypothesis of aging is predicated on the idea that older adults exhibit a specific disruption in the ability to bind together the various elements of a representation within working memory, such that the bound representation can be stored as a durable memory trace (Chalfonte & Johnson, 1996; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000). Support for this hypothesis has been provided in a number of studies wherein the investigators contrasted the effects of aging on memory for the individual features of a representation (e.g., location, color, identity) with memory for conjunctions of features (e.g., location+identity). The primary finding from studies designed to assess the efficacy of the binding hypothesis is that there are typically not age-related differences when individuals encode, and are tested on, information related to the specific features of a stimulus. Instead, age-related differences are observed when memory is assessed for conjunctions of features, with these differences expressed as a decrease in target discrimination and an increase in response time to reject conjunction lures (Chalfonte & Johnson, 1996). The age-related decline in the efficiency of binding is observed when encoding is either incidental or intentional, with the deficit being somewhat greater with intentional encoding (Chalfonte & Johnson, 1996; Mitchell, Johnson, Raye, Mather et al., 2000). Moreover, the effect is not the result of differences in memory load for feature and conjunction conditions (Mitchell, Johnson, Raye, Mather et al., 2000). Neuroimaging studies have suggested that the age-related decline in the efficiency of binding in working memory is associated with a failure on the part of older adults to recruit left anterior hippocampus and right rostral prefrontal cortex in feature conjunction relative to single feature encoding conditions (Mitchell, Johnson, Raye, & D'Esposito, 2000). The linkage of age-related binding changes to goal representation and maintenance has not been made directly, but a plausible interpretation is that binding depends on the top-down biasing effects of goal representations in lateral prefrontal cortex that constrain how different features are integrated together as a memory trace (i.e., in the hippocampus). If this goal-based top-down biasing process is impaired in older adults, then feature binding will not be constrained in a goal-directed manner, which should impair subsequent retrieval. Moreover, as discussed at the end of the chapter, binding operations may be similar to the concept of integration, and thus might represent a distinct executive control process impacted by aging.

Strategic Control of Memory

The idea that control processes play an important role in efficient memory is one that has a rich history in the cognitive aging literature (F. I. M. Craik & Jennings, 1992; Hasher & Zacks, 1979). Many of the findings related to this issue have been thoroughly reviewed in chapters in earlier editions of this volume (Moscovitch & Winocur, 1992; Prull, Gabrieli, & Bunge, 2000; Zacks et al., 2000). In this section, we review recent work examining how distinct forms of memory disruption in older adults might preferentially reflect the contribution of age-related declines in executive processes associated with goal maintenance. We focus on work in both episodic and prospective memory. Whereas episodic memory refers to the encoding and retrieval of items and associations, prospective memory refers to the formation, storage, retrieval and implementation of goals and intentions (see also McDaniel, Einstein & Jacoby, this volume).

Episodic Memory. Some of the key findings from the older literature on the age effects in episodic memory are that age-effects are typically increased when: retrieval of specific contextual details is required relative to when retrieval is limited to item level information (Spencer & Raz, 1995); episodic memory is probed with free recall rather than recognition (F. I. M. Craik & Jennings, 1992); and when the processing demands of retrieval are increased (N. D. Anderson, Craik, & Naveh-Benjamin, 1998). In the present review we highlight evidence from three more recent lines of research that have focused on the specific contributions of frontal lobe function to episodic memory in older adults (Glisky, Polster, & Routhieaux, 1995), goal neglect vs. recollection in older adult retrieval deficits (Jacoby, Bishara, Hessels, & Toth, 2005), and age-related binding deficits in episodic as well as working memory (Mitchell, Johnson, Raye, Mather et al., 2000; Naveh-Benjamin, 2000).

The first line of research examines the degree to which individual differences in measures of executive or frontal lobe function account for age-related differences in episodic memory. One of the more compelling examples of research in this line of inquiry is found in the work of Elizabeth Glisky and colleagues (P. S. Davidson & Glisky, 2002; Glisky et al., 1995). In these studies, individual differences in frontal lobe status (as measured by a standard neuropsychological battery) were found to account for age-related differences in source memory and recollection, but be largely unrelated to memory for item level information or familiarity. Other work in this line of research demonstrated an interaction between the effects of divided attention, and individual differences in frontal (executive) and medial temporal lobe function that seems consistent with goal maintenance theory. Specifically, individuals with low frontal function but high medial temporal function recalled a significant number of additional items once dual task demands were removed, after performing the initial recall under divided attention (Fernandes, Davidson, Glisky, & Moscovitch, 2004). This finding leads to the suggestion that these individuals may have been unable to maintain controlled retrieval processes in the face of divided attention even though the items were clearly accessible in memory. The influence of executive function also extends to the effects of aging on false memories in addition to veridical memory (Butler, McDaniel, Dornburg, Price, & Roediger, 2004). In the Butler et al. (2004) study, older adults that showed high levels of frontal function (using the Glisky battery) showed similar levels of false recall in a DRM paradigm as did younger adults; however, low frontal adults showed significantly increased levels of false recall.

A second line of research demonstrating the contribution of age-related declines in executive function to poor episodic memory in older adults is found in the work of Larry Jacoby and colleagues (Hay & Jacoby, 1999; Jennings & Jacoby, 1993, 2003).

Studies by this group have consistently demonstrated that disruptions of episodic memory in older adults arise from age-related declines in recollection or controlled memory processes. Conversely, aging has relatively little if any effect on more automatic aspects of episodic memory, including familiarity and accessibility bias. While compelling in demonstrating a reliable effect of aging on controlled processes underlying episodic memory, the early work of this group does not directly support the goal maintenance theory. However, findings from a more recent study do converge with the idea that a disruption of goal maintenance may contribute to age-related declines in episodic memory (Jacoby et al., 2005). In this study the investigators sought to examine predictions related to disruptions of goal maintenance and recollection failure in a cued recall task involving a high degree of proactive interference due to misleading primes. Under such task conditions, disruptions of episodic memory can result either from capture errors (representing goal neglect) where a primed but irrelevant response is selected, or from a failure of recollection. Across a series of experiments designed to test a formal multinomial model, Jacoby et al. (2005) demonstrated that the responses of older adults were much more likely to reflect capture errors than those of younger adults, revealing a clear disruption of goal maintenance.

The third line of research follows from the binding deficit account of age-related declines in working memory that was discussed above (Mitchell, Johnson, Raye, Mather et al., 2000). One of the fundamental predictions derived from this hypothesis is that the reduced ability of older adults to bind elements of a representation in working memory should lead to age-related differences in other domains of cognition including episodic memory (Mitchell, Johnson, Raye, Mather et al., 2000). This prediction has been realized in the associative deficit hypothesis of aging, that postulates age-related declines in the ability to form novel associations between elements of a representation as a primary source of disruptions of episodic memory in older adults (Naveh-Benjamin, 2000; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003). Across a series of studies Naveh-Benjamin and colleagues have observed robust age-related declines in the ability to retrieve associative information in the context of no or minimal declines in the ability to retrieve item information (Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Naveh-Benjamin et al., 2003). A potential neural basis of the age-related decline in associative binding was explored in a recent computational modeling study (Li, Naveh-Benjamin, & Lindenberger, 2005). In this study, reducing the gain parameter of model units (which reduced the differentiation of internal representations in response to fine gradations in inputs) produced an associative memory deficit similar to that reported by Naveh-Benjamin (2000). The manipulation of the gain parameter to model age-related differences in associative memory is fundamentally similar to work directly related to goal maintenance theory, in which gain-related disruptions of the dopamine system in prefrontal cortex, are the source of goal-representation and maintenance deficits that occur in aging (T. S. Braver et al., 2001) and psychopathology (T. S. Braver, Barch, & Cohen, 1999). As such, the associative deficit and related binding hypotheses are very compatible with the idea that age-related deficits in these functions are due to reduced distinctiveness in prefrontal goal representations that are needed to appropriately structure associative traces in memory systems such as the hippocampus.

Prospective Memory. Prospective memory situations arise when goals and intentions are not immediately attainable in the environment, and thus must be stored in memory for later retrieval. Some examples include delivering a message to a colleague that one will see at a meeting later in the day, and remembering to check food in the oven in 30 minutes. These examples demonstrate the major classes of prospective memory (i.e., event-based and time-based; Brandimonte, Einstein, & McDaniel, 1996; Shum, Valentine, & Cutmore, 1999) that have been considered in empirical studies, although the greatest emphasis has been related to the processes underlying event-based prospective memory. The prominent role of goal representations in prospective memory tasks suggests that this would be a domain strongly sensitive to age-related impairments, according to the goal maintenance account. Indeed much of the early experimental research on prospective memory was done in the context of cognitive aging (Dobbs & Rule, 1987; Einstein & McDaniel, 1990). Surprisingly, however, early findings seemed to suggest – contrary to the goal maintenance account - that prospective memory may be somewhat immune to the effect of aging (Einstein & McDaniel, 1990; Moscovitch, 1982). In the last decade, research on prospective memory has greatly increased, leading to a substantial rise in the number of published studies on the topic. When taken together, this larger literature has clearly revealed a pronounced age-related deficit in the efficiency of prospective memory, as demonstrated by a recent comprehensive meta-analysis (Henry, MacLeod, Phillips, & Crawford, 2004).

A fundamental conceptual distinction in the prospective memory literature is that the realization of delayed intentions is supported by both prospective and retrospective components (McDaniel & Einstein, 1992). The prospective component is thought to reflect processes that underlie the detection or recognition of a prospective cue when the relevant stimulus is encountered in the environment or the appropriate time arrives. In contrast, the retrospective component is thought to reflect processes that underlie the retrieval of the relevant intention from memory. This basic distinction represents the foundation of a number of theories designed to account for the processes underlying prospective memory. For instance, within the "noticing plus search" and more recently "discrepancy attribution and search theories", the prospective component of prospective memory is thought to be supported by processes that are relatively automatic or spontaneous, while the retrospective component is thought to be supported by relatively more controlled or attention demanding processes (Einstein & McDaniel, 1996; Einstein et al., 2005; McDaniel, Guynn, Einstein, & Breneiser, 2004). This account is directly opposite to the one put forward in strategic monitoring views of prospective memory (Guynn, 2003; R. E. Smith, 2003; R. E. Smith & Bayen, 2004), which postulates that the prospective component is supported by processes that require the allocation of working memory capacity or controlled attention to support the detection of prospective memory cues; the processes underlying the retrospective component may (R. E. Smith & Bayen, 2004) or may not (R. West, Bowry, & Krompinger, 2006) require the allocation of working memory capacity.

This distinction between prospective and retrospective components of prospective memory has served as the basis for a number of studies designed to examine the effects of aging on the two components. Much of this research was motivated by the consistent finding that age-related differences in prospective memory persist when variation in the ability to explicitly recall the demands of the prospective memory task at the end of the testing session is taken into account (Salthouse, Berish, & Siedlecki, 2004; R. West & Craik, 2001). One means of examining the effects of aging on the different components of prospective memory is to use experimental manipulations that involve multiple prospective cue-intention pairings (Mantyla, 1994). This enables a determination of whether prospective memory errors result from failures of cue detection (i.e., prospective cues are ignored in favor of a primary ongoing task response; known as the prospective component) or failures of intention retrieval (i.e., prospective cues elicit the wrong prospective response or individuals are unable to recall the intention after detecting the prospective cue, known as the retrospective component; R. West & Craik, 2001). Two important findings have emerged from studies including multiple prospective cue-intention associations. First, it is clear that dissociable factors underlie the prospective and retrospective components of prospective memory (A. Cohen, West, & Craik, 2001; R. West & Craik, 2001). Second, across these studies the effects of aging have been consistently greater on the prospective component than on the retrospective component (R. West & Craik, 2001), even when the retrospective demands of the task are relatively high (A. Cohen et al., 2001). Evidence from a recent study incorporating a mathematical model of the processes underlying prospective memory is consistent with these findings (R. E. Smith & Bayen, 2006). In this study, Smith and Bayen demonstrated that older adults were less likely to recruit preparatory attentional processes that support the detection of prospective cues than were younger adults, and that aging had little if any effect on retrospective processes underlying prospective memory.

The finding that older adults are less likely than younger adults to recruit the preparatory attentional processes that underlie the prospective component of prospective (R. E. Smith & Bayen, 2006; R. West & Bowry, 2005), leads to the prediction that age-related declines in executive functions or working memory capacity may account for disruptions of prospective memory observed in older adults. The efficacy of this prediction has been tested in studies using two methodologies. One approach has been to examine the effects of dividing attention or increasing the working memory demands of the ongoing activity on the relationship between aging and prospective memory; the second approach has been to determine whether or not individual differences in measures of working memory capacity or executive functions account for age-related variance in prospective memory.

Evidence for the effects of divided attention and variation in the ongoing task demands on the effect of aging on prospective memory is somewhat mixed in existing studies. In the typical prospective memory paradigm where the intention can be realized as soon as the prospective cue is detected, Einstein, McDaniel and colleagues have demonstrated that the effects of divided attention can in some instances be similar for older and younger adults, and in other instances may be greater in magnitude for older than younger adults (Einstein, McDaniel, Manzi, Cochran, & Baker, 2000; Einstein, Smith, McDaniel, & Shaw, 1997). Logie et al. (2004) report data suggesting a greater effect of divided attention in older adults than in younger adults. Other data indicate that the impact of divided attention on prospective memory in older adults may be particularly pronounced when individuals are required to actively maintain the intention over a short delay before it can be realized (Einstein et al., 2000; McDaniel, Einstein, Stout, & Morgan, 2003), or when the need for output monitoring is introduced into the task (Marsh, Hicks, Cook, & Mayhorn, in press). Also, divided attention may serve to increase the number of false prospective responses when output monitoring is required (Einstein, McDaniel, Smith, & Shaw, 1998). Like studies examining the influence of divided attention, work considering the effect of varying the working memory demands of the ongoing activity on age-related differences in prospective memory has produced mixed results. In a study where the working memory demands of the ongoing activity varied between two and three items, there was a tendency for the effects of aging on prospective memory to increase with memory load (Kidder, Park, Hertzog, & Morrell, 1997).

Evidence from a number of studies indicates that age-related differences in working memory capacity and executive functions partially mediate the effects of aging on prospective memory (McDaniel, Glisky, Rubin, Guynn, & Routhieaux, 1999). Across studies, measures of these constructs have accounted for 30% to 100% of the age-related variance in prospective memory (Kliegel, Martin, & Moor, 2003; Salthouse et al., 2004; R. West & Craik, 2001). The degree of mediation appears to be sensitive to the demands of the prospective memory task (Martin, Kliegel, & McDaniel, 2003) and whether or not realization of the intention follows detection of the prospective cue or must be postponed for some period of time (Einstein et al., 2000). Based on the available evidence it seems likely that working memory capacity and executive functions influence the prospective rather than retrospective component of prospective memory, although this idea has not been formally tested.

The evidence reviewed in the previous paragraphs clearly demonstrates that there are robust age-related declines in the efficiency of the processes underlying successful prospective memory, and that these covary with individual differences in working memory capacity and executive functions. These findings motivate the question of whether age-related differences in prospective memory might be accounted for within the goal maintenance theory. Three sets of findings appear to offer an affirmative answer to this question. The first set of findings is related to the transient nature of failures of prospective memory, reflecting the tendency for the same or a similar prospective memory cue to variably elicit a prospective response over the course of task performance. Maylor (1993; 1998) sought to quantify this phenomenon by estimating the probability of forgetting (i.e., the probability of a prospective miss following a prospective hit) and recovery (i.e., the probability of a prospective hit following a prospective miss). For individuals who could recall the requirements of the prospective memory task, Maylor found that forgetting was more frequent in older than in younger adults and that recovery was less frequent in older than in younger adults. This finding could be seen as consistent with goal maintenance theory if one assumes that the fidelity of the prospective cue-intention association becomes degraded over time thereby leading to instances of forgetting. Thus, transient lapses in prospective memory represent a form of goal neglect, due to age-related impairments in the ability to keep the prospective goal maintained at a high level of accessibility (Vogels, Dekker, Brouwer, & de Jong, 2002; R. West & Craik, 1999).

A second set of findings is related to the increased tendency of older adults to make false alarms to prospective memory lures (i.e., stimuli that are perceptually similar to prospective cues but require an ongoing activity response) relative to younger adults (Vogels et al., 2002; R. West & Covell, 2001; R. West & Craik, 1999). Similar to the increased rate of forgetting in older adults, this finding is consistent with the idea that an age-related impairment in goal representation and maintenance results in a degraded representation of the prospective cue-intention association, leading to prospective false alarms. Finally, the third finding that age-related differences in prospective memory are particularly pronounced when individuals are required to actively maintain the intention for as little as five seconds before it can be realized (Einstein et al., 2000; McDaniel et al., 2003) is consistent with other evidence indicating that older adults have difficulty maintaining goal-related contextual information for brief periods of time in order to guide task performance (T. S. Braver et al., 2001; T. S. Braver, Satpute, Rush, Racine, & Barch, 2005).

Inhibition of Prepotent Responses

The ability to inhibit a prepotent response tendency has been recognized as an important executive function in a variety of domains including neuropsychology (Luria, 1966), developmental psychology (Bjorklund & Harnishfeger, 1995; Hasher & Zacks, 1988), and the study of individual differences (R.W. Engle, Conway, Tuholski, & Shisler, 1995; M. J. Kane & Engle, 2003). A number of structurally diverse tasks have been used to examine the factors that influence the inhibition of prepotent responses. However, these paradigms all possess the common feature that successful task performance requires suppressing a dominant response tendency that is incongruent with current internally represented goals, in order to produce an alternative response that is goal-congruent, but weaker in strength. In the current review we consider evidence from three paradigms (Stroop task, antisaccade task, and stop-signal task) wherein age-related differences in the ability to inhibit a prepotent response tendency have been observed, with special attention given to whether or not the extant pattern of age-related differences is consistent with predictions derived from goal maintenance theory.

The Stroop task (Stroop, 1935) is the best-known of a larger class of Stimulus-Stimulus/Stimulus-Response compatibility tasks (Kornblum, 1992), and has been used extensively in the aging literature to examine response inhibition. The classic finding of interference in naming the color of incongruent color-words (i.e., RED presented in blue) relative to color-naming when stimuli are congruent (i.e. RED presented in red) or neutral (i.e., do not contain a color word, such as %%% presented in red) has been repeatedly found to be enhanced in older adults (Verhaeghen & De Meersman, 1998; R. West, 1999). Moreover, large sample studies in within an elderly population have found that the interference effect accelerates in an exponential fashion from the sixth to eighth decades (Uttl & Graf, 1997; van Boxtel, ten Tusscher, Metsemakers, Willems, & Jolles, 2001).

Although the primary accounts of age-related increases in Stroop interference tend to focus on changes in inhibitory processing (Spieler, Balota, & Faust, 1996) or executive functions such as attentional control (A. A. Hartley, 1993) and maintenance of task context and goals (R. West & Baylis, 1998), other work has called into question whether these effects can be explained by non-executive factors. For example, a number of studies, primarily using cross-sectional covariation and meta-analytic techniques, have suggested that increased Stroop effects in older adults can be explained by global or generalized changes in speed of processing (Shilling, Chetwynd, & Rabbitt, 2002; Verhaeghen & De Meersman, 1998), by sensory components such as age-related impairments in low-level visual processing (van Boxtel et al., 2001), or by non-cognitive factors such as circadian rhythms (which are different for younger and older adults; C.P. May & Hasher, 1998). Moreover, the magnitude of Stroop interference is well-known to be sensitive to task practice (MacLeod & Dunbar, 1988), which raises the possibility that age-related changes in the rate of learning (over the course of a task session) might also account for some of the data. There is some indication that practice effects in the Stroop task occur through different mechanisms in younger and older adults (Dulaney & Rogers, 1994), even though the overall amount of practice-related reduction in Stroop interference is similar for both age groups (D. J. Davidson, Zacks, & Williams, 2003). Finally, recent work has suggested that the magnitude of age-related changes in interference effects is strongly moderated by bilingualism, with bilingual older adults showing very similar patterns of interference to monolingual younger adults that were further minimized with task practice (albeit in a Simon rather than Stroop variant of the stimulus-response interference task; Bialystok, Craik, Klein, & Viswanathan, 2004; F. Craik & Bialystok, 2005).

The mixed literature on the mechanisms underlying increased Stroop interference effects in older adults indicates that task performance measures might reflect a mixture of a number of component processes rather than purely an index of inhibitory control. This interpretation is supported by studies using mathematical or computational modeling approaches, that indicate how attentional, inhibitory or executive processes might contribute to performance on congruent and neutral trials, in addition to incongruent ones (J. D. Cohen, Dunbar, & McClelland, 1990; Lindsay & Jacoby, 1994; Melara & Algom, 2003; Spieler et al., 1996). Consequently, it is likely that increased understanding of the role of executive control processes in mediating age effects in the Stroop task will be most advanced by studies utilizing a process analysis approach. We next describe a number of studies of this type that have provided support for goal maintenance theory.

A series of studies conducted by West and colleagues have demonstrated that manipulations of task context substantially increase the prominence of age-related Stroop interference effects. In one study, blocks varied in the proportion of congruent versus incongruent trials (R. West & Baylis, 1998). Age-related differences in the interference effect were significant when incongruent trials were frequent and were not significant when incongruent trials were infrequent. These findings suggest that older adults struggled to actively maintain task goals in a high state of accessibility when this was needed for task performance. Likewise, in related work, older adults showed a dramatically increased rate of intrusion errors (naming the word rather than the ink color), consistent with the idea that they suffered from repeated instances of goal neglect or goal failure (R. West, 1999). In an ERP study of this phenomenon, intrusion errors were associated with a change in brain waves over lateral PFC sites prior to the onset of the Stroop stimuli (R. West & C. Alain, 2000), further supporting the notion of lateral PFC involvement in the generation of goal neglect phenomena in older adults. In more recent work, task context was manipulated by comparing blocked versions of color-naming and word-reading against blocks where the two tasks were cued on a trial-by-trial basis (R. West, 2004). Under such conditions the number of intrusion errors was four to five times greater in older adults relative to younger adults. Analyses of ERP data from this study suggested that the effect resulted from decline in the ability of older adults to recruit a PFC-centered neural system that supports the implementation of cognitive control (R. West, 2004; R. West & Moore, 2005). Importantly, these effects, although occurring in the context of a task-switching paradigm (which are discussed at length in a subsequent section), appeared to be independent of switching demands (R. West &

Schwarb, 2006). Thus, the data clearly indicate that that age-related decline in the processes underlying goal maintenance supported by the lateral PFC may be an important contributor to age-related declines in performance of the Stroop task.

The antisaccade and anticue tasks have also been used to examine the effects of aging on the susceptibility to prepotent inhibition (Butler, Zacks, & Henderson, 1999; De Jong, 2001). The antiscaccade requires that eye movements be generated in the direction opposite to a cued location; in the anticue task, a target decision has to be made regarding a stimulus presented in the anti-cued location. Antisaccade performance requires the suppression of an automatic tendency to attentionally orient towards abrupt visual cues (which is measured in prosaccade conditions), and has been well-established to depend on the integrity of the lateral PFC (Funahashi, Chafee, & Goldman-Rakic, 1993; Guitton, Buchtel, & Douglas, 1985). Studies examining the effects of aging on performance of the antisaccade task have revealed several robust findings. Saccade errors are more frequent in older adults than in younger adults in the antisaccade condition, while error rates are similar for younger and older adults in the prosaccade condition (a condition for which few errors are made). Saccade onset latency is often slower for older than younger adults and this difference is typically greater for correct antisaccades than for correct prosaccades (Munoz, Broughton, Goldring, & Armstrong, 1998), although the age by condition interaction is not always observed (Butler et al., 1999). In studies of the anticue task that have manipulated cue-target intervals (Nieuwenhuis, Ridderinkhof, de Jong, Kok, & van der Molen, 2000), older adults show significantly slower rises to asymptote in terms of both error rates and saccade response latencies (presumably due to the need to correct an initial incorrect prosaccade). These effects do not appear to be generalized changes in speed of eye movement control, as age-related differences are minimal on prosaccade trials.

Evidence from a growing number of studies supports the idea that a deficit in goal maintenance may contribute to the effects on aging on performance of the antisaccade task. For instance, Eenshuistra, Ridderinkhof, and van der Molen (2004) found that the age-related increase in the number of antisaccade errors was greater under dual-task than single-task conditions, when the secondary task involved a working memory load. Other findings have led to the interpretation that some older adults may rely on onset of the target stimulus as an exogenous cue to initiate a (pro)saccade to the target rather than utilizing an endogenous representation of task context (i.e., the goal to make an antisaccade) to initiate an antisaccade following the cue (De Jong, 2001; Nieuwenhuis, Broerse, Nielen, & de Jong, 2004; Nieuwenhuis et al., 2000). Supporting this idea, Nieuwenhuis et al. (2000) observed that filling all possible target locations with stimuli at the onset of the target greatly reduced age-related differences in the asymptote of accuracy in the anticue condition. This finding indicates that age-related differences in context processing may, at least in some instances, reflect a strategic reduction in older adults' tendency to utilize a representation of task context to support efficient behavior, potentially as a compensatory mechanism for degraded task goal representation. This is supported by the failure of older adults to reach the same level as younger adults even in the filled location condition.

In the stop-signal task, an intermittent cue signals the requirement to withhold or stop the execution of an already on-going response to a simple primary task (Logan & Cowan, 1984). The primary measure of interest is the stopping-time, which is typically calculated from the probability of successful response suppression as a function of the stop-signal delay (the interval from stimulus onset to the presentation of the stop-signal). The effects of aging on response inhibition in the stop-signal task have been examined in relatively few studies, but these have led to some evidence of age-related impairment. Data from studies utilizing a life-span approach demonstrate that stop-signal response times increase in later adulthood and that this effect may be essentially linear from the 20's to the 80's (Bedard et al., 2002; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Williams, Ponesse, Schachar, Logan, & R., 1999). The effect of aging on the probability of withholding a response is less clear. Several studies have reported that the probability of stopping is similar for younger and older adults (Bedard et al., 2002; Kramer et al., 1994; Williams et al., 1999). In contrast, May and Hasher reported that the likelihood of stopping was reduced in older adults relative to younger adults (C.P. May & Hasher, 1998), although this was moderated by circadian rhythm (i.e., time-of-day) effects.

A recent study examined age-related changes in stop-signal inhibition compared to other tasks with inhibitory demands (e.g., Stroop, AX-CPT), after careful control for global processing speed effects (Rush, Barch, & Braver, 2006). Although significant age effects were found, they tended to be small relative to other inhibitory measures. These findings suggest that the stop-signal task may index age-related changes in the ability to activate response suppression processes based on cued activation of a task goal. However, it may be that the task is not optimal for examining goal maintenance impairments in older adults. In particular, because the primary measure is the speed of engaging response suppression processes once cued to do so, the dependence of the task on strongly maintained goal representations may be minimal. It may be interesting for future studies to examine task manipulations that increase the demands on goal maintenance processes, for example by pre-cuing participants when a stop-signal trial is likely to occur. In a brain imaging study of this type conducted in younger adults, this manipulation reliably increased pre-target activation within lateral PFC (Hester et al., 2004).

Task Management

A central notion of many theories of executive control is that specialized mechanisms are required to enable flexible coordination and switching between different tasks that need to be completed. These control mechanisms – internal representations of "task-sets" or "task rules" and processes that can rapidly update such representations when needed – are thought to be distinct from the task-specific representations and processes themselves, and as such serve a managerial function in coordinating task flow. It has long been thought that a primary source of cognitive impairment in aging is a loss of the ability to successfully manage and coordinate multiple task demands (F. I. M. Craik & Byrd, 1982). Classically, task-coordination processes have been studied in aging research using dual-task or divided attention paradigms (F. I. M. Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; F. I. M. Craik & McDowd, 1987; J. M. McDowd & Craik, 1988). In such paradigms, performance in dual-task and divided attention conditions are contrasted against performance in single task and full attention conditions, to identify age-related effects. The robust findings of age-related declines in these domains have been reviewed in detail in previous and current editions of this handbook (A.A. Hartley, 1992; J.M. McDowd & Shaw, 2000)(Kramer & Madden, this volume), and have been quantitatively confirmed in a rigorous manner through meta-analyses (Verhaeghen, Steitz, Sliwinski, & Cerella, 2003) and structural equation modeling (Salthouse & Miles, 2002). These latter studies confirm that dual-task slowing in older adults is not accounted for by generalized slowing and that a coherent dual-task latent construct can be defined that has both convergent and divergent validity in its relationship to cognitive aging.

Yet even with these findings, dual-task and divided attention paradigms have acknowledged limitations in their ability to provide a fine-grained analysis of the nature of age-related impairments in task-management processes. As a consequence, there has been a recent shift in focus to potentially more informative paradigms for understanding the nature of task-set representation, coordination, and updating. Two paradigms of particular interest have been the psychological refractory period (PRP) paradigm and task-switching. Studies of these tasks appear to provide rather direct support for the goal maintenance account.

Task-switching. Task-switching paradigms are similar to classic dual-task paradigms in that participants have more than one task to perform within a block of trials, but differ in that only one task is performed at a time, such that task changes occur on a trial-to-trial basis in either a predictable or unpredictable sequence. Thus, task-switching paradigms offer a window into both how task-sets or task-rules are internally represented, and how such representations become updated when needed. Task-switching studies have a long history of study in both the young adult (Jersild, 1927; Spector & Biederman, 1976) and aging literatures (Brinley, 1965), but it is only recently that the paradigm has become an active area of focused research (D. A. Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995). Current task-switching studies focus on the processes and task factors that produce "switching costs" (the reduction in performance that occurs on trials where the task has switched from the previous trial) and "mixing costs" (the reduction in performance that occurs even on non-task-switch trials presented within a task-switching block relative to the same trials presented in a single-task block). A number of findings have been observed in task-switching studies with older adults that provide information regarding how task-management processes are impacted by advancing age, and which have implications for goal maintenance theory.

One of the most intriguing findings in literature on task-switching and aging is that older adults show consistent and large age-related increases in mixing costs and less robust age-related differences in switching costs (Verhaeghen et al., 2005). This pattern was first rigorously investigated and reported in studies by Kray and Lindenberger (2000) and Mayr (2001). Kray and Lindenberger examined task-switching using an alternating runs paradigm (i.e., tasks follow a predictable AABBAABB sequence) in which task preparation time was manipulated by varying the interval between the response and next stimulus (RSI). The results were very clear in illustrating that mixing costs (also termed global switching costs) were significantly higher in older adults and remained so even after extensive practice and with long preparation times. In contrast, after controlling for practice, preparation, and generalized slowing, local switch costs were not greater in older adults. In a follow-up study, Mayr (2001) demonstrated that the same pattern of age-differential effects for mixing but not switching effects could be obtained in a task-cuing paradigm (but for contrasting results see Kray, Li, & Lindenberger, 2002). The task-cuing paradigm allows sequences of task switches to be unpredictably structured, thus removing potential age-confounds related to predictive expectancies and micropractice effects (i.e., learning due to short runs of same-task repetitions).

Since these original reports, the general finding of strong age-related increases in mixing costs, along with weak or absent age effects in switching costs, has been replicated numerous times, including in large sample and life-span studies and thus appears to be highly reliable (Reimers & Maylor, 2005). For example, in a meta-analysis of task-switching studies, Verhaeghen and Cerella (2002) found that after incorporating generalized age-related slowing, older adults showed clear evidence of enhanced mixing costs but no effect in switching costs. Other task-switching studies have been useful in providing important additional constraints on the nature of the mixing cost effect in older adults. For example, mixing cost effects are influenced by whether the tasks being intermixed have overlapping and bivalent stimulus and response features (e.g., the same response or feature could be present when performing either task; Mayr, 2001) which can lead to response incongruencies (i.e., when the stimulus is associated with two different responses, depending on the task being performed; Rubin & Meiran, 2005). The presence of these factors also appears to contribute strongly to age-differences in mixing cost, indicating that the problem for older adults may be in utilizing task-set representations as a means of minimizing task cross-talk or interference (Mayr, 2001; Meiran, Gotler, & Perlman, 2001). De Jong (2001) demonstrated that the mixing cost effect could be removed when older adults were placed under strict response deadlines. This suggests that without such pressures, older adults will tend to keep both task-sets at an equivalent level of activation, rather than prioritize one over the other in a context appropriate manner. Such behavior can be seen as a form of goal neglect, which minimizes control demands, but increases overall mixing costs.

The minimal effect of aging on local switch costs at first seems somewhat surprising from the standpoint of executive control theories of cognitive aging. In particular, a hope of early task-switching research was that local switch costs could provide a direct index of the efficacy of control processes in selecting and updating task-set representations (Monsell, 2003). Specifically, most theories of executive control in aging, including the goal maintenance account, would postulate that task-set selection and management is a core executive process that declines with increasing age. However, it is now becoming clear that local switch costs, similar to Stroop interference effects, represent a complex mixture of factors of which only some may be related to task-set representation. In particular, recent research has suggested that switch costs can be influenced by cue repetitions (Logan & Bundesen, 2003), response repetitions (Meiran, 2000), target-evoked associations (A. Allport & Wylie, 2000), and higher-order sequential effects (J. W. Brown, Reynolds, & Braver, 2006).

The complexity of local switch costs can also be seen in the fact that when long preparatory intervals are provided, as in cueing paradigms, switching costs are significantly reduced, but not eliminated (i.e., leaving a so-called residual switch cost, Monsell, 2003). Interestingly, older adults show similar benefits of preparation as younger adults, but have larger residual switch costs (De Jong, 2001; Meiran et al., 2001). This is consistent with the interpretation that older adults do utilize task cues to engage in general task preparation, but they are less able to use such information to appropriately select the currently relevant task-set and de-select the currently irrelevant set. Such an effect would be fully consistent with the goal maintenance account, which suggests that task goal updating as well as maintenance processes occur less robustly in older adults.

Evidence from ERP and brain imaging studies provide further support for this account, and for the role of lateral PFC in local and global switch costs. Although lateral PFC appears to be reliably engaged following cues that enable preparation for the upcoming task, PFC activation appears to be similar regardless of whether the cue indicates a task-switch or task-repeat trial will be occurring (Brass & von Cramon, 2004; T. S. Braver, Reynolds, & Donaldson, 2003; Ruge et al., 2005; R. West, 2004). Conversely, mixing costs do appear to be associated with sustained activation within anterior regions of lateral PFC (T. S. Braver et al., 2003), suggesting that performance of multi-task blocks is dependent on active task goal maintenance. Although there have been very few brain imaging and ERP studies of task-switching in older adults to date, the available evidence is consistent with the hypothesis that older adults fail to increase activation of lateral PFC during task-switching blocks (DiGirolamo et al., 2001), and show reduced activity following task cues (R. West, 2004). Together, these findings give credence to the idea that age-related impairments in global mixing costs may be a valid indicator of specific goal (i.e., task-set) representation and maintenance problems in lateral PFC that are present during mixed-task conditions, but which occur on both task-switch and task-repeat trials. In contrast, local switch costs may be a more complex measure of task-maintenance processes due to the multi-factorial nature of this measure. Indeed as Mayr (2001, p.106) suggests, global mixing costs "may actually be a more fundamental and less ambiguous indicator of executive control demands in set-selection situations than local costs."

PRP studies. The other approach most recently used to understand age effects on dual-task coordination is the psychological refractory period (PRP) paradigm (Welford, 1952). The key aspect of the PRP paradigm is an explicit manipulation of the temporal overlap between two tasks by varying the SOA (or stimulus onset asynchrony) for the second task (T2) relative to the first (T1). Often a critical variable is the size of the PRP effect, which is the slowing of response latency on T2 (but not T1) for short SOAs relative to long SOAs. The PRP effect is thought to measure the degree of interference caused by dual-task coordination, but with more precision, since in the baseline long SOA condition both tasks are still performed, but sequentially and without overlap (since at long SOAs the T1 response will be given before the T2 stimulus is presented). Thus, the magnitude of overlap interference can be dissociated from more general difficulty effects related to having to complete two different tasks within a short time window (Pashler, 1994). A theoretical advantage of the PRP paradigm for aging research is that provides a means of refining explanations of dual-task interference effects in older adults, In particular, whereas classic accounts of age-related dual-task interference effects typically postulate a reduction in "general processing resources", PRP studies have focused on the more specific question of whether PRP interference reflects a time-sharing deficit at a particular processing stage, or a reduced ability of older adults to update task goals in a rapidly sequential manner.

Findings of enhanced PRP effects in older adults were first reported by Allen et al (1998) and Hartley and Little (1999). Allen et al (1998) suggested that the results indicated older adults had a selective impairment in time-sharing ability. Hartley and Little (1999) carried out an extensive series of studies that attempted to determine whether enhanced PRP effects in older adults could be interpreted as general reduced capacity, generalized slowing, or a more specific impairment in time-sharing. The results appeared inconsistent with a general reduced capacity account, but were consistent with age-related slowing particularly at the response selection stage of processing. In later work, Glass et al. (2000) observed similar results, which were interpreted within the context of the EPIC computational model of adaptive executive control (Meyer & Kieras, 1997). In trying to fit older adult PRP data to the model, the investigators found that in addition to generalized slowing effects, increased slowing of certain specific processes, and changes to time-sharing parameters were required in the model. The latter parameters specifically referred to the time required to “lock” and “unlock” T2 processing at the bottleneck stage after T1 had passed through this stage. This locking process may be similar to a mechanism of rapid task goal activation and updating. In later studies, additional findings were also observed, such as selectively enhanced PRP effects in older adults when both tasks required the same type of motor response (A. A. Hartley, 2001), or when the T2 stimulus was especially salient and so caused an attentional capture effect (Hein & Schubert, 2004). Thus, in both cases, age-related PRP effects appeared to be a reduced ability to manage cross-task interference, either at the perceptual or response level.

Most recently, investigators have used the PRP paradigm to examine whether dual-task coordination can be improved in older adults with extensive practice. Maquestiaux et al (2004) found that practice substantially reduced the magnitude of PRP effects, but to a lesser degree in older adults than younger adults. Thus, practice actually amplified the magnitude of age-related PRP effects. To account for this finding, Maquestiaux et al (2004) suggested that in addition to generalized slowing, older adults had additional difficulty in switching to T2 processing after T1 completion – an effect that was predicted to be present especially in tasks with complex S-R mapping rules (as they had used in training) that would be presumably be more difficult for older adults to maintain in working memory during T1 processing (see also Glass et al. 2000). Consistent with this account, when the practiced participants transferred to either a novel T1 or T2 that was less complex than the practiced one, age-related PRP effects decreased. Bherer et al (2005) found that practice did lead to equivalent dual-task improvements in older adults compared to younger adults, and that these practice effects both maintained over time and transferred to novel task conditions. However, in this study, training did not reduce the larger age-related effects in "task set costs", a measure conceptually similar to mixing costs in task-switching (i.e., the cost of performing the T1 or T2 task within dual-task vs. single-task conditions).

When taken together, the findings of the PRP studies suggest that age-related enhancements in PRP effects are similar to those observed in task-switching paradigms. Thus, if successful dual-task coordination in PRP studies reflects rapid switching between tasks rather than true time-sharing or dividing attentional resources, as most current theoretical models predict (Logan & Gordon, 2001; Pashler, 1994), then older adult deficits in such situations may not reflect poorer time-sharing *per se*, but rather a reduced ability to appropriately select the task-relevant goal representation during T1 and then rapidly update this representation when initiating T2 performance. As such, older adults may tend to keep both task-sets at an equal level of activation, which leads to an increased vulnerability to cross-task interference and task-set costs. Although there have been no neuroimaging studies conducted to examine PRP-type dual-task processing in older adults, recent work in younger adults is consistent with this hypothesis. In particular, lateral PFC regions appear to be the source of PRP-type bottleneck effects, and show evidence of sequential updating from T1 to T2 (Dux, Ivanoff, Asplund, & Marois, 2006). Moreover, these regions appear to be the only ones that show increased activity following extensive dual-task training (Erickson et al., 2007). Thus, a promising direction for future research would be to conduct aging studies of these effects, to determine whether older adults show altered dynamics of lateral PFC activity, and how these dynamics might be impacted by dual-task training.

Context Processing

A recent area of research that has attempted to directly test the ideas of the goal maintenance theory comes from studies that have examined context processing functions. In particular, the AX-CPT paradigm has been designed to directly probe the utilization of contextual cue information in terms of goal-based biasing functions related to active maintenance in working memory, attentional enhancement, and response inhibition (T. S. Braver et al., 2002). The AX-CPT is a variant of the classic Continuous Performance Test (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) that requires utilization and maintenance of contextual cue information to guide responding to subsequent ambiguous probes. The task is structured such that context cues serve to update task goals (i.e., in the form of relevant S-R mappings) and create goal-based expectancies that both direct attention towards target features and responses and enable suppression of probe-evoked interference. These effects can be measured on two types of lure trials, AY and BX, relative to an internal baseline control trial BY. The AY measure provides an index of the strength of context-induced attentional expectancies, whereas the BX measure provides an index of interference due to context-failures. Finally, manipulation of the cue-target interval provides an index of the active maintenance of context over a delay.

The AX-CPT has been extensively examined across a number of both behavioral (T. S. Braver et al., 1999; T. S. Braver & Cohen, 2001; MacDonald et al., 2005; Servan-Schreiber, Cohen, & Steingard, 1996) and brain imaging studies (Barch et al., 1997; Barch et al., 2001; T. S. Braver & Bongiolatti, 2002; MacDonald & Carter, 2003; Perlstein, Dixit, Carter, Noll, & Cohen, 2003). The typical finding is that younger adults show high degrees of context-induced attentional expectancy (poor AY performance) and a low incidence of interference due to context-failure (good BX performance). In functional neuroimaging studies, these trial-type and delay effects have been found to be associated with task-related activation in lateral PFC. These findings are consistent with the idea that a common underlying mechanism – active prefrontal goal representations– tends to lead to both successful BX inhibition and AY cue-invalidity errors, and that these tendencies are sustained over delays via the active maintenance of such goal information.

Braver et al. (2001) conducted the first study of the AX-CPT with older adults, demonstrating that they showed a reversed pattern to young adults, with low levels of context-induced attentional expectancy and high-levels context-failure interference. An especially surprising aspect to the latter finding was that older adults not only showed few errors on AY trials, but also faster reaction times than young adults – an effect which was statistically significant after controlling for generalized response slowing. Moreover, these age-effects were found to be specific to context processing, as manipulations of context processing difficulty (by filling the cue-probe delay interval with distractors) amplified age-related performance differences, but manipulations of general task difficulty had no impact.

A number of subsequent studies have provided further support for context processing deficits in older adults, due to impairments in goal representation and maintenance (T. S. Braver et al., 2005; Haarmann, Ashling, Davelaar, & Usher, 2005; Rush et al., 2006). For example, these studies have demonstrated correlations between AX-CPT impairments in older adults and performance declines in other more standard neuropsychological tasks of executive control domains that should also depend on context processing, such as stop-signal inhibition, Stroop, Trailmaking, verbal-fluency and semantic anomaly judgments. Importantly, though it has also been shown that while AX-CPT measures might tap into similar executive control constructs, such as inhibition, they also appear to account for more age-related variance than these standard measures. Thus, BX trial performance was more significantly correlated with age than equivalent inhibitory measures in the go-nogo, stop-signal and Stroop tasks (Rush et al., 2006). This suggests that goal-representation and maintenance may be a more fundamental construct for understanding cognitive aging than other related executive control constructs. However, as we discuss further at the end of the chapter, there is still a great demand for further work examining the psychometric properties of the AX-CPT task (e.g., reliability), and in establishing the psychometric validity of the context processing construct more generally.

In a recent study, Braver et al. (2005) found evidence that there may be age-related dissociations within the context processing construct, between the representation/updating and maintenance functions. In particular, within a young-old group (65-75 years old), the age-related changes on AY and BX trials were not affected by delay manipulations, whereas in an older group (> 75 years old), context proessing impairments were greater with a long delay (when maintenance functions would be most taxed). Moreover, both types of context processing impairment were found to be further exacerbated in a sample of older adults with very-mild dementia of the Alzheimer's type (DAT), suggesting that deterioration of goal representation and maintenance mechanisms in lateral PFC may contribute to early-stages of cognitive decline in this disease.

A key idea of goal maintenance theory is that impairments in the use of context information in older adults are caused by changes in lateral PFC (and/or DA) function. This idea is also supported by neuroimaging studies of the AX-CPT demonstrating a reduction in delay-related lateral PFC activity in older adults (T. S. Braver & Barch, 2002). In a follow-up event-related fMRI study, it was shown that the activation changes were specifically due to reduced cue-related activation of lateral PFC, even though tonic (i.e., non-specific) activity in this region was increased among older adults (J.L. Paxton, Barch, Racine, & Braver, submitted). This finding is supported by work from using ERPs and a trial-by-trial cueing version of the Stroop task (R. West, 2004). Older adults were found to have reduced cue-related activity in frontal and occipital sites particularly after a delay, a finding that was interpreted as a reduced ability to maintain task cue information as a contextual goal representation that can bias task-specific perceptual processing areas. A related study found that older adults had reduced frontal pre-stimulus ERP activity during a Stroop-like interference task with a long preparatory interval (R. West & Schwarb, 2006).

Recent Developments

Perhaps one of the most significant developments in the study of executive functions over the last decade is the movement toward fractionation of the various cognitive processes and functional neuroanatomy underlying executive functions and the central executive of working memory (Miyake et al., 2000; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004; E. E. Smith & Jonides, 1999; Stuss et al., 2002; Stuss, Shallice, Alexander, & Picton, 1995). In this section, we discuss the emerging trends in the literature, and how these are already, or might in the future, influence our understanding of the aging of executive control.

The research enterprise aimed towards fractionation of executive control was originally motivated by three streams of evidence: 1) an uneven pattern of spared and impaired performance on measures of executive function in patients with focal and diffuse damage to the prefrontal cortex (Luria, 1966; Stuss & Benson, 1986); 2) broadly distributed activation within the prefrontal cortex of healthy young adults during performance of executive function tasks (T. S. Braver & Ruge, 2006; Cabeza & Nyberg, 2000; Duncan & Owen, 2000); and 3) potential differences in the developmental trajectory of executive functions (Casey, Tottenham, Liston, & Durston, 2005; Diamond, 2002; Zelazo, Craik, & Booth, 2004). In two important review papers Stuss et al. (1995)

and later Smith and Jonides (1999) described a set of executive or supervisory processes that are dependent on the functional integrity of the prefrontal cortex. These include activation of relevant information, inhibition of irrelevant information, scheduling processes in complex tasks, planning a sequence of subtasks to accomplish some goal, updating the contents of working memory and coding the time and place of information in working memory, the implementation of if-then logical processes, and monitoring action outcomes.

Empirical support for the conceptual and neuroanatomical fractionation of executive processes has been provided in studies using a variety of methodologies. In a series studies of patients with focal lesions to the prefrontal cortex, Stuss and colleagues (Stuss et al., 2002; Stuss, Bisschop et al., 2001; Stuss, Floden, Alexander, Levine, & Katz, 2001; Stuss et al., 2000) have demonstrated that damage to circumscribed regions within the left and right dorsolateral, inferior medial, and superior medial prefrontal cortex can be associated with disruption of processes supporting activation, monitoring, inhibition, and initiation, respectively. Likewise, work examining individual differences has revealed that distinct constructs reflecting shifting, updating, inhibition, and resistance to interference can be identified in intact individuals (Friedman & Miyake, 2004; Miyake et al., 2000). Furthermore, this work demonstrates that the various executive functions may be differentially related to performance on more complex measures of executive function and working memory including the WCST, the Tower of Hanoi, random number generation, and complex span tasks (Miyake et al., 2000). Lastly, functional neuroimaging and computational studies have probably provided the most explicit attempts at, and evidence for fractionation and dissociation of executive functions

(Botvinick, Braver, Barch, Carter, & Cohen, 2001; T. S. Braver & Ruge, 2006; De Pisapia, Repovs, & Braver, in press; Frank & Claus, 2006). Within this literature, three specific types of executive processes have been emerging as possibly contributing distinct functional and anatomical mechanisms over that provided by the basic goal maintenance and biasing functions of lateral PFC. These are performance / error monitoring, affect-cognition interactions in executive control, and integration. We next discuss each of these functions in turn, in terms of recent research developments and implications for cognitive aging. Lastly, we discuss ideas relating to the dynamics of executive control that may be independent of structural/functional dissociations, but still have significant implications for cognitive aging research.

<u>Error / Performance Monitoring</u>**.** In the last ten years, there has been intense interest in the executive control literature regarding the cognitive processes and functional neuroanatomy underlying performance monitoring (Ridderinkhof et al., 2004). This interest was sparked by the discovery of a specific ERP brain wave component sensitive to error monitoring and detection, known as the error-related negativity (ERN) or error negativity (Ne) (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). Subsequent research suggested that this brain wave is generated within the anterior cingulate cortex (ACC; Carter et al., 1998; Dehaene, Posner, & Tucker, 1994). More recent work has suggested that the ACC and ERN-like brain-waves are activated not only by error commission itself, but also by the occurrence of response conflict (i.e., co-activation of competing response tendencies) in situations where such conflict tends to accompany errors (Yeung, Cohen, & Botvinick, 2004), or conversely by explicit error-feedback under situations where error-

accompanying response conflict tends not to be present (Holroyd & Coles, 2002). Computational and experimental studies have suggested that the ERN and ACC activity might serve as a neural signal that enables the system to learn about task situations requiring a high degree of cognitive control over responding, to prevent errors and to regulate the systems, such as lateral PFC, that implement such control (Botvinick et al., 2001; J.W. Brown & Braver, 2005; Holroyd & Coles, 2002; Kerns et al., 2004). In particular, the ACC and lateral PFC may form a control circuit that facilitates goal-directed action in a variety of tasks, by continually adjusting to the imposed control demands of the particular situation (Botvinick et al., 2001).

The basic research on ERN/conflict monitoring and ACC-PFC interactions in cognitive control regulation has motivated investigation of such effects in older adults. Studies examining the effects of aging on the ERN have consistently demonstrated that the amplitude of this modulation is attenuated in older adults. The effect of aging appears to be relatively general and has been observed in a variety of difficult cognitive tasks for which errors are frequently committed, including mental rotation (Band & Kok, 2000), four-alternative forced choice (Falkenstein, Hoormann, & Hohnsbein, 2001), probabilistic learning (Nieuwenhuis et al., 2002), source memory (Mathewson, Dywan, & Segalowitz, 2005), and picture-word matching (Mathalon et al., 2003). Likewise, studies of conflict detection in interference tasks, such as the Stroop, have observed attenuated ERP activity arising from medial frontal regions in high conflict (incongruent) trials (R. West, 2004; R. West & C. Alain, 2000; R. West & Schwarb, 2006). A promising discovery within the context of the goal maintenance theory comes from findings of a computational study examining the mechanisms underlying age-related declines in the amplitude of the ERN (Nieuwenhuis et al., 2002). In this study the effects of aging on the ERN in the flanker task and a probabilistic learning task were captured by a reduction in the magnitude of a dopamine-mediated error feedback signal from the basal ganglia to the anterior cingulate.

Related work has suggested that age-related changes in Stroop interference might also be due to ACC and conflict monitoring impairments, as well as declines in the goal-maintenance functions supported by lateral PFC (Milham et al., 2002; R. West & Schwarb, 2006). The primary account of ACC-PFC interactions suggests that detection of high-conflict situations in the ACC leads to a subsequent adjustment in cognitive control via increased goal maintenance in lateral PFC (Botvinick et al., 2001; J.D. Cohen, Botvinick, & Carter, 2000). Thus, impaired goal maintenance in older adults might be due to a disruption of this dynamic, via age-related alterations of either lateral PFC or ACC mechanisms. Consistent with this hypothesis, West and Baylis (1998) observed that older adults were less efficient that younger adults at modulating the magnitude of the Stroop effect in response to variation in task context as might be expected if aging has a negative impact on the conflict monitor supported by ACC. Thus, aging may be associated not only with impairments in goal maintenance via changes in lateral PFC function, but also with disrupted regulation of cognitive control that may arise out of a change in ACC function as well (that is potentially DA-mediated) which alters the nature of the interaction between ACC-PFC.

<u>Affect-Cognition Interactions in Executive Control.</u> Interest in the potentially dissociable role of affective processes in executive control was first launched by work on "somatic marker" theory (A Bechara, Damasio, Tranel, & Damasio, 1997; Damasio,

1994), which postulated that affective bodily signals are explicitly (though non-consciously) represented within ventromedial (VM) regions of PFC, and used as an additional source of top-down bias on decision-making. The independence of such VM-PFC biasing signals from more cognitive biasing signals in lateral PFC was supported by a double dissociation finding (A. Bechara, Damasio, Tranel, & Anderson, 1998), in which VM-PFC patients exhibited normal performance on a working memory task, but never developed predictive bodily reactions to poor upcoming choices in a gambling task (and thus tended to persist in making such poor choices throughout the session). Patients with dorsolateral (DL) PFC lesions showed the opposite pattern. This work also supported the accumulated findings from many neuropsychological case studies demonstrating a general pattern of risky decision-making behavior in patients with VM-PFC damage (A. Bechara, Damasio, & Damasio, 2000). In subsequent years there has been an explosion of functional neuroimaging studies of gambling and related decision-making tasks (Fellows, 2004; Krawczyk, 2002), including the original Iowa gambling task just discussed (Fukui, Murai, Fukuyama, Hayashi, & Hanakawa, 2005; Northoff et al., 2006).

These studies support the involvement of VM and orbital PFC in responding to negative and positive feedback information that signal behavioral changes are needed (O'Doherty, Critchley, Deichmann, & Dolan, 2003; O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001). However, the independence of VM and DLPFC regions is not so clear-cut, as other studies have shown that regulation of the emotional response to affectively-valenced stimuli appears to involve DL-PFC regions, interacting with both VM-PFC (or more ventral ACC regions) and the amygdala (Clark, Manes, Antoun, Sahakian, & Robbins, 2003; Fellows & Farah, 2005; Manes et al., 2002; Ochsner, Bunge, Gross, & Gabrieli, 2002).

There is a growing literature on both affect-dependent decision-making and VM-PFC function in healthy aging, but this has also been mixed with regard to the extent of age-related changes in these functions. In a direct comparison of executive functions supported by DL-PFC vs. VM-PFC, MacPherson, Phillips, and Della Sala (2002) found consistent aging effects on measures of DL-PFC function (e.g., WCST), but no clear age-related change in the tasks used to measure VM-PFC function (e.g., Iowa Gambling task). These behavioral findings are consistent with other similar studies (Wood, Busemeyer, Koling, Cox, & Davis, 2005) and with older behavioral evidence showing conservative rather than risky decision-making behavior in older adults (Botwinick, 1969). Moreover, they are consistent with neuroanatomical investigations examining gray matter volume with MRI that indicate stronger effects of aging (in terms of volume reduction) for lateral PFC than for medial and orbital PFC (Convit et al., 2001; Raz, 2000). Yet the findings are not unequivocal, as more recent work with the Iowa Task and other gambling-type paradigms have demonstrated that older adults show slower learning curves from negative feedback and a higher tolerance for risk (Deakin, Aitken, Robbins, & Sahakian, 2004; Denburg, Tranel, & Bechara, 2005). An imaging study in this kind of paradigm also revealed age-related changes in activation of both PFC and reward-related subcortical structures, such as the ventral striatum (Marschner et al., 2005).

A different literature on emotion-cognition interactions in older adults has also produced mixed results with regard to whether aging changes the nature of bidirectional regulation across these domains. There is now a relatively well-established literature on emotional control and the so-called “positivity bias” in older adults (Carstensen & Mikels, 2005). This research suggests that, compared to young adults, older adults are able to exert equivalent or better control over their emotions, and as such show a reduced impact of negative (vs. positive) information on memory and attention (Mather & Carstensen, 2005). This research is interesting, especially in light of the recent literature from younger adults, suggesting that control over emotional responses (especially for negative information) appears to depend on lateral (rather than medial) PFC function (Ochsner & Gross, 2005). One approach to reconciling this discrepancy has been put forward by Mather and Carstensen (Mather & Carstensen, 2005), who suggest that older adults prioritize emotional regulation goals over other cognitive ones, thus improving emotional control but at the expense of cognitive control. A recent study (Mather & Knight, 2005) has supported this finding, in demonstrating that: a) age-related positivity biases were found only in older adults with good cognitive control function (as indexed by a neuropsychological battery); and b) reducing cognitive control resources via divided attention abolished the age-related positivity bias.

When taken together, these results suggest that even if VM regions of PFC are not directly impacted by age, older adults may show some level of impairments in gambling and reward-related decision-making domains and a qualitative shift in emotion regulation. These behavioral phenomena may reflect an altered input from lateral PFC regions. In particular, interaction between lateral and VM PFC regions may reflect important emotion-cognition dynamics that adjust affect and decision-making biases in response to actively maintained goal representations. Older adults may show a shift in how these biases are implemented and maintained, although further research is clearly required.

Integration. A third domain of executive control garnering recent attention in the basic cognitive neuroscience literature is that of integration (Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000). Recent studies have suggested that the anterior-most regions of PFC might be selectively engaged by specific executive processes related to the integration of higher-order goal information actively maintained in working memory with other internally represented information (De Pisapia, Slomski, & Braver, 2006; Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999; Ramnani & Owen, 2004). For example, one study found that anterior PFC was not engaged by processing of a subtask (semantic classification) or working memory, but was engaged when the subtask had to be integrated with information previously stored in working memory to achieve the correct result (T. S. Braver & Bongiolatti, 2002). Integration operations may also be a critical component of tasks involving feature binding within working memory. As discussed previously, these tasks also engage anterior PFC regions (Mitchell, Johnson, Raye, Mather et al., 2000). A similar effect was observed in a study that found selective anterior PFC actvity under conditions requiring the integration of verbal and spatial information in working memory (Prabhakaran et al., 2000). Some theorists have suggested that these forms of integration are a key element of goal-subgoal coordination that occurs in many planning and reasoning tasks (Christoff & Gabrieli, 2000). For example, in reasoning tasks such as analogy verification and matrix reasoning, a number of different dimensions of stimuli have to be simultaneously (or sequentially considered) in order to determine whether a match on a desired dimension is present. Anterior PFC activity is selectively engaged in analogy and reasoning tasks that require relational integration (Bunge, Wendelken, Badre, & Wagner, 2004; Christoff et al., 2001). Moreover, activity in this region was found to increase parametrically with the number of dimensions needing to be considered in a set of stimuli (Kroger et al., 2002).

In cognitive aging research, age differences in reasoning and higher-order thinking and planning tasks are well established (Phillips, MacLeod, & Kliegel, 2005; Salthouse, 2005a). It has been commonly assumed that such declines reflect a generalized loss of cognitive resources or impaired executive control function. However, it is possible that age-related changes in reasoning and higher-order cognition could be due in part to the preferential dependence of certain types of these tasks on integration processes dependent on anterior PFC function. Although to date there have been no studies directly examining this question, the notion of relational integration seems similar to the construct of coordinative complexity developed by Mayr and Kliegl (1993). In a series of studies, coordinative complexity was found to lead to very large interactive slowing effects in older adults, suggesting that such tasks tap into a selectively age-impaired control mechanism (Verhaeghen, Kliegl, & Mayr, 1997). In another related study, Viskontas et al (2004) examined relational integration complexity in analogy verification, and found that age-related impairments were increased as integration complexity increased. Moreover, these effects were exacerbated when irrelevant information had to be suppressed from relational comparisons, especially at high levels of complexity. A fruitful direction for future research would be to draw on the advances and task paradigms developed in the basic cognitive neuroscience literature on anterior PFC and integration processes. Such studies could help determine whether age-related impairments in reasoning, planning, and higher-cognition tasks are reflective of a selective reduction in integration mechanisms, due to changes in anterior PFC function.

Temporal dynamics of executive control. A final domain of recent work in executive control relevant to cognitive aging research concerns dynamic rather than structural dissociations in control mechanisms. A series of research studies, carried out by West and colleagues, has examined age-related changes related to transient fluctuations of executive control during task performance (R. West, 2001). Importantly, in this work it was observed that both older and younger adults experienced periodic and transient episodes of goal neglect during the performance of different control tasks, such as Stroop, prospective memory and N-back working memory. What primarily differentiated older from younger adults, was not the number of episodes of reduced control, but their longer duration (e.g., measured by number of consecutive intrusion errors). Subsequent studies extended and refined well-established finding of age-related increases in performance variability (Hultsch et al, this volume), by observing that such variability is particularly present under conditions of high control demands (R. West, Murphy, Armilio, Craik, & Stuss, 2002). Likewise, modelling of reaction time distributions in older adults indicated that age-related variability effects were independent of general slowing, and appeared to be due to relatively transient periods of poor (slower) performance rather than a generalized increase in variability.

A second recent theme of research on the dynamics of cognitive control in aging has been put forward by Braver and colleagues as part of the Dual Mechanisms of Control (DMC) account (T. S. Braver, Gray, & Burgess, in press). The DMC account suggests that cognitive control can occur in two distinct modes: reactive and proactive.

Proactive control involves sustained active maintenance of goal representations and anticipatory biasing of attention and action systems prior to the onset of imperative events. In contrast, reactive control involves transient, stimulus-driven re-activation of goal information only in situations where such information is critical to avoid inappropriate performance. An important aspect of the DMC model is that cognitive control is flexible, such that transitions between transient and sustained goal activation can occur within individuals, in relationship to changing task conditions or internal states. According to the model, older adults may have a reduced tendency to use proactive control, but a relatively spared or even enhanced tendency to engage in reactive control.

This idea was recently tested in an event-related fMRI study of the AX-CPT task, in which it was found that older adults showed reduced cue-related activation of lateral PFC, but increased activation in lateral PFC and other regions during probe periods, especially for high interference BX trials (J.L. Paxton et al., submitted). Critically, however, these age-related changes in AX-CPT activation were not fixed, but instead were significantly impacted by strategic training in the use of proactive control in AX-CPT performance (i.e., by improving predictive cue utilization). Following training, behavioral results indicated a pattern of performance in older adults that was more similar to that of young adults (J. L. Paxton, Barch, Storandt, & Braver, 2006), and was accompanied by both an increase in cue-related activation and a decrease in probe-related activation of lateral PFC (T. S. Braver, Locke, Paxton, & Barch, in preparation). Thus, the results suggested that older adults could in fact rely upon the neural mechanisms of proactive control, but only following explicit training.

These findings suggest that altered PFC function in older adults may not be a static phenomenon, but may interact with the dynamics of task processing and cognitive demands on goal activation and maintenance. The recent work suggesting that these dynamic changes in older adult cognitive control might be amenable to training, provide a promising potential for future research.

Summary and Future Directions

In this chapter, we have examined the literature on changes in executive control that occur with advancing age. The older literature on executive functions in aging typically occurred within the context of other cognitive domains, such as working memory, attention and episodic memory (J.M. McDowd & Shaw, 2000; Zacks et al., 2000). More recently, however, aging effects on executive control are being studied as a primary focus of research. This shift has arisen in part from a realization that even in domains such as working memory and episodic memory, age-related deficits may be primarily due to impaired executive control, rather than in the mechanisms of storage per se.

We considered a number of domains of executive control in which age-related effects are prominent, including working memory, strategic control of episodic and prospective memory, response inhibition, task-management and context processing. In each of these domains, aging effects have been investigated using a variety of approaches, including cross-sectional covariation, neurocognitive methods, and process-based task-analysis. We situated this review within the context of a theoretical framework known as goal maintenance theory, which postulates that older adults suffer from a primary impairment in internally representing, updating and maintaining task-related goals. These cognitive changes are directly linked to an underlying neurobiological change in the function of lateral PFC in its interaction with the mid-brain DA system, as both of these neural substrates are well-established to exhibit prominent changes with advancing age. The goal maintenance framework provides an organizing account of the data that appears to explain the nature of older adult deficits in a range of executive control domains and tasks. Nevertheless, theoretical and experimental investigations of executive control in aging utilizing the goal maintenance framework are still at an early stage, and much work remains to be done to better establish the validity and explanatory power of the theory.

One important direction for future research is to better establish the boundary conditions of the goal maintenance framework as a predictive and explanatory tool in studying cognitive aging. In particular, it will be necessary to better determine which tasks and performance measures are most sensitive to age-related goal maintenance deficits. Such determinations are often difficult to make in practice, as many of the executive control tasks commonly used in the literature are complex, such that obvious performance measures may reflect multiple processes in addition to goal maintenance. Interference costs in the Stroop task, and switch costs in task-switching paradigms provide good examples of this point. As we described, systematic studies of these measures reveal that they are multi-factorial in nature, and thus may not provide transparent indices of goal maintenance impairments in older adults. In this regard, process-based task analyses may help to better design paradigms that provide performance measures in such paradigms that are more sensitive and specific with regard to goal maintenance effects. A potentially more powerful approach may be to utilize computational and mathematical modeling techniques to better extract estimates of goal-maintenance processes within complex executive control tasks. Another, exciting alternative is to use neurocognitive techniques, such as ERP or fMRI, to directly index activation within lateral PFC and other brain regions during performance of executive control tasks. In this way, estimates of neural activity may serve as something analogous to a latent construct, that can form the basis for age-related comparisons across multiple tasks. Of course, such work will need to establish the validity of these activity measures through analyses of brain-behavior relationships. But it may be the case that activity within lateral PFC of older adults serves as a better indicator of age-related cognitive impairment than specific behavioral measures themselves.

A critical further goal of this work will be to try to identify multiple indices of the goal maintenance construct (via brain-based or behavior-based process estimates) across task domains, in order to more rigorously establish that such a coherent construct can be formed and utilized to understand cognitive aging more broadly. In this endeavor, the psychometrically rigorous approaches advocated by Salthouse and others (Salthouse, 2001, 2005b, 2006) will become invaluable. In particular, if and when a coherent goal maintenance construct can be established, it can form the basis for the types of cross-sectional (and longitudinal) covariation studies that have are so powerful and useful within aging research. The key questions that need to be answered concern whether the goal maintenance construct can explain significant amounts of age-related variation relative to other potential constructs (e.g. processing speed), and the degree to which the goal maintenance construct is distinct from other constructs that may also impact cognitive aging. In this regard, the recent work examining error/performance monitoring, emotion-cognition interactions, and integration are potentially very informative, as they are suggestive of other dimensions of executive control and associated neural mechanisms that may be independent of goal maintenance, but may also show interesting interactions.

The final recent development that was discussed in this chapter suggests that it is equally important to consider the temporal dynamics of executive control in terms of the role of goal maintenance. In particular, recent work suggests that older adults may not have a static impairment in the ability to represent and maintain goals, but rather that the dynamics of this process become dysregulated with advancing age. Thus, it may be the case that older adults suffer from greater fluctuations in the activation level of maintained goals, or show a reduced tendency to engage and maintain goal representations in a proactive fashion. However, initial work examining these processes suggest that such changes in goal maintenance dynamics may not be a fixed impairment in older adults, but could be potentially amenable to direct training and instruction (Erickson et al., 2007; J. L. Paxton et al., 2006). Such work, though currently only in its infancy, may provide a path towards arguably the most important goal of cognitive aging research –to translate improved understanding of the fundamental age-related cognitive impairments into effective interventions that can minimize, or ideally, reverse them.

REFERENCES

Allen, P. A., Smith, A. F., Vires-Collins, H., & Sperry, S. (1998). The psychological refractory period: evidence for age differences in attentional time-sharing. *Psychol Aging, 13*(2), 218-229.

Allport, A., & Wylie, G. (2000). Task-Switching, stimulus-response bindings, and negative priming. In S. Monsell & J. S. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 35-70). Cambridge, MA: MIT Press.

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and Performance XV* (pp. 421-452). Cambridge, MA: MIT Press.

Anderson, N. D., Craik, F. I., & Naveh-Benjamin, M. (1998). The attentional demands of encoding and retrieval in younger and older adults: 1. Evidence from divided attention costs. *Psychol Aging, 13*(3), 405-423.

Anderson, S. W., Damasio, H., Jones, D. R., & Tranel, D. (1991). Wisconsin card sorting test performance as a measure of frontal lobe damage. *Journal of Clinical and Experimental Neuropsychology, 13*(6), 909-922.

Babcock, R. L., & Salthouse, T. A. (1990). Effects of increased processing demands on age differences in working memory. *Psychol Aging, 5*(3), 421-428.

Backman, L., & Farde, L. (2005). The role of dopamine systems in cognitive aging. In R. Cabeza, L. Nyberg & D. Park (Eds.), *Cognitive Neuroscience of Aging: Linking Cognitive and Cerebral Aging* (pp. 58-84). New York, NY: Oxford University Press.

Baddeley, A. (1986). *Working Memory*. Oxford, UK: Oxford University Press.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nat Rev Neurosci, 4*(10), 829-839.

Band, G. P., & Kok, A. (2000). Age effects on response monitoring in a mental-rotation task. *Biol Psychol, 51*(2-3), 201-221.

Barch, D. M., Braver, T. S., Nystrom, L. E., Forman, S. D., Noll, D. C., & Cohen, J. D. (1997). Dissociating working memory from task difficulty in human prefrontal cortex. *Neuropsychologia, 35*(10), 1373-1380.

Barch, D. M., Carter, C. S., Braver, T. S., Sabb, F. W., MacDonald, A., 3rd, Noll, D. C., et al. (2001). Selective deficits in prefrontal cortex function in medication-naive patients with schizophrenia. *Arch Gen Psychiatry, 58*(3), 280-288.

Bechara, A., Damasio, H., & Damasio, A. R. (2000). Emotion, decision making and the orbitofrontal cortex. *Cerebral Cortex, 10*, 295-307.

Bechara, A., Damasio, H., Tranel, D., & Anderson, S. W. (1998). Dissociation of working memory from decision making within the human prefrontal cortex. *Journal of Neuroscience, 18*(1), 428-437.

Bechara, A., Damasio, H., Tranel, D., & Damasio, A. R. (1997). Deciding advantageously before knowing the advantageous strategy. *Science, 275*, 1293-1295.

Bedard, A. C., Nichols, S., Barbosa, J. A., Schachar, R., Logan, G. D., & Tannock, R. (2002). The development of selective inhibitory control across the life span. *Dev Neuropsychol, 21*(1), 93-111.

Bherer, L., Kramer, A. F., Peterson, M. S., Colcombe, S., Erickson, K., & Becic, E. (2005). Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychol Aging, 20*(4), 695-709.

Bialystok, E., Craik, F. I., Klein, R., & Viswanathan, M. (2004). Bilingualism, aging, and cognitive control: evidence from the Simon task. *Psychol Aging, 19*(2), 290-303.

Bjorklund, D. F., & Harnishfeger, K. K. (1995). The Evolution of Inhibition Mechanisms and Their Role in Human Cognition and Behavior. In F. N. Dempster & C. J. Brainerd (Eds.), *Interference and inhibition in cognition*. San Diego: Academic Press.

Bopp, K. L., & Verhaeghen, P. (2005). Aging and verbal memory span: a meta-analysis. *J Gerontol B Psychol Sci Soc Sci, 60*(5), P223-233.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychol Rev, 108*(3), 624-652.

Botwinick, J. (1969). Disinclination to venture versus cautiousness in responding: Age differences. *Journal of Genetic Psychology, 115*, 55-62.

Bowles, R. P., & Salthouse, T. A. (2003). Assessing the age-related effects of proactive interference on working memory tasks using the Rasch model. *Psychol Aging, 18*(3), 608-615.

Brandimonte, M., Einstein, G., & McDaniel, M. (Eds.). (1996). *Prospective memory: Theory and applications*. Hillsdale, NJ: Erlbaum.

Brass, M., & von Cramon, D. Y. (2004). Decomposing components of task preparation with functional magnetic resonance imaging. *J Cogn Neurosci, 16*(4), 609-620.

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience and Biobehavioral Reviews, 26*, 809-817.

Braver, T. S., Barch, D. M., & Cohen, J. D. (1999). Cognition and control in schizophrenia: A computational model of dopamine and prefrontal function. *Biological Psychiatry, 46*, 312-328.

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., et al. (2001). Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General, 130*, 746-763.

Braver, T. S., & Bongiolatti, S. R. (2002). The role of frontopolar cortex in subgoal processing during working memory. *Neuroimage, 15*(3), 523-536.

Braver, T. S., & Cohen, J. D. (2000). On the control of control: The role of dopamine in regulating prefrontal function and working memory. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII* (pp. 713-738). Cambridge, MA: MIT Press.

Braver, T. S., & Cohen, J. D. (2001). Working memory, cognitive control, and the prefrontal cortex: Computational and empirical studies. *Cognitive Processing, 2*, 25-55.

Braver, T. S., Cohen, J. D., & Barch, D. M. (2002). The role of the prefrontal cortex in normal and disordered cognitive control: A cognitive neuroscience perspective. In D. T. Stuss & R. T. Knight (Eds.), *Principles of Frontal Lobe Function* (pp. 428-448). Oxford: Oxford University Press.

Braver, T. S., Gray, J. R., & Burgess, G. C. (in press). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In Conway.A., J. C., M. J. Kane, A. Miyake & J. Towse (Eds.), *Variation in Working Memory*. Oxford: Oxford University Press.

Braver, T. S., Locke, H. S., Paxton, J. L., & Barch, D. M. (in preparation). Flexible neural mechanisms of cognitive control in human prefrontal cortex.

Braver, T. S., Reynolds, J. R., & Donaldson, D. I. (2003). Neural mechanisms of transient and sustained cognitive control during task switching. *Neuron, 39*(4), 713-726.

Braver, T. S., & Ruge, H. (2006). Functional neuroimaging of executive functions. In R. Cabeza & A. Kingstone (Eds.), *Functional neuroimaging of cognition* (pp. 307-347). Cambridge, MA: MIT Press.

Braver, T. S., Satpute, A. B., Rush, B. K., Racine, C. A., & Barch, D. M. (2005). Context processing and context maintenance in healthy aging and early-stage dementia of the Alzheimer's type. *Psychology & Aging, 20*, 33-46.

Brinley, J. F. (1965). Cognitive sets, speed and accuracy of performance in the elderly. In A. T. Welford & J. E. Birren (Eds.), *Behavior, aging, and the nervous system* (pp. 114-149). Springfield: Charles C Thomas.

Brown, J. W., & Braver, T. S. (2005). Learned predictions of error likelihood in the anterior cingulate cortex. *Science, 307*, 1118-1121.

Brown, J. W., Reynolds, J. R., & Braver, T. S. (2006). A computational model of fractionated conflict-control mechanisms in task-switching. *Cognit Psychol*.

Bunge, S. A., Wendelken, C., Badre, D., & Wagner, A. D. (2004). Analogical Reasoning and Prefrontal Cortex: Evidence for Separable Retrieval and Integration Mechanisms. *Cereb Cortex*.

Butler, K. M., McDaniel, M. A., Dornburg, C. C., Price, A. L., & Roediger, H. L., 3rd. (2004). Age differences in veridical and false recall are not inevitable: the role of frontal lobe function. *Psychon Bull Rev, 11*(5), 921-925.

Butler, K. M., Zacks, R. T., & Henderson, J. M. (1999). Suppression of reflexive saccades in younger and older adults: age comparisons on an antisaccade task. *Mem Cognit, 27*(4), 584-591.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: the HAROLD model. *Psychol Aging, 17*(1), 85-100.

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience, 12*, 1-47.

Cabeza, R., Nyberg, L., & Park, D. (2005). *Cognitive Neuroscience of Aging: Linking Cognitive and Cerebral Aging*. New York: Oxford University Press.

Carstensen, L. L., & Mikels, J. A. (2005). At the intersection of emotion and cognition: Aging and the positivity effect. *Current Directions in Psychological Science, 14*, 117-121.

Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science, 280*(5364), 747-749.

Casey, B. J., Tottenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: what have we learned about cognitive development? *Trends Cogn Sci, 9*(3), 104-110.

Chalfonte, B. L., & Johnson, M. K. (1996). Feature memory and binding in young and older adults. *Mem Cognit, 24*(4), 403-416.

Christoff, K., & Gabrieli, J. D. (2000). The frontopolar cortex and human cognition: Evidence for a rostrocaudal hierarchical organization within the human prefrontal cortex. *Psychobiology, 28*, 168-186.

Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., Holyoak, K. J., et al. (2001). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. *Neuroimage, 14*(5), 1136-4119.

Clark, L., Manes, F., Antoun, N., Sahakian, B. J., & Robbins, T. W. (2003). The contributions of lesion laterality and lesion volume to decision-making impairment following frontal lobe damage. *Neuropsychologia, 41*(11), 1474-1483.

Cohen, A., West, R., & Craik, F. I. M. (2001). Modulation of the prospective and retrospective components of memory for intentions in younger and older adults. *Aging Neuropsychology and Cognition, 8*(1), 1-13.

Cohen, J. D., Botvinick, M., & Carter, C. S. (2000). Anterior cingulate and prefrontal cortex: who's in control? *Nat Neurosci, 3*(5), 421-423.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). *On the control of automatic processes: A parallel distributed processing account of the Stroop effect* (Vol. 97 3).

Convit, A., Wolf, O. T., de Leon, M. J., Patalinjug, M., Kandil, E., Caraos, C., et al. (2001). Volumetric analysis of the pre-frontal regions: findings in aging and schizophrenia. *Psychiatry Res, 107*(2), 61-73.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104*, 163-191.

Cowan, N. (1995). *Attention and Memory*. Oxford: Oxford University Press.

Cowan, N. (1999). An embedded-process model of working memory. In A. Miyake & P. Shah (Eds.), *Models of Working Memory* (pp. 62-101). Cambridge, UK: Cambridge University Press.

Craik, F., & Bialystok, E. (2005). Intelligence and executive control: evidence from aging and bilingualism. *Cortex, 41*(2), 222-224.

Craik, F. I., Morris, L. W., Morris, R. G., & Loewen, E. R. (1990). Relations between source amnesia and frontal lobe functioning in older adults. *Psychol Aging, 5*(1), 148-151.

Craik, F. I. M. (1977). Age differences in human memory. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the Psychology of Aging* (pp. 384-420). New York: Van Nostrand Reinhold.

Craik, F. I. M., & Byrd, M. (1982). Aging and cognitive deficits: The role of attentional resources. In F. I. M. Craik & S. Trehub (Eds.), *Aging & Cognitive Processes: Advances in the Study of Communication and Affect* (Vol. 8, pp. 191-211). New York: Plenum Press.

Craik, F. I. M., Govoni, R., Naveh-Benjamin, M., & Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology: General, 2*, 159-180.

Craik, F. I. M., & Jennings, J. M. (1992). Human memory. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (pp. 51-110). Hillsdale, NJ: Erlbaum.

Craik, F. I. M., & McDowd, J. M. (1987). Age differences in recall and recognition. *Journal of Experimental Psychology: Learning, Memory and Cognition, 13*, 474-479.

Damasio, A. R. (1994). *Descartes' error: Emotion, reason and the human brain*. New York: Grosset/Putnam.

Davidson, D. J., Zacks, R. T., & Williams, C. C. (2003). Stroop interference, practice, and aging. *Aging, Neuropsychology, and Cognition, 10*, 85-98.

Davidson, P. S., & Glisky, E. L. (2002). Neuropsychological correlates of recollection and familiarity in normal aging. *Cogn Affect Behav Neurosci, 2*(2), 174-186.

De Jong, R. (2001). Adult age differences in goal activation and goal maintenance. *European Journal of Cognitive Psychology, 13*(1/2), 71-89.

De Pisapia, N., Repovs, G., & Braver, T. S. (in press). Computational models of attention and cognitive control. In R. Sun (Ed.), *Handbook on computational cognitive modelling*. Cambridge: Cambridge University Press.

De Pisapia, N., Slomski, J. A., & Braver, T. S. (2006). Functional Specializations in Lateral Prefrontal Cortex Associated with the Integration and Segregation of Information in Working Memory. *Cereb Cortex.*

Deakin, J., Aitken, M., Robbins, T., & Sahakian, B. J. (2004). Risk taking during decision-making in normal volunteers changes with age. *J Int Neuropsychol Soc, 10*(4), 590-598.

Dehaene, S., Posner, M. I., & Tucker, D. M. (1994). Localization of a neural system for error detection and compensation. *Psychological Science, 5*(5), 303-306.

Demakis, G. J. (2003). A meta-analytic review of the sensitivity of the Wisconsin Card Sorting Test to frontal and lateralized frontal brain damage. *Neuropsychology, 17*(2), 255-264.

Denburg, N. L., Tranel, D., & Bechara, A. (2005). The ability to decide advantageously declines prematurely in some normal older persons. *Neuropsychologia, 43*(7), 1099-1106.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18*, 193-222.

Diamond, A. (1998). Evidence for the importance of dopamine for prefrontal cortex functions earlyl in life. In A. C. Roberts, T. W. Robbins & L. Weiskrantz (Eds.), *The Prefrontal Cortex: Executive and Cognitive Functions* (pp. 144-164). Oxford, UK: Oxford University Press.

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 466-503). UK: Oxford University Press.

DiGirolamo, G. J., Kramer, A. F., Barad, V., Cepeda, N. J., Weissman, D. H., Milham, M. P., et al. (2001). General and task-specific frontal lobe recruitment in older adults during executive processes: A fMRI investigation of task-switching. *NeuroReport, 12*(9), 2065-2071.

Dobbs, A. R., & Rule, B. G. (1987). Prospective memory and self-reports of memory abilities in older adults. *Can J Psychol, 41*(2), 209-222.

Dulaney, C. L., & Rogers, W. A. (1994). Mechanisms underlying reduction in Stroop interference with practice for young and older adults. *Journal of Experimental Psychology: Learning, Memory and Cognition, 20*, 470-484.

Duncan, J. (1995). Attention, intelligence, and the frontal lobes. In M. Gazzaniga (Ed.), *The Cognitive Neurosciences* (pp. 721-733). Cambridge, MA: MIT Press.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology, 30*, 257-303.

Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends Neurosci, 23*(10), 475-483.

Dux, P. E., Ivanoff, J., Asplund, C. L., & Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved fMRI. *Neuron, 52*, 1109-1120.

Eenshuistra, R. M., Ridderinkhof, K. R., & van der Molen, M. W. (2004). Age-related changes in antisaccade task performance: inhibitory control or working-memory engagement? *Brain Cogn, 56*(2), 177-188.

Einstein, G. O., & McDaniel, M. A. (1990). Normal aging and prospective memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16*(4), 717-726.

Einstein, G. O., & McDaniel, M. A. (1996). Retrieval processes in prospective memory: Theoretical approaches and some new empirical findings. In M. Brandimonte, G. O. Einstein & M. A. McDaniel (Eds.), *Prospective memory: Theory and applications* (pp. 115-142). Mahwah, NJ: Erlbaum.

Einstein, G. O., McDaniel, M. A., Manzi, M., Cochran, B., & Baker, M. (2000). Prospective Memory and Aging: Forgetting Intentions Over Short Delays. *Psychology and Aging, 15*(4), 1-13.

Einstein, G. O., McDaniel, M. A., Smith, R. E., & Shaw, P. (1998). Habitual prospective memory and aging: Remembering intentions and forgetting actions. *Psychological Science, 9*(4), 284-288.

Einstein, G. O., McDaniel, M. A., Thomas, R., Mayfield, S., Shank, H., Morrisette, N., et al. (2005). Multiple processes in prospective memory retrieval: factors determining monitoring versus spontaneous retrieval. *J Exp Psychol Gen, 134*(3), 327-342.

Einstein, G. O., Smith, R. E., McDaniel, M. A., & Shaw, P. (1997). Aging and prospective memory: The influence of increased task demands at encoding and retrieval. *Psychology and Aging, 12*(3), 479-488.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*, 19-23.

Engle, R. W., Conway, A. R. A., Tuholski, S. W., & Shisler, R. J. (1995). A resource account of inhibition. *Psychological Science, 6*, 122-125.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*, 309-331.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., et al. (2007). Training-induced functional activation changes in dual-task processing: an FMRI study. *Cereb Cortex, 17*(1), 192-204.

Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalogr Clin Neurophysiol, 78*(6), 447-455.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (2001). Changes of error-related ERPs with age. *Exp Brain Res, 138*(2), 258-262.

Fellows, L. K. (2004). The cognitive neuroscience of human decision making: a review and conceptual framework. *Behav Cogn Neurosci Rev, 3*(3), 159-172.

Fellows, L. K., & Farah, M. J. (2005). Different underlying impairments in decision-making following ventromedial and dorsolateral frontal lobe damage in humans. *Cereb Cortex, 15*(1), 58-63.

Fernandes, M. A., Davidson, P. S., Glisky, E. L., & Moscovitch, M. (2004). Contribution of frontal and temporal lobe function to memory interference from divided attention at retrieval. *Neuropsychology, 18*(3), 514-525.

Frank, M. J., & Claus, E. D. (2006). Anatomy of a decision: striato-orbitofrontal interactions in reinforcement learning, decision making, and reversal. *Psychol Rev, 113*(2), 300-326.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: a latent-variable analysis. *J Exp Psychol Gen, 133*(1), 101-135.

Fristoe, N. M., Salthouse, T. A., & Woodard, J. L. (1997). Examination of age-related deficits on the Wisconsin Card Sorting Test. *Neuropsychology, 11*(3), 428-436.

Fukui, H., Murai, T., Fukuyama, H., Hayashi, T., & Hanakawa, T. (2005). Functional activity related to risk anticipation during performance of the Iowa Gambling Task. *Neuroimage, 24*(1), 253-259.

Funahashi, S., Chafee, M. V., & Goldman-Rakic, P. S. (1993). Prefrontal neuronal activity in rhesus monkeys performing a delayed anti-saccade task. *Nature, 365*(October 21), 753-755.

Gehring, W. J., Goss, B., Coles, M. G. H., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science, 4*, 385-390.

Glass, J. M., Schumacher, E. H., Lauber, E. J., Zurbriggen, E. L., Gmeindl, L., Kieras, D. E., et al. (2000). Aging and the psychological refractory period: task-coordination strategies in young and old adults. *Psychol Aging, 15*(4), 571-595.

Glisky, E. L., Polster, M. R., & Routhieaux, B. C. (1995). Double dissociation between item and source memory. *Psychology and Aging, 9*, 229-235.

Guitton, D., Buchtel, H. A., & Douglas, R. M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research, 58*, 455-472.

Gunning-Dixon, F. M., & Raz, N. (2003). Neuroanatomical correlates of selected executive functions in middle-aged and older adults: a prospective MRI study. *Neuropsychologia, 41*(14), 1929-1941.

Guynn, M. J. (2003). A two-process model of strategic monitoring in event-based prospective memory: Activation/retrieval mode and checking. *International Journal of Psychology, 38*, 245-256.

Haarmann, H. J., Ashling, G. E., Davelaar, E. J., & Usher, M. (2005). Age-related declines in context maintenance and semantic short-term memory. *Q J Exp Psychol A, 58*(1), 34-53.

Hartley, A. A. (1992). Attention. In F. I. M. Craik & T. Salthouse (Eds.), *The Handbook of Aging and Cognition* (pp. 3-49). Hillsdale, NJ: Erlbaum.

Hartley, A. A. (1993). Evidence for the selective preservation of spatial selective attention in old age. *Psychol Aging, 8*(3), 371-379.

Hartley, A. A. (2001). Age differences in dual-task interference are localized to response-generation processes. *Psychol Aging, 16*(1), 47-54.

Hartley, A. A., & Little, D. M. (1999). Age-related differences and similarities in dual-task interference. *J Exp Psychol Gen, 128*(4), 416-449.

Hartley, J. T. (1986). Reader and text variables as determinants of discourse memory in adulthood. *Psychology & Aging, 1*, 150-158.

Hartman, M., Bolton, E., & Fehnel, S. E. (2001). Accounting for age differences on the Wisconsin Card Sorting Test: decreased working memory, not inflexibility. *Psychol Aging, 16*(3), 385-399.

Hasher, L., Chung, C., May, C. P., & Foong, N. (2002). Age, time of testing, and proactive interference. *Can J Exp Psychol, 56*(3), 200-207.

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology, 108*(3), 356-388.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: a review and a new view. *The Psychology of Learning and Motivation, 22*, 193-225.

Hay, J. F., & Jacoby, L. L. (1999). Separating habit and recollection in young and older adults: effects of elaborative processing and distinctiveness. *Psychol Aging, 14*(1), 122-134.

Hedden, T., & Park, D. (2001). Aging and interference in verbal working memory. *Psychol Aging, 16*(4), 666-681.

Hedden, T., & Park, D. C. (2003). Contributions of source and inhibitory mechanisms to age-related retroactive interference in verbal working memory. *J Exp Psychol Gen, 132*(1), 93-112.

Hein, G., & Schubert, T. (2004). Aging and input processing in dual-task situations. *Psychol Aging, 19*(3), 416-432.

Henry, J. D., MacLeod, M. S., Phillips, L. H., & Crawford, J. R. (2004). A meta-analytic review of prospective memory and aging. *Psychol Aging, 19*(1), 27-39.

Hester, R. L., Murphy, K., Foxe, J. J., Foxe, D. M., Javitt, D. C., & Garavan, H. (2004). Predicting success: patterns of cortical activation and deactivation prior to response inhibition. *J Cogn Neurosci, 16*(5), 776-785.

Hofer, S. M., & Sliwinski, M. J. (2001). Understanding Ageing. An evaluation of research designs for assessing the interdependence of ageing-related changes. *Gerontology, 47*(6), 341-352.

Holroyd, C. B., & Coles, M. G. (2002). The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. *Psychol Rev, 109*(4), 679-709.

Jacoby, L. L., Bishara, A. J., Hessels, S., & Toth, J. P. (2005). Aging, subjective experience, and cognitive control: dramatic false remembering by older adults. *J Exp Psychol Gen, 134*(2), 131-148.

Jacques, S., & Zelazo, P. D. (2001). The Flexible Item Selection Task (FIST): a measure of executive function in preschoolers. *Dev Neuropsychol, 20*(3), 573-591.

Jennings, J. M., & Jacoby, L. L. (1993). Automatic versus intentional uses of memory: aging, attention, and control. *Psychol Aging, 8*(2), 283-293.

Jennings, J. M., & Jacoby, L. L. (2003). Improving memory in older adults: Training recollection. *Neuropsychological Rehabilitation, 13*, 417-440.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology, 89*.

Johnson, M. K., Mitchell, K. J., Raye, C. L., & Greene, E. J. (2004). An age-related deficit in prefrontal cortical function associated with refreshing information. *Psychol Sci, 15*(2), 127-132.

Johnson, M. K., Reeder, J. A., Raye, C. L., & Mitchell, K. J. (2002). Second thoughts versus second looks: an age-related deficit in reflectively refreshing just-activated information. *Psychol Sci, 13*(1), 64-67.

Jonides, J., Marshuetz, C., Smith, E. E., Reuter-Lorenz, P. A., Koeppe, R. A., & Hartley, A. (2000). Age differences in behavior and PET activation reveal differences in interference resolution in verbal working memory. *Journal of Cognitive Neuroscience, 12*, 188-196.

Kane, M. J., & Engle, R. W. (2000). Working-memory capacity, proactive interference, and divided attention: limits on long-term memory retrieval. *J Exp Psychol Learn Mem Cogn, 26*(2), 336-358.

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin and Review, 9*, 637-671.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *J Exp Psychol Gen, 132*(1), 47-70.

Kerns, J. G., Cohen, J. D., MacDonald, A. W., 3rd, Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*(5660), 1023-1026.

Kidder, D. P., Park, D. C., Hertzog, C., & Morrell, R. W. (1997). Prospective memory and aging: The effects of working memory and prospective memory task load. *Aging, Neuropsychology, and Cognition, 4*(93-112).

Kliegel, M., Martin, M., & Moor, C. (2003). Prospective memory and ageing: Is task importance relevant? . *International Journal of Psychology, 38*, 207-214.

Koechlin, E., Basso, G., Pietrini, P., Panzer, S., & Grafman, J. (1999). The role of the anterior prefrontal cortex in human cognition. *Nature, 399*, 148-151.

Kornblum, S. (1992). Dimensional overlap and dimensional relevance in stimulus-response and stimulus-stimulus compatibility. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor Behavior II* (pp. 743-777): Elsevier Science Publishers B.V.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9*(4), 491-512.

Krawczyk, D. C. (2002). Contributions of the prefrontal cortex to the neural basis of human decision making. *Neurosci Biobehav Rev, 26*(6), 631-664.

Kray, J., Li, K. Z., & Lindenberger, U. (2002). Age-related changes in task-switching components: the role of task uncertainty. *Brain Cogn, 49*(3), 363-381.

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15*(1), 126-147.

Kroger, J. K., Sabb, F. W., Fales, C. L., Bookheimer, S. Y., Cohen, M. S., & Holyoak, K. J. (2002). Recruitment of anterior dorsolateral prefrontal cortex in human reasoning: a parametric study of relational complexity. *Cereb Cortex, 12*(5), 477-485.

Li, S. C., Naveh-Benjamin, M., & Lindenberger, U. (2005). Aging neuromodulation impairs associative binding: a neurocomputational account. *Psychol Sci, 16*(6), 445-450.

Light, L. L., & Anderson, P. A. (1985). Working-memory capacity, age, and memory for discourse. *Journal of Gerontology, 40*(6), 737-747.

Lindsay, D. S., & Jacoby, L. L. (1994). Stroop process dissociations: The relationship between facilitation and interference. *Journal of Experimental Psychology: Human Perception & Performance, 20*(2), 219-234.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task cuing procedure. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 575-599.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review, 91*(3), 295-327.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychol Rev, 108*(2), 393-434.

Logie, R. H., Maylor, E. A., Della Sala, S., & Smith, G. (2004). Working memory in event- and time-based prospective memory tasks: Effects of secondary demand and age. *European Journal of Cognitive Psychology, 16*, 441-456.

Luria, A. R. (1966). *Higher Cortical Functions in Man*. London: Tavistock.

Lustig, C., Hasher, L., & Tonev, S. T. (2006). Distraction as a determinant of processing speed. *Psychonomic Bulletin and Review, 13*, 619-625.

Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *J Exp Psychol Gen, 130*(2), 199-207.

MacDonald, A. W., 3rd, & Carter, C. S. (2003). Event-related FMRI study of context processing in dorsolateral prefrontal cortex of patients with schizophrenia. *J Abnorm Psychol, 112*(4), 689-697.

MacDonald, A. W., 3rd, Goghari, V. M., Hicks, B. M., Flory, J. D., Carter, C. S., & Manuck, S. B. (2005). A convergent-divergent approach to context processing, general intellectual functioning, and the genetic liability to schizophrenia. *Neuropsychology, 19*(6), 814-821.

MacLeod, C. M., & Dunbar, K. (1988). Training and Stroop-like interference: Evidence for a continuum of automaticity. *Journal of Experimental Psychology, 14*, 126-135.

MacPherson, S. E., Phillips, L. H., & Della Sala, S. (2002). Age, executive function, and social decision making: a dorsolateral prefrontal theory of cognitive aging. *Psychol Aging, 17*(4), 598-609.

Manes, F., Sahakian, B., Clark, L., Rogers, R., Antoun, N., Aitken, M., et al. (2002). Decision-making processes following damage to the prefrontal cortex. *Brain, 125*(Pt 3), 624-639.

Mantyla, T. (1994). Remembering to remember: adult age differences in prospective memory. *J Gerontol, 49*(6), P276-282.

Maquestiaux, F., Hartley, A. A., & Bertsch, J. (2004). Can practice overcome age-related differences in the psychological refractory period effect? *Psychol Aging, 19*(4), 649-667.

Marschner, A., Mell, T., Wartenburger, I., Villringer, A., Reischies, F. M., & Heekeren, H. R. (2005). Reward-based decision-making and aging. *Brain Res Bull, 67*(5), 382-390.

Marsh, R. L., Hicks, J. L., Cook, G. I., & Mayhorn, C. B. (in press). Comparing younger and older adults in an event-based prospective memory paradigm containing an output monitoring component. *Aging, Neuropsychology and Cognition.*

Martin, M., Kliegel, M., & McDaniel, M. A. (2003). The involvement of executive functions in prospective memory performance of adults. *International Journal of Psychology, 38*, 193-206.

Mathalon, D. H., Bennett, A., Askari, N., Gray, E. M., Rosenbloom, M. J., & Ford, J. M. (2003). Response-monitoring dysfunction in aging and Alzheimer's disease: an event-related potential study. *Neurobiol Aging, 24*(5), 675-685.

Mather, M., & Carstensen, L. L. (2005). Aging and motivated cognition: the positivity effect in attention and memory. *Trends Cogn Sci, 9*(10), 496-502.

Mather, M., & Knight, M. (2005). Goal-directed memory: the role of cognitive control in older adults' emotional memory. *Psychol Aging, 20*(4), 554-570.

Mathewson, K. J., Dywan, J., & Segalowitz, S. J. (2005). Brain bases of error-related ERPs as influenced by age and task. *Biol Psychol, 70*(2), 88-104.

May, C. P., & Hasher, L. (1998). Synchrony effects in inhibitory control over thought and action. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 363-379.

May, C. P., Hasher, L., & Kane, M. J. (1999). The role of interference in memory span. *Mem Cognit, 27*(5), 759-767.

May, C. P., Zacks, R. T., Hasher, L., & Multhaup, K. S. (1999). Inhibition in the processing of garden-path sentences. *Psychology and Aging, 14*(2), 304-313.

Maylor, E. A. (1993). Aging and forgetting in prospective and retrospective memory tasks. *Psychol Aging, 8*(3), 420-428.

Maylor, E. A. (1998). Changes in event-based prospective memory across adulthood. *Aging, Neuropsychology, and Cognition, 5*, 107-128.

Mayr, U. (2001). Age differences in the selection of mental sets: the role of inhibition, stimulus ambiguity, and response-set overlap. *Psychol Aging, 16*(1), 96-109.

Mayr, U., & Kliegl, R. (1993). Sequential and coordinative complexity: age-based processing limitations in figural transformations. *J Exp Psychol Learn Mem Cogn, 19*(6), 1297-1320.

McCabe, J., & Hartman, M. (2003). Examining the locus of age effects on complex span tasks. *Psychol Aging, 18*(3), 562-572.

McDaniel, M. A., & Einstein, G. O. (1992). Aging and prospective memory: basic findings and practical applications. *Advances in Learning and Behavioral Disabilities, 7*, 87-105.

McDaniel, M. A., Einstein, G. O., Stout, A. C., & Morgan, Z. (2003). Aging and maintaining intentions over delays: do it or lose it. *Psychol Aging, 18*(4), 823-835.

McDaniel, M. A., Glisky, E. L., Rubin, S. R., Guynn, M. J., & Routhieaux, B. C. (1999). Prospective memory: A neuropsychological study. *Neuropsychology, 13*(1), 103-110.

McDaniel, M. A., Guynn, M. J., Einstein, G. O., & Breneiser, J. (2004). Cue-focused and reflexive-associative processes in prospective memory retrieval. *J Exp Psychol Learn Mem Cogn, 30*(3), 605-614.

McDowd, J. M., & Craik, F. I. (1988). Effects of aging and task difficulty on divided attention performance. *J Exp Psychol Hum Percept Perform, 14*(2), 267-280.

McDowd, J. M., & Shaw, R. J. (2000). Attention and aging: A functional perspective. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed., pp. 221-292). Mahwah, NJ: Lawrence Erlbaum.

McElree, B. (2001). Working memory and focal attention. *Journal of Experimental Psychology: Learning, Memory and Cognition, 27*(3), 817-835.

Meiran, N. (1996). Reconfiguration of Processing Mode Prior to Task Performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*(6), 1423-1442.

Meiran, N. (2000). Modeling cognitive control in task-switching. *Psychological Research, 63*, 234-249.

Meiran, N., Gotler, A., & Perlman, A. (2001). Old age is associated with a pattern of relatively intact and relatively impaired task-set switching abilities. *Journals of Gerontology: Series B: Psychological Sciences & Social Sciences, 56B*, P88-P102.

Melara, R. D., & Algom, D. (2003). Driven by information: a tectonic theory of Stroop effects. *Psychol Rev, 110*(3), 422-471.

Milham, M. P., Erickson, K. I., Banich, M. T., Kramer, A. F., Webb, A., Wszalek, T., et al. (2002). Attentional control in the aging brain: insights from an fMRI study of the stroop task. *Brain Cogn, 49*(3), 277-296.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 21*, 167-202.

Milner, B. (1963). Effects of different brain lesions on card sorting. *Archives of Neurology, 9*, 90-100.

Mitchell, K. J., Johnson, M. K., Raye, C. L., & D'Esposito, M. (2000). fMRI evidence of age-related hippocampal dysfunction in feature binding in working memory. *Brain Res Cogn Brain Res, 10*(1-2), 197-206.

Mitchell, K. J., Johnson, M. K., Raye, C. L., Mather, M., & D'Esposito, M. (2000). Aging and reflective processes of working memory. *Psychology & Aging, 15*(3), 527-541.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49-100.

Monsell, S. (2003). Task Switching. *Trends in Cognitive Sciences, 7*, 134-140.

Moscovitch, M. (1982). A neuropsychological approach to memory and perception in normal and pathological aging. In F. I. M. Craik & S. Trehub (Eds.), *Aging and Cognitive Processes* (pp. 55-78). New York: Plenum.

Moscovitch, M. (1992). Memory and working-with-memory: A component process model based on modules and central systems. *Journal of Cognitive Neuroscience, 4*, 257-267.

Moscovitch, M., & Winocur, G. (1992). The neuropsychology of memory and aging. In F. I. M. Craik & T. A. Salthouse (Eds.), *Handbook of aging: Cognition*. Hillsdale, NJ: Erlbaum.

Munoz, D. P., Broughton, J. R., Goldring, J. E., & Armstrong, I. T. (1998). Age-related performance of human subjects on saccadic eye movement tasks. *Exp Brain Res, 121*(4), 391-400.

Myerson, J., Emery, L., White, D. A., & Hale, S. (2003). Effects of age, domain, and processing demands on memory span: Evidence for differential decline. *Aging, Neuropsychology, and Cognition, 10*, 20-27.

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: tests of an associative deficit hypothesis. *J Exp Psychol Learn Mem Cogn, 26*(5), 1170-1187.

Naveh-Benjamin, M., Guez, J., Kilb, A., & Reedy, S. (2004). The associative memory deficit of older adults: further support using face-name associations. *Psychol Aging, 19*(3), 541-546.

Naveh-Benjamin, M., Hussain, Z., Guez, J., & Bar-On, M. (2003). Adult age differences in episodic memory: further support for an associative-deficit hypothesis. *J Exp Psychol Learn Mem Cogn, 29*(5), 826-837.

Nieuwenhuis, S., Broerse, A., Nielen, M. M., & de Jong, R. (2004). A goal activation approach to the study of executive function: an application to antisaccade tasks. *Brain Cogn, 56*(2), 198-214.

Nieuwenhuis, S., Ridderinkhof, K. R., de Jong, R., Kok, A., & van der Molen, M. W. (2000). Inhibitory inefficiency and failures of intention activation: age-related decline in the control ofsaccadic eye movements. *Psychology and Aging, 15*(4), 635-647.

Nieuwenhuis, S., Ridderinkhof, R. K., Talsma, D., Coles, M. G. H., Holroyd, C. B., Kok, A., et al. (2002). A computational account of altered error processing in older age: Dopamine and the error-related negativity. *Cognitive, Affective and Behavioral Neuroscience, 2*, 19-36.

Northoff, G., Grimm, S., Boeker, H., Schmidt, C., Bermpohl, F., Heinzel, A., et al. (2006). Affective judgment and beneficial decision making: ventromedial prefrontal activity correlates with performance in the Iowa Gambling Task. *Hum Brain Mapp, 27*(7), 572-587.

O'Doherty, J., Critchley, H., Deichmann, R., & Dolan, R. J. (2003). Dissociating valence of outcome from behavioral control in human orbital and ventral prefrontal cortices. *J Neurosci, 23*(21), 7931-7939.

O'Doherty, J., Kringelbach, M. L., Rolls, E. T., Hornak, J., & Andrews, C. (2001). Abstract reward and punishment representations in the human orbitofrontal cortex. *Nat Neurosci, 4*(1), 95-102.

Oberauer, K. (2001). Removing irrelevant information from working memory: a cognitive aging study with the modified Sternberg task. *J Exp Psychol Learn Mem Cogn, 27*(4), 948-957.

Oberauer, K. (2002). Access to information in working memory: exploring the focus of attention. *J Exp Psychol Learn Mem Cogn, 28*(3), 411-421.

Oberauer, K. (2005a). Binding and inhibition in working memory: individual and age differences in short-term recognition. *J Exp Psychol Gen, 134*(3), 368-387.

Oberauer, K. (2005b). Control of the contents of working memory--a comparison of two paradigms and two age groups. *J Exp Psychol Learn Mem Cogn, 31*(4), 714-728.

Oberauer, K., Demmrich, A., Mayr, U., & Kliegl, R. (2001). Dissociating retention and access in working memory: an age-comparative study of mental arithmetic. *Mem Cognit, 29*(1), 18-33.

Oberauer, K., & Kliegl, R. (2001). Beyond resources: Formal models of complexity effects and age differences in working memory. *European Journal of Cognitive Psychology, 13*(1/2), 187-215.

Ochsner, K. N., Bunge, S. A., Gross, J. J., & Gabrieli, J. D. (2002). Rethinking feelings: an FMRI study of the cognitive regulation of emotion. *J Cogn Neurosci, 14*(8), 1215-1229.

Ochsner, K. N., & Gross, J. J. (2005). The cognitive control of emotion. *Trends Cogn Sci, 9*(5), 242-249.

Parkin, A. J., & Walter, B. M. (1992). Recollective experience, normal aging, and frontal dysfunction. *Psychology and Aging, 7*, 290-298.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116(2)*, 220-244.

Paxton, J. L., Barch, D. M., Racine, C. A., & Braver, T. S. (submitted). Context processing and prefrontal function in healthy aging.

Paxton, J. L., Barch, D. M., Storandt, M., & Braver, T. S. (2006). Effects of environmental support and strategy training on older adults' use of context. *Psychol Aging, 21*(3), 499-509.

Perlstein, W. M., Dixit, N. K., Carter, C. S., Noll, D. C., & Cohen, J. D. (2003). Prefrontal cortex dysfunction mediates deficits in working memory and prepotent responding in schizophrenia. *Biol Psychiatry, 53*(1), 25-38.

Phillips, L. H., MacLeod, M., & Kliegel, M. (2005). Adult aging and cognitive planning. In G. Ward & R. Morris (Eds.), *The cogitive psychology of planning* (pp. 111-139). Hove, UK: Psychology Press.

Prabhakaran, V., Narayanan, K., Zhao, Z., & Gabrieli, J. D. (2000). Integration of diverse information in working memory within the frontal lobe. *Nat Neurosci, 3*(1), 85-90.

Prull, M. W., Gabrieli, J. D. E., & Bunge, S. A. (2000). Age-related changes in memory: A cognitive neuroscience perspective. In F. I. M. Craik & T. A. Salthouse (Eds.), *The Handbook of Aging and Cognition, Second Edition* (pp. 91-153). Mahwah, New Jersey: Lawrence Erlbaum Associates, Publishers.

Ramnani, N., & Owen, A. M. (2004). Anterior prefrontal cortex: insights into function from anatomy and neuroimaging. *Nat Rev Neurosci, 5*(3), 184-194.

Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F. I. M. Craik & T. A. Salthouse (Eds.), *The Handbook of Aging and Cognition, Second Edition*. Mahwah, New Jersey: Lawrence Erlbaum Associates, Publishers.

Raz, N., Gunning-Dixon, F. M., Head, D., Dupuis, J. H., & Acker, J. D. (1998). Neuroanatomical correlates of cognitive aging: evidence from structural magnetic resonance imaging. *Neuropsychology, 12*(1), 95-114.

Reimers, S., & Maylor, E. A. (2005). Task switching across the life span: effects of age on general and specific switch costs. *Dev Psychol, 41*(4), 661-671.

Reuter-Lorenz, P., & Sylvester, C.-Y. C. (2005). The cognitive neuroscience of working memory and aging. In R. Cabeza, L. Nyberg & D. Park (Eds.), *Cognitive Neuroscience of Aging: Linking Cognitive and Cerebral Aging* (pp. 186-217). New York, NY: Oxford University Press.

Rhodes, M. G. (2004). Age-related differences in performance on the Wisconsin card sorting test: a meta-analytic review. *Psychol Aging, 19*(3), 482-494.

Ridderinkhof, K. R., van den Wildenberg, W. P., Segalowitz, S. J., & Carter, C. S. (2004). Neurocognitive mechanisms of cognitive control: The role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. *Brain Cogn, 56*(2), 129-140.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*(2), 207-231.

Rosvold, H. E., Mirsky, A. F., Sarason, I., Bransome, E. D., & Beck, L. H. (1956). A continuous performance test of brain damage. *Journal of Consulting Psychology, 20*(5), 343-350.

Royall, D. R., Palmer, R., Chiodo, L. K., & Polk, M. J. (2004). Declining executive control in normal aging predicts change in functional status: the Freedom House Study. *J Am Geriatr Soc, 52*(3), 346-352.

Rubin, O., & Meiran, N. (2005). On the origins of the task mixing cost in the cuing task-switching paradigm. *J Exp Psychol Learn Mem Cogn, 31*(6), 1477-1491.

Ruge, H., Brass, M., Koch, I., Rubin, O., Meiran, N., & von Cramon, D. Y. (2005). Advance preparation and stimulus-induced interference in cued task switching: further insights from BOLD fMRI. *Neuropsychologia, 43*(3), 340-355.

Rush, B. K., Barch, D. M., & Braver, T. S. (2006). Accounting for cognitive aging: context processing, inhibition or processing speed? *Neuropsychol Dev Cogn B Aging Neuropsychol Cogn, 13*(3-4), 588-610.

Rypma, B., & D'Esposito, M. (2000). Isolating the neural mechanisms of age-related changes in human working memory. *Nature Neuroscience, 3*, 509-515.

Salthouse, T. A. (1990). Working memory as a processing resource in cognitive aging. *Developmental Review, 10*(1), 101-124.

Salthouse, T. A. (1992). Influence of processing speed on adult age differences in working memory. *Acta Psychol (Amst), 79*(2), 155-170.

Salthouse, T. A. (1994). The aging of working memory. *Neuropsychology, 8*(4), 535-543.

Salthouse, T. A. (2000). Methodological assumptions in cognitive aging research. In F. I. M. Craik & T. A. Salthouse (Eds.), *Handbook of aging and cognition* (2nd ed., pp. 467-498). Hillsdale, NJ: Erlbaum.

Salthouse, T. A. (2001). A research strategy for investigating group differences in a cognitive construct: Application to ageing and executive processes. *European Journal of Cognitive Psychology, 13*(1/2), 29-46.

Salthouse, T. A. (2005a). Effects of aging on reasoning. In K. Holyoak & R. G. Morrison (Eds.), *The Cambridge handbook of thinking and reasoning* (pp. 589-605). New York, NY: Cambridge University Press.

Salthouse, T. A. (2005b). Relations between cognitive abilities and measures of executive functioning. *Neuropsychology, 19*(4), 532-545.

Salthouse, T. A. (2006). Theoretical issues in the psychology of aging. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (6th ed.).

Salthouse, T. A., Atkinson, T. M., & Berish, D. E. (2003). Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *J Exp Psychol Gen, 132*(4), 566-594.

Salthouse, T. A., Berish, D. E., & Siedlecki, K. L. (2004). Construct validity and age sensitivity of prospective memory. *Mem Cognit, 32*(7), 1133-1148.

Salthouse, T. A., & Miles, J. D. (2002). Aging and time-sharing aspects of executive control. *Mem Cognit, 30*(4), 572-582.

Salthouse, T. A., Mitchell, D. R., Skovronek, E., & Babcock, R. L. (1989). Effects of adult age and working memory on reasoning and spatial abilities. *J Exp Psychol Learn Mem Cogn, 15*(3), 507-516.

Servan-Schreiber, D., Cohen, J. D., & Steingard, S. (1996). Schizophrenic deficits in the processing of context: A test of a theoretical model. *Archives of General Psychiatry, 53*(Dec), 1105-1113.

Shilling, V. M., Chetwynd, A., & Rabbitt, P. M. (2002). Individual inconsistency across measures of inhibition: an investigation of the construct validity of inhibition in older adults. *Neuropsychologia, 40*(6), 605-619.

Shum, D., Valentine, M., & Cutmore, T. (1999). Performance of individuals with severe long-term traumatic brain injury on time-, event-, and activity-based prospective memory tasks. *J Clin Exp Neuropsychol, 21*(1), 49-58.

Smith, E. E., & Jonides, J. (1999). Storage and executive processes in the frontal lobes. *Science, 283*, 1657-1661.

Smith, R. E. (2003). The cost of remembering to remember in event-based prospective memory: Investigating the capacity demands of delayed intention performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 347-361.

Smith, R. E., & Bayen, U. J. (2004). A multinomial model of event-based prospective memory. *J Exp Psychol Learn Mem Cogn, 30*(4), 756-777.

Smith, R. E., & Bayen, U. J. (2006). The source of adult age differences in event-based prospective memory: a multinomial modeling approach. *J Exp Psychol Learn Mem Cogn, 32*(3), 623-635.

Spector, A., & Biederman, I. (1976). Mental set and shift revisited. *American Journal of Psychology, 89*, 669-679.

Spencer, W. D., & Raz, N. (1995). Differential effects of aging on memory for content and context: a meta-analysis. *Psychology of Aging, 10*(4), 527-539.

Spieler, D. H. (2001). Modelling age-related changes in information processing. *European Journal of Cognitive Psychology, 13*(1/2), 217-234.

Spieler, D. H., Balota, D. A., & Faust, M. E. (1996). Stroop performance in healthy younger and older adults and in individuals with dementia of the Alzheimer's type. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 461-479.

Sternberg, S. (1966). High-speed scanning in human memory. *Science, 153*, 652-654.

Stine, E. A., & Wingfield, A. (1990). How much do working memory deficits contribute to age differences in discourse memory. *European Journal of Cognitive Psychology, 2*, 289-304.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643-662.

Stuss, D. T., Alexander, M. P., Floden, D., Binns, M. A., Levine, B., McIntosh, A. R., et al. (2002). Fractionation and localization of distinct frontal lobe processes: Evidence from focal lesions in humans. In D. T. Stuss & R. T. Knight (Eds.), *Principles of Frontal Lobe Function* (pp. 392-407). New York, NY: Oxford University Press.

Stuss, D. T., & Benson, D. F. (1986). *The frontal lobes*. New York: Raven Press.

Stuss, D. T., Bisschop, S. M., Alexander, M. P., Levine, B., Katz, D., & Izukawa, D. (2001). The Trail Making Test: a study in focal lesion patients. *Psychol Assess, 13*(2), 230-239.

Stuss, D. T., Floden, D., Alexander, M. P., Levine, B., & Katz, D. (2001). Stroop performance in focal lesion patients: dissociation of processes and frontal lobe lesion location. *Neuropsychologia, 39*(8), 771-786.

Stuss, D. T., Levine, B., Alexander, M. P., Hong, J., Palumbo, C., Hamer, L., et al. (2000). Wisconsin Card Sorting Test performance in patients with focal frontal and posterior brain damage: effects of lesion location and test structure on separable cognitive processes. *Neuropsychologia, 38*(4), 388-402.

Stuss, D. T., Shallice, T., Alexander, M. P., & Picton, T. W. (1995). A multidisciplinary approach to anterior attentional functions. *Ann N Y Acad Sci, 769*, 191-211.

Troyer, A. K., Graves, R. E., & Cullum, C. C. (1994). Executive functioning as a mediator of the relationship between age and episodic memory in healthy aging. *Aging, Neuropsychology and Cognition, 1*, 45-53.

Uttl, B., & Graf, P. (1997). Color-Word Stroop test performance across the adult life span. *J Clin Exp Neuropsychol, 19*(3), 405-420.

van Boxtel, M. P., ten Tusscher, M. P., Metsemakers, J. F., Willems, B., & Jolles, J. (2001). Visual determinants of reduced performance on the Stroop color-word test in normal aging individuals. *J Clin Exp Neuropsychol, 23*(5), 620-627.

Verhaeghen, P., & Basak, C. (2005). Ageing and switching of the focus of attention in working memory: results from a modified N-back task. *Q J Exp Psychol A, 58*(1), 134-154.

Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: a review of meta-analyses. *Neurosci Biobehav Rev, 26*(7), 849-857.

Verhaeghen, P., Cerella, J., Bopp, K. L., & Basak, C. (2005). Aging and varieties of cognitive control: A review of meta-analyses on resistance to interference, coordination, and task switching, and an experimental exploration of age-sensitivity in the newly identified process of focus switching. In R. W. Engle, G. Sedeek, U. v. Hecker & D. M. McIntosh (Eds.), *Cognitive Limitations in Aging and Psychopathology: Attention, Working Memory, and Executive Functions* (pp. 160-189). Cambridge, UK: Cambridge University Press.

Verhaeghen, P., & De Meersman, L. (1998). Aging and the Stroop effect: a meta-analysis. *Psychology and Aging, 13*(1), 120-126.

Verhaeghen, P., Kliegl, R., & Mayr, U. (1997). Sequential and coordinative complexity in time-accuracy functions for mental arithmetic. *Psychol Aging, 12*(4), 555-564.

Verhaeghen, P., Steitz, D. W., Sliwinski, M. J., & Cerella, J. (2003). Aging and dual-task performance: a meta-analysis. *Psychol Aging, 18*(3), 443-460.

Viskontas, I. V., Morrison, R. G., Holyoak, K. J., Hummel, J. E., & Knowlton, B. J. (2004). Relational integration, inhibition, and analogical reasoning in older adults. *Psychol Aging, 19*(4), 581-591.

Vogels, W. W., Dekker, M. R., Brouwer, W. H., & de Jong, R. (2002). Age-related changes in event-related prospective memory performance: a comparison of four prospective memory tasks. *Brain Cogn, 49*(3), 341-362.

Welford, A. T. (1952). *The 'psychological refractory period' and the timing of high-speed performance--a review and a theory* (Vol. 43).

West, R. (1999). Age differences in lapses of intention in the stroop task. *Journal of Gerontology: Psychological Sciences, 54B*(1), P34-P43.

West, R. (2001). The transient nature of executive control processes in younger and older adults. *European Journal of Cognitive Psychology, 13*(1/2), 91-105.

West, R. (2004). The effects of aging on controlled attention and conflict processing in the Stroop task. *J Cogn Neurosci, 16*(1), 103-113.

West, R., & Alain, C. (2000). Age-related decline in inhibitory control contributes to the increased Stroop effect observed in older adults. *Psychophysiology, 37*, 179-189.

West, R., & Alain, C. (2000). Effects of task context and fluctuations of attention on neural activity supporting performance of the Stroop task. *Brain Research, 873*, 102-111.

West, R., & Baylis, G. C. (1998). Effects of increased response dominance and contextual disintegration on the Stroop interference effect in older adults. *Psychology & Aging, 13*(2), 206-217.

West, R., & Bowry, R. (2005). Effects of aging and working memory demands on prospective memory. *Psychophysiology, 42*(6), 698-712.

West, R., Bowry, R., & Krompinger, J. (2006). The effects of working memory demands on the neural correlates of prospective memory. *Neuropsychologia, 44*(2), 197-207.

West, R., & Covell, E. (2001). Effects of aging on event-related neural activity related to prospective memory. *Neuroreport, 12*(13), 2855-2858.

West, R., & Craik, F. I. (2001). Influences on the efficiency of prospective memory in younger and older adults. *Psychol Aging, 16*(4), 682-696.

West, R., & Craik, F. I. M. (1999). Age-related decline in prospective memory: The roles of cue accessibility and cue sensitivity. *Psychology and Aging, 14*(2), 264-272.

West, R., & Moore, K. (2005). Adjustments of cognitive control in younger and older adults. *Cortex, 41*(4), 570-581.

West, R., Murphy, K. J., Armilio, M. L., Craik, F. I., & Stuss, D. T. (2002). Lapses of intention and performance variability reveal age-related increases in fluctuations of executive control. *Brain Cogn, 49*(3), 402-419.

West, R., & Schwarb, H. (2006). The influence of aging and frontal function on the neural correlates of regulative and evaluative aspects of cognitive control. *Neuropsychology, 20*(4), 468-481.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120*(2), 272-292.

Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & R., T. (1999). Development of inhibitory control across the life span. *Developmental Psychology, 35*(1), 205-213.

Wood, S., Busemeyer, J., Koling, A., Cox, C. R., & Davis, H. (2005). Older adults as adaptive decision makers: evidence from the Iowa Gambling Task. *Psychol Aging, 20*(2), 220-225.

Yeung, N., Cohen, J. D., & Botvinick, M. M. (2004). The neural basis of error detection: conflict monitoring and the error-related negativity. *Psychol Rev, 111*(4), 931-959.

Zacks, R. T., Hasher, L., & Li, K. Z. H. (2000). Human Memory. In F. I. M. Craik & T. A. Salthouse (Eds.), *The Handbook of Aging and Cognition 2nd Edition* (pp. 293-357). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Zelazo, P. D., Craik, F. I., & Booth, L. (2004). Executive function across the life span. *Acta Psychol (Amst), 115*(2-3), 167-183.