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# Inhibitory Mechanisms and the Control of Attention

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"Bigger is better." So goes the message of many theoretical perspectives on working memory, views that emphasize working memory as a "mental workspace," which houses the representations and processes that, at any given moment, are in the focus of attention. The intuition of such views is that the larger this workspace, or the more representations one can have active at any given time, the better performance will be on most cognitive and social tasks. [1] Virtually all views of working memory share this perspective, including Baddeley's (1986, 1992, 2000) and Just and Carpenter's (1992). We describe an alternative view, one that could be described as "good things come in small packages". Our work and that of our collaborators focuses on the executive control processes that keep the mental representation "packages" small and goal relevant. This, we have argued, enables a maximally efficient information processing system (e.g., Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999).

Our focus is on a set of attentional or executive control processes, all inhibitory, that operate in the service of an individual's goals to narrow and constrain the contents of consciousness to be goal-relevant. An uncluttered or narrowly focused 'working memory', rather than a large one, is the ideal processing system: It will be faster to achieve a goal than will a more broadly dispersed system because it will not be slowed by nonrelevant stimuli that occur in the task context, or by environmentally triggered thoughts, or by self-generated distraction. The narrow focus maximizes the speed and accuracy of on-line processing because it reduces the likelihood of switching attention to goal irrelevant representations such as those connected to a previous task, an upcoming task, environmental distraction, or subsidiary goals.

A narrowly focused processing system is also ideal because it has the downstream benefit of ensuring accurate and rapid retrieval of the information it once focused on (Anderson & Bower, 1973). This claim follows from rich literatures all pointing to substantial costs for retrieval of having entertained nonrelevant information during encoding. Sometimes the nonrelevant information is explicitly part of the task environment as is the case, for example, when highly similar or overlapping information is learned (Anderson & Bower, 1973; Watkins & Watkins, 1976), when encoding takes places under divided attention conditions (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Fernandes & Moscovitch, 2000), or when actually presented information triggers related information (e.g., Deese, 1959; Roediger & McDermott, 1995; Underwood, 1965). Whatever its source, the additional information activated during encoding "enriches" the memory representation of presented items and forms the basis from which intrusions are drawn and memory lapses occur. We note that all tasks that depend on rapid and accurate retrieval of information that was once attended to will suffer to the

[1] We do not discuss the relevant social and personality literatures in this chapter but note that there is empirical and theoretical overlap among the domains in both tasks and the mechanisms that regulate them (see e.g.,Eysenck, 1995; Muraven & Baumeister, 2000). For example, schizophrenic, creative and low span young adults are all more likely to pick up information on the unattended track in a dichotic listening experiment (Conway, Cowan, & Bunting, 2001; Dykes & McGhie, 1976). Psychosis prone, creative and older adults all show less habituation to repeated stimuli (e.g., Raine, Benishay, Lencz & Scarpa, 1997; McDowd & Filion, 1992).

degree to which the processing system was initially broadly rather than narrowly tuned at encoding.

The detrimental effects of an "embarrassment of riches" – i.e., of having *too much* information activated and in the focus of attention – have been the primary interest of our research program, rather than working memory per se. To that end, we have explored the nature of the inhibitory attentional control processes that limit the momentary consideration of irrelevant information. We have also explored the importance of these attentional regulation processes to a wide variety of cognitive tasks, including: (a) traditional working memory tasks (e.g., simple span, verbal and visuo-spatial working memory span; Lustig & Hasher, 2002; Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999; Rowe, Turcotte & Hasher, 2004) (b) basic-level perceptual speed tasks as used in the intelligence, developmental, and aging literatures (Lustig, Hasher, & Tonev, 2005); (c) more conceptual tasks such as reading speed and reading comprehension (Carlson, Hasher, Connelly, & Zacks, 1995; Connelly, Hasher, & Zacks, 1991; Li, Hasher, Jonas, Rahhal, & May, 1998), problem solving and decision making (May, 1999; Tentori, Osherson, Hasher, & May, 2001) ; (d) attentional regulation (May, Kane, & Hasher, 1995) and control of primed or prepotent (but task-irrelevant) responses (Butler, Zacks, & Henderson, 1999; May & Hasher, 1998); and (e) long-term explicit and implicit memory (Gerard, Zacks, Hasher, & Radvansky, 1991; Lustig & Hasher, 2001; Zacks, Radvansky, & Hasher, 1996.

Our particular focus on these *inhibitory-based* executive control processes differs from much of the early work on working memory, which centered on capacity for simultaneous mental operations and storage. However, our emphasis on executive processes fits well with the recent explosion of work on "executive control" across the cognitive and cognitive neuroscience literatures, including evidence that the control processes involved in attention, working memory, and long-term memory share common neural substrates (Cabeza, Dolcos, Prince, Rice, Weissman, & Nyberg, 2003; Ranganath, Johnson, & D'Esposito, 2003). Recent work by Engle and colleagues has a similar perspective to our own, as their emphasis increasingly shifts towards working memory as an executive attention system rather than as a "memory" system (e.g., Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001; see also Kane et al., this volume, pp XX). Finally, our work also fits well with the general effort to understand the processes involved in Baddeley's construct of the "central executive" (e.g., Baddeley, 2003).

In sum, our work is similar to that of many other investigators in its focus on executive processes as a critical source of working memory variation, as well as variation in many cognitive domains. There is broad agreement that for individuals sharing common goals, it is the efficiency of executive processes that is a major source of variation in the contents of consciousness, and in many of the mental and physical processes (e.g., memory and motor control) subsequently determined by the initial breadth of focus (e.g., see Braver & Gray, this volume; Kane et al., this volume ; but see Reuter-Lorenz & Jonides, this volume, for a somewhat different view).

Our work differs from many others' in that we emphasize the role of *inhibitory* processes – processes that keep consciousness free of irrelevant information that can impede the successful and efficient completion of a current goal. Our assumption is that the initial stage of activating representations is largely automatic and is driven by environmental and social contexts, by specific perceptual cues, by instructions in the context of an experiment, and to some degree by an individual's momentary and long-term goals and values.[2] It is immediately after activation that goal-driven attentional/executive processes come into play and we assume that these include both excitatory mechanisms that increase the activation of goal-relevant information, and inhibitory processes that decrease the activation of irrelevant information.

We focus on inhibitory processes on the assumption that the initial stages of activation are largely automatic and so do not differ much among individuals within the same contexts and with the same goals. For example, semantic priming effects, or the facilitated recognition of one word (e.g., "nurse") after exposure to a related word (e.g., "doctor") often do not differ across populations such as younger and older adults with different apparent working memory abilities, or if they do, the differences favor older adults (e.g., Cameli & Phillips, 2000; Giffard, Desgranges, Kerrouche, Piolino, & Eustache, 2003; Laver, 2000). Our reading of such results is that groups differing in age or working memory span or reading ability differ less in their abilities to activate relevant concepts than in their abilities to keep activation and attention restricted to what is relevant.

In our own work the need to focus on the processes involved in restricting attention to goal relevant information was stimulated by age differences found in an inference generation task, differences that could not be accounted for by differences in working memory capacity, since estimates of the latter did not differ with age (Hamm & Hasher, 1992). The study tested for the inferences people generated while reading. When the context of a passage requiring an inference was slightly ambiguous, young adults generated one inference and older adults tended to generate two. When subsequent information made it clear that the initial inference drawn by young adults and one of the two inferences drawn by older adults was incorrect, young adults generated the correct inference and abandoned the no longer correct one. Older adults accessed the correct inference, they simply did not abandon their original, but no longer correct inference. These two findings from garden path passages, a larger range of inferences generated and a lengthier consideration of rejected inferences by older than by younger adults (see Hamm & Hasher, 1992, for details), led us to posit (Hasher & Zacks, 1988) the existence of inhibitory functions that in young adults limit the range of ideas that enter the focus of attention and that quickly suppress ideas that prove unhelpful. These mechanisms were clearly less efficient in older adults than in young adults.

These observations about inference generation and control, along with the failure of working memory to explain them, led us to build a theoretical framework in which variation in *inhibitory efficiency* accounts for much of the variation in cognitive performance. In fact, we take the strong position that it is inhibition that is a fundamental determinant of the apparent differences in what many investigators term "working memory capacity".

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[2] In the lab, experimenters typically set goals for participants, whereas in life people set goals for themselves, sometimes a short term one (finding a cup of coffee in an unfamiliar city) and sometimes long term ones (finding first editions of classic Psychology texts). Sometimes, the lab and life goals conflict, setting the stage for poor performance. Sometimes, participants do not adopt the goals set by the experimenters.

Although much of our empirical work has used age-comparative studies rather than individual differences methods per se, our theoretical work has always emphasized the general importance of inhibitory variation across groups and among individuals, and more recently even within the same individual across different physiological and psychological states (Hasher & Zacks, 1988, Hasher et al., 1999). As it happens, work on individual differences is generally supportive of the idea that inhibitory processes play a large role in cognition (Chiappe, Hasher, & Siegel, 2000; Chiappe, Siegel, & Hasher, 2002; Gernsbacher & Faust, 1991; Harnishfeger & Bjorklund, 1994; Kane et al, 2001; Lustig, May, & Hasher, 2001; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Nigg, 2001; Persad, 2001; Persad, Abeles, Zacks & Denberg, 2002; Wenzlaff & Wegner, 2000; but see Park et al., 1996; Salthouse, 1996 for alternative interpretations). We note that the potential correspondence between individual-differences work and between group-comparative work has tended to be overlooked (to judge from cross citations), a situation we hope this volume will begin to redress.

Our major empirical efforts to understand inhibitory control over the contents of consciousness and implications of failures of control have taken two approaches: (1) the study of age-related inhibitory control deficits (i.e., group differences) and (2) the study of inhibitory control across the day (i.e., intra-individual differences). The latter line of work is quite unusual in mainstream cognition but, as will be seen, it leads nicely to the conclusion that inhibitory control can vary not just among groups and individuals within a group, but *within individuals themselves*.

Because the intraindividual differences approach we take is an unusual one, we describe it briefly before returning to elaborate on inhibition. Our studies typically compare participants with a particular type of circadian arousal pattern, Evening-types and Morning-types; Horne & Ostberg, 1976) who are tested early in the morning versus late in the afternoon to provide a snapshot of how fundamental cognitive processes function across the day (see Winocur & Hasher, 2002 for a brief review of related animal model evidence).[3] Despite the folk nomenclature of these two "types," they are well substantiated in physiology (e.g., Kerkhof & Lancel, 1991**)**, including most recently with evidence of genetic contributions to extremes in arousal patterns (e.g., Cermakian & Boivin, 2003; Hur, Bouchard & Lykken, 1998; see also the final section of this paper). We also note that there are lifespan differences in overall arousal patterns with more than 70% of older adults (and many young children) more likely to be at a peak in the morning, while this same time is likely a trough for many young adults, under 10% of whom have Morning type arousal patterns (Kim, Dueker, Hasher, & Goldstein, 2002; Yoon, May, & Hasher, 2000; Yoon, May, Goldstein & Hasher, in press).[4]

Of particular importance for present purposes, the data suggest that whether one is a Morning or Evening type person, it is *inhibitory* processes that differ most across the circadian cycle; excitatory-based processes seem to show little variation across the day

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[3] Although there is a rich literature exploring performance across the day, most studies use individuals without reference to differences in circadian arousal patterns. Although nontrivial for the study of younger adults, the failure to take arousal differences into account when comparing across ages is particularly worrisome, given the substantial differences in arousal patterns.

[4] This large age difference in arousal patterns is what has largely limited us to comparing Evening-type young adults and Morning-type older adults across the day (see Yoon, et al., 2000; Yoon et al., in press).

(e.g., Hasher, Goldstein & May, 2005; Yoon et al., 2000). Our evidence suggests that inhibitory efficiency follows the arousal cycle and our assumption is that studying groups and individuals with varying degrees of inhibitory function (or single individuals at different points in their circadian arousal function) will help illuminate inhibitory processes and the roles they play in cognition, including in determining apparent differences in working memory capacity.

The decision to highlight inhibitory processes as critical determinants of both online and downstream efficiency places us with a small group of investigators who early on and quite independently looked at cognition from a similar point of view and across many different groups and individuals (initially Gernsbacher & Faust, 1991, and Dempster [e.g., 1991]). Many investigators subsequently arrived at similar or partially overlapping views (see Braver & Gray, , this volume; Kane et al., this volume; Oberauer & Sander, this volume; Reuter-Lorenz & Jonides, this volume; see also, Duchek, Balota, & Thessing, 1998; Harnishfeger & Bjorklund, 1994; Nigg, 2001; Wenzlaff & Wegner, 2000). By focusing specifically on the role of inhibitory processes, we differ somewhat from other investigators who deal with executive or controlled attention processes in a generalized fashion, or who tie them to particular tasks such as set switching.

As more researchers focus on executive control processes, it has become increasingly clear that "executive control" is not a unitary construct and that the nature of the specific processes remains to be understood (e.g., Friedman & Miyake, 2004; Miyake et al., 2000; Sylvester et al., 2003). Although in its early stages, recent work suggests that different aspects of executive control (which we view largely as different aspects of inhibitory function) may be dissociable across individuals, brain regions, and times of day (e.g., Friedman & Miyake, 2004; Lustig & Meck, 2001; May, Hasher & Foong, 2005; Sylvester et al., 2003; West, Murphy, Armilio, Craik, & Stuss, 2002).

Our own attempts to understand the nature of inhibitory processes and their contributions to performance led us to a framework that draws distinctions between three separate functions of inhibition, all of which serve to keep working memory (i.e., the focus of attention) free of irrelevant information (e.g., Hasher, et al., 1999; Zacks & Hasher**,** 1994). Inhibitory processes act in the service of goals to (1) prevent irrelevant information from gaining *access* to the focus of attention, (2) to *delete* no longer relevant items from consideration, and (3) to *restrain* prepotent responses so that other, initially weaker response candidates can be evaluated and influence behavior as appropriate for current goals.

In the next section of the paper, we briefly describe inhibitory functions and the effects that variations in their efficiency can have on performance on a number of tasks with an emphasis on speed of processing and working memory. We suggest that a view of executive control emphasizing inhibitory processes can offer a competing account for group, individual, and intra-individual differences in speed and working memory (among other cognitive phenomenon) without appealing to notions of "capacity" that in the attention literature have been sharply criticized (e.g., Navon, 1984). Indeed, our evidence raises the possibility that what most working memory span tasks measure is inhibitory control, not something like the size of operating capacity (e.g., Just & Carpenter, 1992). In the final section, we discuss the potential neurobiological underpinnings of the age and circadian changes that we show have such profound behavioral effects on inhibitory regulation.

## Inhibitory Processes

We have posited three inhibitory functions: access, deletion, and restraint (Hasher & Zacks, 1988; Hasher et al., 1999; Hasher, Tonev, Lustig, & Zacks, 2001; Zacks & Hasher, 1994). Each is a powerful player in determining the speed and success of on-line processing. Two of them (access and deletion) are also major determinants of the speed and success of explicit retention while the third (restraint) can influence both successes, for example when strong or prepotent responses are correct (e.g., stopping at a traffic signal when it is red), and failures, when strong responses are wrong (cf. Radvansky & Curiel, 1998). Our work over the past 10 years has focused on exploring the nature of these inhibitory functions and showing that they (a) operate across a wide range of tasks (b) diminish with age over adulthood, and (c) vary across the day with an individual's circadian arousal pattern. It is important to note that although our work takes a group and intraindividual difference approach, the theory behind the work is a general theory of cognition and as such, applies to individual differences.

### Access

The initial activation of representations is presumed to be broad and virtually automatic. The *access* function of inhibition is engaged in the service of goals to determine which activated representations enter the focus of attention (Cowan, 1993; Miyake et al., this volume). When efficient, all nonrelevant representations are suppressed and the contents of consciousness will be narrowly tied to goals. A dramatic example of narrow focus of attention is the 'inattentional blindness' effect in which unattended items in the center of the visual field are literally not "seen" (Mack & Rock, 1998; Most et al., 2001). Another is the state of "flow" by which intense concentration enables individuals to ignore the external world and passing of time (e.g., Csikszentmihalyi, Rathunde, & Whalen, 1993).

Our original work on the inferences generated while reading suggested age differences in the amount of information that gains access to the focus of attention; as noted above, in an ambiguous context in which young adults generated only one interpretation, older adults generated more (Hasher & Zacks, 1988, Hamm & Hasher, 1991). evidence suggests that e.g., May, 1999; Kim, Hasher & Zacks, 2005). Our recent work on the access function has focused on its role in determining the speed with which tasks can be performed. To this end, we manipulated the extent and nature of extraneous information present in a task environment.

For example, for older adults the speed with which a decision about whether two letter strings (e.g., XPFGN and XPFCN ) are the same or different is at least partially determined by whether there are other letter strings also simultaneously present and competing for access to attention (Lustig et al., 2005). For young adults, the presence of other letter-string problems has no effect on the speed with which problems are solved. These findings are critical because letter comparison is one of a number of tasks used to assess the notion of "perceptual speed," a concept that in the lifespan and intelligence literatures is thought of as a cognitive primitive that establishes limits to an individual's performance across a range of high level cognitive tasks including reasoning (Kail, 1993;

Salthouse, 1996). As it happens, most tasks that assess 'perceptual speed' use highly cluttered displays (with many similar problems on a page), an arrangement likely to disrupt the performance of some participants (those with reduced inhibitory function), but not others. Our work suggests that the source of disruption and the underlying cognitive primitive is the access function which determines the ability to constrain task focus to the momentarily relevant item.

Inefficient control over access can also slow even highly practiced skills such as reading. For example, interspersing irrelevant words (in a distinctive font) amidst target text differentially slows reading for older adults (Carlson et al., 1995; Connelly et al., 1991; Dywan & Murphy, 1996; Li et al., 1998; Phillips & Lesperance, 2003). There are comparable data showing age differences in disruption effects when the distraction is in the auditory rather than visual mode (Tun, O'Kane, & Wingfield, 2002). The selective attention literature shows a similar phenomenon: Older adults are differentially slowed to find a target amidst distraction (e.g., Plude & Hoyer, 1986; Zacks & Zacks, 1993). From our perspective, all of these effects are consistent with the idea that the access function of inhibition is not as efficient for older adults as it is for younger adults. These findings, and particularly those using simple perceptual speed tasks pose a challenge to views that see processing speed as a cognitive primitive that underlies intelligence and the developmental trajectory of cognition across the lifespan (e.g., Kail, 1993; Salthouse, 1996). They suggest that attentional regulation and particularly the access function of inhibition are part of the underlying mechanisms critical to cognition.

We note that the efficiency of the access function also varies across the day in patterns consistent with morning versus evening arousal schedules. In one relevant study (May, 1999), participants were given a variant of the classic Remote Associates Task in which three very loosely related words (e.g., rat, blue, and cottage) were presented and the task was to generate a word (cheese) that connects them. The target words were presented alone on control trials and with distraction on experimental trials; participants were warned to ignore the distraction which had been normed to either lead towards the solution word or away from it.

Evening-type younger and Morning-type older adults were tested early in the morning or late in the afternoon. Performance on the control (or distraction-free) sets did not differ with age or time of testing, however the impact of distraction differed for both ages and times of testing. Young adults were completely able to ignore the distraction when tested in the afternoon, an effect similar to that seen in the inattentional blindness phenomenon (Mack & Rock, 1998; Most et al., 2001) and in perceptual speed tasks completed in the presence versus absence of distraction (Lustig et al., 2005). In the morning, however, young adults showed reliable costs and benefits as the distraction 'leaked' in to influence performance. Thus, for young adults, control over the access function is more efficient in the afternoon than in the morning, a pattern consistent with their Evening arousal typology.

For older adults, distraction is not ignored, it helps or hurts performance at both testing times, but more so in the afternoon than in the morning. The results for the older adults (and for young adults tested in the morning) cannot easily be written off as "general performance deficits," since baselines were equivalent when no distraction was present. Instead, the extraneous information sometimes led to greater costs but also to greater *benefits*, depending on the type of distraction that was present. What remained constant was the older adults' relative failure to restrict attention away from the distractor items, consistent with the assumption that control over the access function diminishes with age, and for everyone tested at nonoptimal times of day.

As an aside, what the data also show is that failing to attend to the time at which younger and older adults are tested is probably a major mistake, since more than 70% of older adults are Morning-types and a third or more of young adults are Evening-types (see e.g., May et al., 1993; Yoon et al., 2000; Yoon et al., in press). If early morning testing times are not used, and most participants are tested later in the day (see May, Hasher & Stoltzfus, 1993), age differences in access control will be exaggerated. As subsequent data show, this argument can likely be extended to the two other inhibitory functions (deletion and restraint) and critically, the argument can also be extended to other cognitive tasks that have inhibitory components.

In sum, our work and that of others suggests that across many situations, the ability to keep attention focused away from nonrelevant information aids the fast and accurate processing of goal-relevant information. The access control function influences performance on tests of processing speed, a construct often used along with or in competition with working memory capacity as an explanation for performance variation across the lifespan (Park et al., 1996; Salthouse, 1996), and on tests of reading and problem solving, tasks often used as outcome measures in studies examining the predictive power of working memory tasks (see review by Daneman & Merikle, 1996). From a theoretical perspective, efficient inhibitory function is critical for controlling which pieces of information gain access to attention, and, on the assumption that co-occurrence is a major determinant of association formation, for how large the initial memory bundles are. This in turn determines how fast and accurate subsequent retrieval can be (Anderson & Bower, 1973). The impact of cluttered or large memory bundles will be discussed following the next section.

**Deletion.**

Inhibition also serves to *delete* nonrelevant information from the focus of attention. Irrelevant information may be active in the first instance because of the failure of the access function to control 'leakage' tied to subsidiary goals or to a mismatch between the goals of an individual and those set by an experimenter or situation. Deletion is critical to removing nonrelevant representations from the focus of attention to enable efficient processing of goal-driven representations. Deletion also removes once-relevant information that has become irrelevant due to a change in goals, context, task or situational demands such as can occur in a conversation when a topic changes, in a task (whether attention, memory or problem solving), when one set of materials (or procedures) ends and another begins.

As noted earlier, the stimulus for this aspect of our theoretical framework came from the observation that older adults not only allowed alternative interpretations of a passage to gain *access* to their attention, but also failed to *delete* those alternatives from consideration even when it became clear that they were incorrect (Hamm & Hasher, 1991; Hasher & Zacks, 1988). To establish the generality of these initial findings, we created garden path sentences that ended with a highly predictable but missing word that the participant generated and that was replaced, a few seconds later, by a less predictable word provided by the experimenter. We then used an implicit task to measure the accessibility of the initially generated word (the highly predictable ending) – a word that became irrelevant in the context of the task as soon as the experimenter provided an alternative ending to the sentence. We measured access to the no longer relevant words (and for other control items) for both older and younger adults.

Across a series of studies, the ability to delete a no longer relevant inference from memory varied as a function of adult age and time of testing (e.g., Hartman & Hasher, 1991; May & Hasher, 1998; May, Zacks, Hasher, & Multhaup, 1999). For Evening-type young adults tested in the afternoon (see May & Hasher, 1998), deletion actually *suppressed* the no longer relevant word to such a degree that subsequent use of those words to end new sentences was actually *below baseline levels*. Early in the morning however, the availability of the no longer relevant term is reliably *above* baseline levels, showing time of day differences in the efficiency of the deletion function for young adults that is consistent with their arousal pattern. Older adults also show time of day differences in deletion regulation, with worse performance in the afternoon, consistent with their circadian arousal type. Overall, there were profound age and time of day differences in inhibitory control over deletion.

Vulnerability to the effects of no longer relevant information has been shown to vary across groups and individuals who differ in reading ability, in span scores and on intelligence tests (e.g., Chiappe et al., 2000, 2002; Dempster, 1991; Gernsbacher & Faust, 1991; Kane & Engle, 2000). Note that if deletion is inefficient, the memory bundle representing a given event or moment will consist of (at least) both relevant information and irrelevant information that remained active in consciousness, thus enabling an "enriched" or cluttered memory bundle during encoding. These larger bundles in turn result in differentially poor retrieval (e.g., Anderson & Bower, 1973). In the next section, we consider the impact that the deletion function plays in tasks intended to measure working memory.

**Deletion and Working Memory Span.**

Working memory span tasks, including the by-now classic reading span task of Daneman and Carpenter (1980), typically present the participant with a series of 'study' and recall test trials, each of which consists of a set of sentences to understand while preparing to recall the final word of each followed by an immediate recall of those final words. These sets vary in size (e.g., from 2 to 6 sentences), and by convention (i.e., at least since the earliest IQ tests developed by Binet), they are presented in an "ascending" order so that the smallest sets are presented first. The largest set size at which a participant is reliably able to understand and recall all items in the set is a commonly used index of working memory capacity.

The ascending administration requires deletion to be efficient so that at any point in the series of study trials, consideration is narrowly focused on only the currently relevant set. If deletion is inefficient, items from prior sets will "enrich" the memory representations of the current set, reducing the ability of participants to recall the current set accurately. The failure to suppress no longer relevant words enables proactive interference (PI) to build up across trials, and to have its most detrimental effects on the large set-size trials that are last in the series yet critical to attaining a high working memory score.

Based on these observations of the typical operations involved in assessing working memory span, May, et al., (1999) reversed the order of administration so that the largest trials occurred first, before PI had a chance to accumulate. This simple manipulation should have no effect on the measurement of working memory capacity per se, at least if capacity simply reflects the amount of information an individual can store and process in their "mental workspace." On the other hand, if deletion (and attendant PI) is involved in standard span tasks, the sequence manipulation should affect how much irrelevant information is available to that workspace from previous trials when participants are attempting to recall the current items. Indeed, the reversed administration dramatically improved the performance of older adults on the reading span task, so that rather startlingly, their performance no longer differed from young adults'. (A more extreme manipulation designed to reduce PI also improved the scores of young adults.) These findings suggest that variation in deletion function (or, inversely, *in proactive interference caused by failures of the deletion function*), plays a major role in producing variation in working memory span (see also Bowles & Salthouse, 2003).

Recent work suggests that this conclusion extends beyond the limits of the various versions of the Daneman and Carpenter reading and listening span tasks. The reversed order manipulation also increased the span scores of older adults on a Corsi-block version of a visuo-spatial working memory span task (Rowe, Turcotte, & Hasher, 2004). Bunting (2003) has shown that the operation span task introduced by Engle and colleagues (e.g., Engle, Cantor, & Carullo, 1992) which is based on verifying the accuracy of equations while remembering words, is also vulnerable to PI. We have also found that circadian influences can affect PI-heavy measures of working memory span (Hasher et al., 2003; Yoon, et al., 2000) consistent with the conclusion that the efficiency of the deletion function varies across the day. Together, these data suggest that several of the most widely used versions of working memory span are likely measuring something other than 'capacity'. We think it likely they index the efficiency of inhibitory control.

Deletion may play a critical role not only in variability on working memory span tasks per se, but also in those tasks' ability to predict performance on other measures. Lustig, et al., (2001) replicated the May et al. (1999) results by showing that reducing PI eliminated age differences in working memory span performance, and further showed that the deletion-demanding aspects of the span task were critical for its ability to predict performance on prose recall (a standard outcome measure in the individual difference tradition). For both young and older adults, manipulations that reduced PI and improved span scores also reduced the ability of individual differences in span scores to predict individual differences in prose recall. By broad generalization, these data suggest that whenever span tasks are used to select participants to perform on other tasks and whenever reliable correlations obtain, the mediating variable may well be inhibitory control, not working memory capacity.

Further evidence that working memory span tasks do not measure capacity but instead something like interference proneness comes from a study that demonstrates that prior experience with other memory tasks can reduce estimates of the size of an individual's working memory span (Lustig & Hasher, 2002). Performance on other retrieval tasks (e.g., paired associates and serial learning) has long been known to be disrupted by prior laboratory experience (Greenberg & Underwood, 1950; Keppel, Postman, & Zavortink, 1968; Underwood, 1957; Zechmeister & Nyberg, 1982). As with these classic memory tasks, working memory span tasks may also be influenced by across-task proactive interference. Indeed, recent neuroimaging work suggests that the same brain areas may mediate both short and long term interference effects (Postle, Berger, Goldstein, Curtis, & D'Esposito, 2001; Brush & Postle, 2003), a finding consistent with the behavioral data.

The deletion function is critical not just for immediate performance and working memory tasks (with their immediate recall trials); it is also critical for longer term retrieval since a broad focus at encoding results in poorer retrieval (Anderson & Bower, 1973; Watkins & Watkins, 1976).[5] It is not surprising then that older adults typically show differentially poor retrieval relative to younger adults (see Kane & Hasher, 1995; Zacks, Hasher, & Li, 2000 for reviews). Consistent with this pattern of findings is evidence that retrieval is better, for both younger and older adults, at peak as compared to off peak times of day. This conclusion stems from a series of studies using materials ranging from prose to word lists and test tasks ranging from free recall to recognition (see Winocur & Hasher, 2002 and Yoon et al., 2000; Yoon et al., in press, for reviews).

**Restraint.**

This is the inhibitory mechanism that controls strong responses. It is probably also the most widely studied inhibitory mechanism and is actually the mechanism that many simply refer to as 'inhibition' (e.g., Miyake et al., 2000 among others). Restraint has been studied using a variety of tasks including inhibition of return, Stroop tasks of various sorts and the stop signal task. It can also be studied by looking at slips of thought and action as well as at schema-driven errors at retrieval, on the assumption that schemas are strong responses to memory cues and so need to be restrained for more detailed memories to be retrieved (see Alba & Hasher, 1983).

Direct evidence showing age and time of day effects on control over strong responses comes from a variant of the "stop signal" task in which an occasional signal occurs informing people of the need to withhold a response that they otherwise make quickly and accurately. A critical dependent measure is the proportion of stop trials on which errors are made (i.e., a "go" response is made). In one study, older adults made more errors overall than young adults and everyone made more errors at a nonoptimal time of day (afternoon for older adults and morning for young adults) than at an optimal time (morning for older adults and afternoon for young adults). The ability to withhold a strong response is reduced with age and also with performance at an off peak time of day (May & Hasher, 1998).

Comparable evidence with respect to age differences at least comes from the antisaccade task, in which people are instructed to respond to a peripheral stimulus (a brief onset) by looking in the *opposite* direction to detect a limited-duration discrimination target. Because a peripheral onset elicits a reflex response of looking *toward* the cue, restraint is required to look in the correct direction (away from the onset

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[5] We note that access, too, plays a role in determining both short and long term memory performance, including on working memory tasks, because this process also influences the size of the memory bundles that are created during encoding. These will be small or large to the degree that access is or is not efficient, respectively.

location) and older adults have greater difficulty than younger adults deploying the required restraint. In particular, older adults make more looking direction errors in the antisaccade task (Butler, et al., 1999). Given the role inhibition plays in determining span size, it is not surprising that young adults show a relationship between span and performance on the antisaccade task (Kane, et al., 2001).

The ability to control strong responses can also play a role in tasks requiring retrieval of detailed information when a strong response is triggered by a cue or context. A classic example of such errors occurs in the “Moses Illusion” effect (Reder & Kusbit, 1991). Here people are asked to answer general knowledge questions such as “Who did Clark Kent turn into when he went into a telephone booth?” Embedded in the midst of sensible questions are some that are nonsensible such as “How many animals of each type did Moses take on the ark?” Yoon et al. (2000, see also Hasher, et al., in press) reported that errors driven by strong responses (e.g., to the biblical theme in the sentence) are more likely to occur at nonpeak times of day, and are more likely to occur for older than for younger adults.

Other work shows that at nonoptimal times, people are more likely to use easily accessible stereotypes to judge individuals than they are at optimal times (Bodenhausen, 1990). These errors of thought can be termed “slips” of thought, relating them to the “slips” of action literature. This literature shows that strong motor responses are less controllable at nonoptimal times (Manley, Lewis, Robertson, Watson, & Datta, 2002; May & Hasher, 1998), just as thoughts are.

Attentional regulation of strong responses, like attentional regulation over distraction/access and deletion appears to vary with circadian arousal and those variations are also seen in old rats. Winocur and Hasher (1999) found a similar pattern for old rats that are tested in a classic go/no go task at the beginning versus end of their activity cycle (Winocur & Hasher, 1999). “Go” responses do not change across the day, although the ability to withhold a strong response is diminished at the end of the day for the old rats. Old rats also have more difficulty performing a delayed matching to sample test (on which they have to reverse a previous response) at the end of their activity cycle (Winocur & Hasher, 2004).

From a view emphasizing inhibitory function, restraint processes are likely involved in situations that are conceived of by others as tapping “task set” or “goal maintenance”. For example, a series of Stroop experiments by Kane and Engle (2003) manipulated the ratio of congruent (so that the ink color matched the color named by the word) to incongruent (so that the ink color conflicted with the color named by the word) trials. When there were many congruent trials, participants with low working memory spans were error-prone on those few trials that were incongruent, and also, they were faster on congruent trials. This was the case even though low-span participants understood the goals of the task, and even when they received feedback after every trial. These data can be seen as reflecting a failure of “task set” or “goal maintenance”, at least at the level of having a goal control behavior (e.g., Kane & Engle, 2003).

An inhibitory based alternative explanation is at least equally possible. Like others (e.g., Arbuckle & Gold, 1993), we consider the Stroop task to be an inhibitory control task which requires control over strong responses (naming the word) in order to carry out a less dominant response (naming the color), thus primarily tapping into the restraint function. Since working memory tasks have an inhibitory component that includes control over deletion and very likely, given deletion failures, control over strong responses from previous sets, it would not be surprising that control lapses in the Stroop task would be associated with poor performance on a span task and this might be particularly the case when the need to control the nondominant response is not regularly reinforced. [6]

Thus strong responses can seize control both of action and of thought and both patterns can be seen for older adults and participants tested at nonoptimal items of day. These effects can be seen across a range of tasks including attention, memory and language comprehension. It is important to note that when strong responses are correct, no time of day differences are expected, since it is inhibition, not excitation that varies with the arousal cycle and other important individual differences. As an example, the time to classify a word (e.g., 'chair') as a member of a category (furniture) does not differ across the day (e.g., May & Hasher, 1998; see Yoon et al., 2000).

## Working Memory Theory, Capacity, and Inhibition

In the previous sections we outlined our current understanding and some of the relevant evidence for the inhibitory control processes that in our view are responsible for much of the variation in working memory and performance more generally. The relations between our views to others in this volume and to working memory theory in general have been touched on throughout this discussion, but here we focus on them.

The working memory model of Baddeley and colleagues (Baddeley, 1986, 1992, 2000, 2003; Baddeley & Hitch, 1974) provides a common heritage for most of the chapters in this volume, and for the vast majority of the working memory literature more generally. Our work can be seen as focusing on the Central Executive component of Baddeley's system and we, like Baddeley, were initially influenced by Allport's (e.g., 1989) and Shallice's (e.g., Shallice & Burgess, 1993) conceptions of control . Furthermore, we consider the executive processes important for "working memory" to be domain-general and important across many areas of cognition, particularly attention and memory, in close agreement with the majority of contributors to this volume (Braver & Gray; Towse & Hitch, Kane et al., Oberauer et al., Reuter-Lorenz & Jonides). Finally, we note that several contributors are considering the potential relations between group-level variation and individual-differences level variation (e.g., Braver & Gray; Hale et al., Kane et al., Reuter-Lorenz & Jonides, Waters et al.). As with several others (Hale et al., Reuter-Lorenz et al., Waters et al.), we are especially concerned with variation due to aging.

We differ from most other views by emphasizing inhibitory processes as sources of attentional regulation and so of working memory variation. Inhibitory processes are included in other views (especially Kane et al., Oberauer et al., Reuter-Lorenz & Jonides). We differ somewhat by giving them primary importance, and in so doing turning away from notions of capacity, avoiding even using the term in a loose sense, as

[6] We note that deletion failures also set the stage for the need for source monitoring, that is for the need to distinguish whether an item or set of items came from the current trial or a previous trial. Had items from a previous trial been successfully deleted initially, no source decisions would be required. Further, had items from a previous trial been successfully deleted when that trial was over and the new trial started, source decisions would be easier to make.

we find it too easily confused with the idea that the ability to have more information activated and at the focus of attention is always beneficial. In so doing we also turn away from the metaphor of a large desk or workspace as the best working memory, and consider something more similar to a (truly effective) spam blocker, allowing into the system only that information relevant to one's goals and concerns. A mental workspace narrowly focused on current concerns will be, as we have argued throughout this paper, fast and accurate at online processing in part because it is only doing one task. Such a workspace is not cluttered with previous tasks, upcoming tasks, social obligations, short and long term personal concerns; it is simply doing the current task. Simply doing the task also happens to result subsequently in fast and accurate retrieval of the information within that task. What a narrow focus probably does not do is to foster creativity (Carson, Peterson & Higgins, 2003).

Where we differ from others in the lifespan developmental literature and in the intelligence literature is in our view that aspects of inhibition regulation are central to determining individual and time of day differences in both perceptual speed and apparent working memory capacity. In our view, the cognitive primitives upon which higher order tasks build are neither speed nor 'capacity', but instead is inhibitory regulation in the service of goals. It is important to note that individuals differ in their long term goals (e.g., Kahneman, 1973) and in their values (e.g., Rokeach, 1976) and it is particularly noteworthy when doing work across the adult lifespan (and probably with all non university students), that younger and older adults differ on these important dimensions (e.g., Carstensen & Löckenhoff, 2003). If information matches goals and values, the use of inhibitory processes should be maximally efficient. Encoding will then be narrow and retention levels high. Indeed recent evidence suggests that age differences in memory can be entirely eliminated when the materials to be remembered match the goals and values of older adults (May, Rahhal, Berry & Leighton, 2004; Rahhal, Hasher, & Colcombe, 2001; Rahhal, May & Hasher, 2001).

**Biological bases for inhibitory variation**

The effects of age and time of day on inhibitory function described above strongly suggest that biological influences play a major role in variations in inhibitory efficiency. The field is in near-unanimous agreement that individual and group differences in frontal lobe structure and function contribute to individual and group differences in executive processes such as inhibition (e.g. Engle, Tuholski, Laughlin, & Conway, 1999; Miyake et al., 2000; Moscovitch & Winocur, 1995; Park, Polk, Mikels, Taylor, & Marschuetz, 2001; Persad, et al., 2002; West, 1996, 2000). The evidence for frontal lobe involvement in individual and group differences in inhibition and other executive attention processes has been reviewed extensively elsewhere and will be covered in more depth in other chapters in this volume (see especially Braver & Gray; Kane et al.; Munakata et al.; Reuter-Lorenz & Jonides; Waters et al.; for external references see citations above). Here, we focus specifically on biological evidence for variability in inhibitory function, especially that due to age and circadian arousal.

Adult age differences in the structure and function of the frontal lobe structures most often associated with working memory and inhibition are a major focus of the cognitive neuroscience of aging (see reviews by Cabeza, 2002; Grady & Craik, 2000; Raz, 2000; Reuter-Lorenz et al., 2001; Reuter-Lorenz, 2002). The neuroimaging findings in this regard will be discussed in more detail by the chapter by Reuter-Lorenz and Jonides (this volume). To summarize some of the most ubiquitous patterns: Prefrontal cortex structures including those most often associated with working memory and inhibition typically show the largest effects of age in structural brain studies (Raz, 2000). In functional imaging studies, older adults often differ from young adults either by showing less activation in the brain regions typically associated with task performance in young adults, or by showing more activation – often in regions not associated with task performance in young adults (Cabeza, 2002; Grady & Craik, 2000; Reuter-Lorenz et al., 2001; Reuter-Lorenz, 2002). This additional activation is frequently interpreted as a form of compensation for age-related increases in task difficulty or damage to structures more typically associated with the task. Others have raised the possibility that it may represent a failure to create distinct representations, or a lack of functional inhibition (e.g., Logan, Sanders, Snyder, Morris, & Buckner, 2002; see Reuter-Lorenz & Lustig, 2005 for discussion of the functional implications of additional activations.).

Although the neuroimaging literature most often focuses on changes in prefrontal cortex, there are also large changes in the subcortical structures and neurotransmitter systems that interact with prefrontal cortex to modulate its function. The size of age effects on the caudate and putamen, basal ganglia structures involved in dopamine function, and on the locus coeruleus, a brain structure involved in norepinephrine function, are a close second to those found for prefrontal cortex (Raz, 2000). These two catecholamine neurostransmitters, dopamine and norepinephrine, play important roles in attention and working memory. Changes in these systems may play an important but underrated role in age changes in cognition (see discussions by Braver & Barch, 2002; Li & Sekstrom, 2002; Rubin, 1999).

Of particular interest to the current discussion, dopamine and norepinephrine function appears to be essential to the “gating” of information – that is, maintaining target information and preventing irrelevant, nontarget information from becoming activated (see reviews by Arnsten, 1998; Aston-Jones, Rajkowski, & Cohen, 1999; Berridge, Arnsten, & Foote, 1993; Braver & Barch, 2002; in current volume see chapter by Braver & Grey). For example, neural recording studies in rodents and primates show that the phasic (stimulus-related) firing of certain basal ganglia and locus coeruleus neurons is largely target-specific under normal conditions, with little or no firing to distractors (see review by Arnsten, 1998). However, disruptions in the tonic (state-related) levels of either dopamine or norepinephrine lead to a loss of discriminability; both phasic firing to distractors and behavioral false alarms increase (Arnsten,1998; Aston-Jones et al., 1999). In humans and other mammals, dopamine and norepinephrine function shows variation both with age (Arnsten, 1998; Volkow et al., 1998) and with circadian cycle (Aston-Jones, Chen, Zhu, & Oshinksy, 2001; Karlsson, Farde, & Halldin; 2000; Wirz-Justice, 1984, 1987); further, there is an interaction such that increased age is associated with shorter, flatter, and often more irregular circadian cycles (Edgar, 1994; Hofman, 2000; Monk & Kupfer, 2000; Weinert, 2000). These systems are thus prime candidates for the source of age- and circadian-related variation.

Event-related potentials (ERPs), also provide evidence for age- and circadian-related changes in the brain functions associated with working memory. In particular, the P300, an ERP component strongly associated with the detection of target or unusual stimuli against a background of distractors, shows significant variation in both amplitiude and latency over the course of the day (Geisler & Polich, 1990, 1992; Higuchi, Lui, Yuasa, Maeda, & Motohashi, 2000; Polich & Kok, 1995). The P300 also shows differences as a result of aging (see review by Polich, 1996), and animal studies provide compelling evidence for its link to locus coeruleus activity (Foote, Berridge, Adams, & Pineda, 1991; Swick, Pineda, Schacher, & Foote, 1994). Thus far there has been very little functional neuroimaging (PET or fMRI) of the influence of circadian or age-circadian interactions on brain function. However, the evidence from neurotransmitter and ERP studies suggest these as very promising areas of future investigation.

With regards to the possible relationships among different functions of inhibition, we note a recent fMRI study that compared the brain regions involved in switching to those involved in the restraint of a prepotent response (Sylvester et al., 2003; see Nelson, Reuter-Lorenz, Sylvseter, Jonides, & Smith, 2003 for a similar study by this group). On each trial, participants were presented with an arrow facing to either the right or left. For the switching task, participants had to count the number of times each type of arrow (right or left) appeared during a block of trials; the arrow's direction switched unpredictably during the block. For the restraint task, participants had to press a button either corresponding to the direction in which the arrow was pointing (i.e., press the right button if the arrow is pointing right; low-restraint condition) or opposite to it (i.e., press the left button if the arrow is pointing right; high-restraint condition).

Although each task undoubtedly tapped multiple processes, the switching task might be thought of as preferentially requiring the *deletion* of one task set from working memory (e.g., count right arrows) to allow concentration on another (e.g., count left arrows). In contrast, the restraint task likely preferentially required the restraint or *suppression* of a natural inclination to press the button corresponding to the direction in which the arrow was pointing. Thus an intriguing question is the degree to which these two tasks elicited the same patterns of brain activity, suggesting a general executive function involved in both, versus distinct patterns specific to each task, suggesting different functions of executive control or inhibition.

There was a good deal of overlap in the brain regions activated by the two tasks: regions in superior parietal cortex, medial frontal cortex, and left dorsolateral prefrontal cortex. There were also several interesting differences. The switching task activated several posterior regions more than did the restraint task; that is switching differentially activated bilateral extrastriate cortex and left posterior parietal cortex. The restraint task preferentially activated regions in right parietal cortex, premotor cortex, frontopolar cortex, and bilateral basal ganglia regions include caudate and putamen. These results on young adult participants provide intriguing evidence for the possibility that different functions of inhibition (or executive control more generally) may be mediated by different brain structures (Sylvester et al., 2003). These different structures may vary in their sensitivity to factors such as age and time of day, and that difference should manifest itself behaviorally.

In short, there is extensive evidence that the brain structures associated with working memory show a great deal of change with age, and that the functioning of those structures may show further variation across different times of day. In addition, recent brain imaging data support the idea of a distinction between different functions of inhibition or executive control, by suggesting that different functions may be distinguished by which regions of the brain are most involved in their implementation (Sylvester et al., 2003). Behavioral evidence (from this book, Miyake) and elsewhere (Friedman & Miyake, 2004) are also suggestive in this regard. Attempts to make direct connections between age-, circadian-, and function-related variations in working memory performance are relatively new, but represent a rich and exciting area for future research.

Our central view is that working memory capacity is not the issue for understanding higher order cognition (nor is speed, as has been argued in the aging literature), rather inhibition and possibly other executive functions are. The contents of consciousness, or working memory, are controlled by executive functions operating in the service of goals. These executive functions are largely inhibitory in nature. On this view, there is a good deal of evidence, both in the present volume and elsewhere. Indeed, many views in this book have some overlap with the ones we propose here, with those of Kane and Engle being the closest. Of course, inhibitory views have not gone uncriticized (e.g., MacLeod, Dodd, Sheard, Wilson & Bibi, 2003: Miller & Cohen, 2002). The aging and time of day differences reviewed here, however, will ultimately require some accommodation by these alternative views.

**Conclusions and the Four Questions**

Question 1. What is your theory of working memory that guides your research in working memory variation?

We proposed a general theory of cognition whose central view is that the best performance on a variety of tasks occurs when the contents of consciousness are narrowly focused on goal-relevant information (e.g., Hasher et al., 1999). Narrowing occurs in the face of an individual's internal and external context- a world in which there is massive activation triggered by the environment, by the recent past, by near future tasks and by subsidiary goals. To tune this massive activation, we suggest that inhibitory control is required and we proposed that there are at least three such control processes:, access, deletion and restraint. Together with goals, these processes determine the contents of consciousness – or working memory. Our hypothesized attentional mechanisms can be thought of as at least partially fulfilling the functions of the executive system of Baddeley's working memory model (1986, 1992, 2003).

Question 2. What are the critical sources of working memory variability within the populations we study? Why do you focus on the specific source(s) of variability in your research?

Our work presumes that activation processes vary minimally within and among individuals and thus, the critical source of individual and group differences is the efficiency of inhibitory mechanisms and their underlying biology. Inhibitory control appears to vary with age, with the synchrony between an individual's circadian arousal pattern and the time of testing and there are substantial individual differences within any age group. Inhibitory control is particularly critical in situations in which there are strong but erroneous response tendencies and in which there are salient sources of distraction, whether in thought or in the environment.

What we do not yet know is the degree to which the three proposed attentional mechanisms (access, deletion and restraint) are fully independent or partially overlapping mechanisms and whether the pattern of interdependence or independence remains the same or changes across the adult lifespan and within circadian arousal pattern at different times of testing. The work of Friedman and Miyake (this volume) suggests that access and deletion may be the same for younger adults while restraint is a separable process. Our ongoing work addresses these issues.

Question 3. Are other sources of variability proposed here applicable to our target population? Are these sources of working memory variation compatible or incompatible with our views of our target population?

A major alternative view proposes that the capacity of working memory is the critical determinant of individual differences in a wide range of tasks. Our view stands in sharp contrast to this and suggests, instead, that individual differences in measures of capacity (e.g., operation span, sentence span) and in the ability of those measures to predict other cognitive functions is actually due to variation in inhibitory control processes.

We agree with Kane et al (this volume) that the critical aspect of working memory measures is not that they measure capacity, but that they measure executive (or, in our view, attentional) control processes. Indeed, we believe they best measure the ability to deal with distraction (past, present and future). We agree that 'executive attention' capabilities are the major source of variation among individuals and that these capabilities are general and critical for a variety of intellectual functions, including controlling interference, memory, problem solving and fluid intelligence. We centrally differ since in our view, the central aspects of control are inhibitory in nature and the Kane et al. view includes excitatory mechanisms for maintaining the activation of representations, including goals. We reviewed evidence of equivalent activation across the day between younger and older adults and so do not see the need for assuming significant variation in activation processes, and in this, our view differs from that of Munakata (this volume) as well.

Question 4. What does the variability within our target population tell us about the structure, function and organization of working memory in general?

Our view speaks rather directly to the nature of working memory. It suggests that working memory capacity is not the cognitive primitive it once appeared to be. Indeed our view instead suggests that the cognitive primitive (if there is one) is inhibitory attentional control. We have done this work with younger and with older adults and with individuals of this age range who differ in their circadian arousal rhythms. We have also done some work with animal models. All of this work points in the direction of attentional regulation as a critical determinant of intellectual performance. This conclusion might remind readers of Navon's classic article (1977) on capacity as a theoretical soupstone.

Our emphasis on inhibitory processes, rather than on constructs such as capacity or resources, may be the characteristic that most differentiates our view from that others. For example, Kane et al (this volume) now describe executive attention as the critical resource, determining both working memory capacity and inhibition. Our views have much in common. We have consistently emphasized that inhibitory *control* processes are the most likely sources of individual, group, and intraindividual variation in working memory; more automatic functions that are also often grouped under the term "inhibition" are less likely to be affected (see Hasher & Zacks, 1979 for earlier work on controlled processes as a source of variation). Further, our original theory statement (Hasher & Zacks, 1988) was rather unique for its time in explicitly acknowledging the importance of goals. However, while Kane, Engle, and colleagues describe executive control as a resource or capacity that can itself vary across individuals and that is excitatory in nature, we see the controlled, effortful aspects of inhibitory processesing as a common feature but not a construct *per se*. (See the introduction of this chapter for a discussion of divided attention; Hasher, Tonev et al (2001) for a detailed discussion of the relation between our view and resource- or capacity-based views.)

In our theoretical work, we proposed the existence of three inhibitory processes, access, deletion and restraint (e.g., Hasher et al., 1999) that together and possibly independently operate to regulate the contents of consciousness. Our age and time of day work with individuals at different points in their arousal cycle suggests that all three change with age and also across the day such that regulation is better at peak times of day than at off peak times. The findings from animal model work overlap, albeit not precisely, on both the age and time of day effects we have seen for people (Winocur & Hasher, 1999, 2002, 2004), suggesting a biological basis for these mechanisms. As well, we reported evidence that inhibitory processes underlie age differences in speed of processing and good evidence that they underlie most tasks that measure working memory capacity. We reported evidence on the role of inhibition (and circadian patterns) in determining long term memory performance. We also have clear evidence that excitatory processes do not change across the day (e.g., Yoon et al., 2000) and we and others believe they do not change with age (e.g., Duchek et al., 1998). Thus we see these inhibitory processes, which we argue work together with an individual's goals to determine the contents of consciousness, to be at the heart of what many call working memory. These mechanisms can be thought of as an at least partially fulfilling the functions of the executive system of Baddeley's working memory model (1986, 1992, 2003)

Thus, the critical source of working memory variability among (and within) people is inhibition. At the very least, we also know that circadian arousal patterns (and individual differences therein) influence the efficiency of inhibitory control What we do not know is the degree to which the three proposed inhibitory executive functions (access, deletion and restraint or suppression) are fully independent or partially overlapping mechanisms and (b) whether the pattern of interdependence or independence remains the same or changes across the adult lifespan and within an age group with circadian arousal. The work of Friedman and Miyake (this volume) suggests that access and deletion may be the same for younger adults and that restraint is a separable process. An ongoing project of ours also attempts to address this question. Although the research reviewed in the section on "Biological bases for inhibition variation" indicates that relevant findings are beginning to appear in the literature, we also do not know a great deal about the underlying biology of inhibitory control.

We would simply add that the richest explications of the problems of mental control will come from research on a very broad range of participants using a broad range of approaches, including those represented in this book, and work done in other guises, including, self regulation of motivated behavior (e.g., Muraven & Baumeister, 2000). Our read of the overall literature suggests that for cognitive efficiency reasons, a narrow, goal driven focus is ideal for both online and subsequent performance. To achieve a narrow focus (or to regulate attention effectively), inhibitory processes are required. We argue there are three such processes (access, deletion and restraint) and that they vary within an individual, among individuals, and across the lifespan. Our views are not particularly tied to aging or to circadian rhythms, but instead are tied to a general theory of cognition that suggests that fundamental regulatory mechanisms are inhibitory in nature.

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CITATIONS TO CHAPTERS IN THE PRESENT BOOK (to be included when titles, authors are known)

Braver and Gray
Towse and Hitch
Oberauer
Reuter-Lorenz
Hale et al
Kane
Waters
Munakuta
Friedman and Miyake