

9

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 as well as 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 irrelevant 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 a rich literature pointing to substantial costs for retrieval of having entertained irrelevant information during encoding. Sometimes the irrelevant

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 place under divided-attention conditions (Craig, Govoni, Naveh-Benjamin, & Anderson, 1996; Fernandes & Moscovitch, 2000), or when actually presented information triggers activation of related information (e.g., Deese, 1959; Roediger & McDermott, 1995; Underwood, 1965). Whatever the source, any 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, the latter due to fundamental interference processes. We note that all tasks which depend on rapid and accurate retrieval of information that was once attended to will suffer to the 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 visuospatial working memory span; Lustig & Hasher, 2002; Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999; Rowe, Turcotte & Hasher, 2006); (b) basic-level perceptual speed tasks used in the intelligence, developmental, and aging literatures (Lustig, Hasher, & Tonev, in press); (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; Kim, Hasher & Zacks, in press; Lustig & Hasher, 2001; Rowe, Valderrama, Lenartowicz & Hasher, in press; 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. Our emphasis on executive processes fits well, however, 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 et al., 2003; Ranganath, Johnson, & D'Esposito, 2003). Recent work by Engle and colleagues has a similar perspective to our own, as their emphasis has shifted toward working memory as an executive attention system rather than as a "memory" system (e.g., Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001; see also Chapter 2, this volume). 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) that are subsequently determined by the initial breadth of focus (e.g., see Chapters 2 and 4, but see Chapter 10 for a somewhat different view).

Our work differs from many others' in that we emphasize the role of *inhibitory* processes, or those 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 or 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 working memory abilities; or, if they do, the differences actually 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 they do 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 initially stimulated by age differences found in an inference generation task, differences that could not be accounted for by those 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. Although older adults initially generated the correct inference, they 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 entering the focus of attention and 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 inhibition is a fundamental determinant of the apparent differences in what many investigators term "working memory capacity."

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 within the same individual across different physiological and psychological states (Hasher & Zacks, 1988, Hasher et al., 1999). 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 et al., 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 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 intra-individual-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 and late in the afternoon to provide a snapshot of fundamental cognitive processes functioning across the day (see Winocur & Hasher, 2002, for a brief review of related animal model evidence). Despite the folk nomenclature of these two "types," they are well substantiated in physiology (e.g., Kerkhof & Lancel, 1991), including recent 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 chapter). We also note that there are life span 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 than later in the day. 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).³

Of particular importance for present purposes, the data suggest that regardless of 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 (e.g., 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 il-

luminare 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 on-line and downstream efficiency places us within 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, 1991). Many investigators subsequently arrived at similar or partially overlapping views (see Duchek, Balota, & Thessing, 1998; Harnishfeger & Bjorklund, 1994; Nigg, 2001; Wenzlaff & Wegner, 2000; Chapters 2, 3, 4, and 10, this volume). 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) *delete* no-longer relevant items from consideration, and (3) *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 chapter, 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 that focuses on 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 have profound behavioral effects on inhibitory regulation.

INHIBITORY PROCESSES

We have posited three inhibitory functions: access, deletion, and restraint (Hasher et al., 1999; Hasher, Tonev, Lustig, & Zacks, 2001; Hasher & Zacks, 1988; 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 retrieval while the third (restraint) can influence 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). Over the past 20 years our work 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 intra-individual-differences approach, the theory be-

hind 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 (e.g., Cowan, 1993). When efficient, all irrelevant representations are suppressed and the contents of consciousness will be narrowly tied to goals. A dramatic example of narrow focus of attention is the "inattention 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, 1992, Kim, Hasher, & Zacks, in press). 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 at which a decision is made about two letter strings (e.g., XPFGN and XPFCN) being the same or different is at least partially determined by whether there are other letter strings simultaneously present and competing for access to attention (Lustig et al., in press). For young adults, the presence of other letter-string problems has no effect on the speed at 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 life-span 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 just 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; Duchek, et al., 1998; 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: under many circumstances, 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 of processing speed as a cognitive primitive that underlies intelligence and the developmental trajectory of cognition across the life span (e.g., Kail, 1993; Salthouse, 1996). Such findings 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 vs. 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 *cot-*

tage) 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 that had been normed to either lead toward 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 inattentive blindness phenomenon (Mack & Rock, 1998; Most et al., 2001) and in perceptual speed tasks completed in the presence or absence of distraction (Lustig et al., in press). 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. This failure also held for everyone tested at suboptimal times of day.

More recent work shows that the consequences of a failure to control distraction are not just immediate, but can also impact on "downstream" performance 15 or 20 minutes after initial exposure to the distraction

(Kim et al., in press; Rowe, Valderrama, Lenartowicz & Hasher, in press). Furthermore, these experiments show "far transfer" effects, such that distraction in the context of one task can influence performance on very different subsequent tasks. Indeed, in these two unique circumstances, the data show greater benefits for older as compared to younger adults, rather than the typically seen greater costs. As well, the benefits are greater at nonoptimal times than at optimal times (Rowe et al., in press).

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 in university settings are Evening types (see, e.g., May, Hasher, & Stoltzfus, 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 et al., 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 irrelevant 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 or in competition with working memory capacity as an explanation for performance variation across the life span (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, 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* irrelevant 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 for removing irrelevant representations from the focus of attention so as to enable efficient processing of goal-driven representations. Deletion also removes once-relevant information that has become irrelevant because of a change in goals, context, task, or situational demands, as can occur in a conversation when a topic changes, or 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 comes from the observation that older adults not only allow alternative interpretations of a passage to gain *access* to their attention but also fail to *delete* those alternatives from consideration, even when it becomes clear that they were incorrect (Hamm & Hasher, 1992; 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 was reliably *above* baseline levels, showing time-of-day differences in the efficiency of the deletion function for young adults that are consistent with their arousal pattern. Older adults also showed 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 of the deletion function on 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 two to six 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 that a participant can reliably understand and for which all items in the set can be recalled 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.

On the basis of these observations of the typical operations involved in assessing working memory span, May, Hasher & Kane (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." However, 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 that of 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 ver-

sions of Daneman and Carpenter's reading and listening span tasks. The reversed-order manipulation also increased the span scores of older adults on a Corsi-block version of a visuospatial working memory span task (Rowe et al., 2006). Bunting (2006) 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 (see also Rowe et al., 2006). We have also found that circadian influences can affect PI-heavy measures of working memory span (Hasher et al., 2005; Yoon et al., 2000), consistent with the conclusion that the efficiency of the deletion function varies across the day. Taken 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 that they index the efficiency of inhibitory aspects of attention regulation.

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, Hasher & Kane (1999) results by showing that delivering a span task in reverse order (so 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 younger 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 raise the possibility that whenever span tasks are used to select participants to perform on other tasks and whenever reliable correlations are obtained, the mediating variable may well be inhibitory control over nonrelevant information, 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 demonstrating 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, the Lustig and Hasher (2002) finding suggests that 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 (Brush & Postle, 2003; Postle, Berger, Goldstein, Curtis, & D'Esposito, 2001), 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).⁴ It is not surprising, then, that older adults typically show differentially poor retrieval relative to that of 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 than at 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; Yoon et al., 2000, in press, for reviews).

Restraint

Restraint 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 as well as with performance at an off-peak time of day (May & Hasher, 1998).

Comparable evidence with respect to age differences 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 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 nonsense, such as "How many animals of each

type did Moses take on the ark?" Yoon et al. (2000) 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 or 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 tested in a classic Go-NoGo task at the beginning and at the end of their activity cycle (Winocur & Hasher, 1999). Go responses did not change across the day, although the ability to withhold a strong response was diminished at the end of the day for the old rats. Old rats also had 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 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 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 that 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. This might particularly be the case when the need to control the nondominant response is not regularly reinforced.

Thus strong responses can seize control of both action and thought, and both patterns can be seen for older adults and participants tested at nonoptimal times 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 it takes to classify a word (e.g., *chair*) as a member of a familiar 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 cognition more generally. The relations between our views and those of other authors in this volume, and working memory theory in general, have been

touched on throughout this discussion, but here we focus more specifically 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 own work can be seen as focusing on the central executive component of Baddeley's system. Like Baddeley, we were initially influenced by Allport's (1989) and Shallice's (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 most of the contributors to this volume (see Chapters 2, 3, 4, 5, and 10). Finally, we note that several contributors address the potential relations between group-level variation and individual differences—level variation (see Chapters 2, 4, 8, 10, and 11). Like several other contributors (Chapters 8, 10, and 11), we are especially concerned with variation due to aging.

Our approach differs from most other views in emphasizing inhibitory processes as sources of attentional regulation and thus of working memory variation. Although inhibitory processes are included in other views (see especially Chapters 2, 3, and 10), we differ somewhat from these views by giving inhibition primary importance, and in so doing turning away from notions of capacity. We have avoided using this term in a loose sense, as 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. Thus, 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 information that is relevant to one's goals and concerns. As we have argued throughout this chapter, a mental workspace narrowly focused on current concerns will be fast and accurate at on-line processing, in part because it is only doing one task. Such a workspace is not

cluttered with previous tasks, upcoming tasks, social obligations, and short- and long-term personal concerns; it is simply doing the current task. Simply doing the current 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 foster creativity (Carson, Peterson, & Higgins, 2003).

Where we differ from others in the life-span developmental literature and in the intelligence literature is in the notion that aspects of inhibitory 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 are inhibitory regulation that occurs in the service of goals. It is important to note that individuals differ in their long-term goals (e.g., Kahneman, 1973) and values (e.g., Rokeach, 1976). When researchers are doing work across the adult life span (and probably with all non-university students), it is particularly important to recognize 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, values and interests of older adults (May, Rahhal, Berry, & Leighton, 2005; Rahhal, Hasher, & Colcombe, 2001; Rahhal, May, & Hasher, 2002).

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 in-

hibition (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 is covered in more depth in other chapters in this volume (see especially Chapters 2, 4, 7, 10, and 11). 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 work in the cognitive neuroscience of aging (see reviews by Cabeza, 2002; Grady & Craik, 2000; Raz, 2000; Reuter-Lorenz, 2002; Reuter-Lorenz et al., 2001). The relevant neuroimaging findings are discussed in more detail in Chapter 10; we will summarize some of the more ubiquitous patterns here. 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 in showing either less activation in the brain regions typically associated with task performance in young adults or showing more activation, often in regions not associated with task performance in young adults (Cabeza, 2002; Grady & Craik, 2000; Reuter-Lorenz, 2002; Reuter-Lorenz et al., 2001). 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. Other investigators 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, is a close second to the amount found for prefrontal cortex (Raz, 2000). These two catecholamine neurotransmitters, 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 & Sikström, 2002; Rubin, 1999).

Of particular interest to the current discussion is that dopamine and norepinephrine function appears to be essential to the "gating" of information—that is, maintaining target information and preventing irrelevant, non-target information from becoming activated (see reviews by Arnsten, 1998; Aston-Jones, Rajkowski, & Cohen, 1999; Berridge, Arnsten, & Foote, 1993; Braver & Barch, 2002; see Chapter 4, this volume). 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 with both age (Arnsten, 1998; Volkow et al., 1998) and circadian cycle (Aston-Jones, Chen, Zhu, & Oshinsky, 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, P300, an ERP component strongly associated with the detection of target or unusual stimuli against a background of distractors, shows significant variation in both amplitude and latency over the course of the day (Geisler & Polich, 1990, 1992; Higuchi, Lui, Yuasa, Maeda, & Motohashi, 2000; Polich & Kok, 1995). 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) evidence of the influence of circadian or age-circadian interactions on brain function. However, the evidence from neurotransmitter and ERP studies suggests that these interactions are very promising areas for future investigation.

With regard to the possible relationships among different functions of inhibition, we note a recent fMRI study that compared the brain regions involved in switching with those involved in the restraint of a prepotent response (Sylvester et al., 2003; see Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003, for a similar study by this group). On each trial, participants were presented with an arrow facing 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 one opposite this direction (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. An intriguing question is the degree to which these two tasks elicited the same patterns of brain activity, thus suggesting a general executive function involved in both, or distinct patterns specific to each task, implying 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 the restraint task did—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 including 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 this 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 the regions of the brain most involved in their implementation (Sylvester et al., 2003). Behavioral evidence (e.g., Friedman & Miyake, 2004) is 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 main issue for understanding higher-order cognition (nor is speed, as has been argued in the literature on aging), 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. There is a good deal of evidence to support this view, both in the present volume and elsewhere. Indeed, many views in this book have some overlap with those we propose here, the ideas of Kane and colleagues (Chapter 2) being the closest. For example, Kane et al. now describe executive attention as the critical resource that determines both working memory capacity and inhibition. Of course, approaches favoring inhibitory processes 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

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 of others. We have consistently maintained that inhibitory *control* processes are the most likely sources of individual, group, and intra-individual variation in measures of working memory. We have 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 processes change with age and across the day, such that regulation is better at peak times of day than at off-peak times. The findings from animal models overlap, albeit not precisely, 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. We have also reported evidence that inhibitory processes underlie age differences in speed of processing and underlie most tasks that measure working memory capacity, as well as

BOX 9.1. SUMMARY ANSWERS TO BOOK QUESTIONS

1. THE OVERARCHING THEORY OF WORKING MEMORY

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, the recent past, near-future tasks, and subsidiary goals. To tune this massive activation, we suggest that inhibitory control is required, through at least three 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).

2. CRITICAL SOURCES OF WORKING MEMORY VARIATION

Our work presumes that activation processes vary minimally within and among individuals, 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, and the synchrony between an individual's circadian arousal pattern and the time of testing. There are also substantial individual differences within any age group. Inhibitory control is particularly critical in situations to which there are strong but erroneous response tendencies and where 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. Also unclear is whether the pattern of interdependence or independence remains the

same or changes across the adult life span and within circadian arousal patterns at different times of testing. The work of Friedman and Miyake (2004) suggests that access and deletion may be the same for younger adults whereas restraint is a separable process (see Chapter 8). Our ongoing work addresses these issues.

3. OTHER SOURCES OF WORKING MEMORY VARIATION

A major alternative view proposes that the capacity of working memory is the critical determinant of individual differences on 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 are actually due to variation in inhibitory control processes.

We agree with Kane et al. (Chapter 2) 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. In our view, however, the central aspects of control are inhibitory in nature; Kane et al.'s view includes excitatory mechanisms for maintaining the activation of representations, including goals. We have reviewed evidence of equivalent activation across the day in younger and older adults and so do not see the need for assuming significant variation in activation processes. In this regard our view differs from that of Munakata et al. (Chapter 7).

(continued)

BOX 9.1. (continued)**4. CONTRIBUTIONS TO GENERAL WORKING MEMORY THEORY**

Our approach speaks directly to the nature of working memory. It suggests that working memory capacity is not the cognitive primitive it once appeared to be, and instead suggests that the cognitive primitive (if there is one) is inhibitory attentional control. Our studies have

included younger and older adults, as well as individuals of this age range who differ in their circadian arousal rhythms. We have also done some work with animal models. All of these studies point toward 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 soup stone.

evidence to support the role of inhibition (and circadian patterns) in determining long-term memory performance. There are also clear findings that excitatory processes do not change across the day (e.g., Yoon et al., 2000); we and others believe these processes 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 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 (a) 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 with circadian arousal the pattern of interdependence or independence remains the same or changes across the adult life span and within an age group. Although the research reviewed above in the section Biological Bases for Inhibition Variation indicates that relevant findings are beginning to appear in the literature, we do not know a great deal about the underlying biology of inhibitory control.

We would simply add that the richest explanations of the problems of mental control will come from research on a very broad range

of participants studied through a broad range of approaches, including self-regulation of motivated behavior (e.g., Muraven & Baumeister, 2000). From our analysis of the overall literature, we suggest that for cognitive efficiency, a narrow, goal-driven focus is ideal for both on-line performance and subsequent retention of details. To achieve a narrow focus (or to regulate attention effectively), inhibitory processes are required. We argue that there are three such processes (access, deletion, and restraint) and that they vary within an individual, among individuals, and across the life span. Our views are not particularly tied to aging or circadian rhythms, but instead represent a general theory of cognition that suggests that fundamental regulatory mechanisms are inhibitory in nature.

Notes

1. In this chapter we do not discuss the relevant literature on social issues and personality, 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., McDowd & Fillion, 1992; Raine, Benishay, Lencz & Scarpa, 1997).
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). Lab and life goals can conflict, setting the stage for poor performance. Sometimes, participants may not adopt the goals set by the experimenters.

3. Although there is a rich literature exploring performance across the day, most of these studies are done without reference to differences in circadian arousal patterns. Although important 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 (see Goldstein et al., 2006).
4. We note that access, too, plays a role in determining both short- and long-term memory performance, including that on working memory tasks, because this process also influences the size of the memory bundles created during encoding. These will be small or large, to the degree that access is or is not efficient, respectively.
5. We note that deletion failures also set the stage for the need for source monitoring, that is, the need to distinguish whether an item or set of items came from the current trial or a previous trial. If items from a previous trial are successfully deleted initially, few source decisions would be required. Further, if items from a previous trial were successfully deleted when that trial was over and the new trial started, source decisions would be easier to make.

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