

# 23 Inhibitory Control, Circadian Arousal, and Age

Lynn Hasher, Rose T. Zacks, and Cynthia P. May

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**ABSTRACT** The empirical work reported here is based on a model of cognitive control over the contents of working memory. Using a variety of tasks, we consider three major functions of inhibition: access, deletion, and restraint over strong thoughts and actions. The data suggest that inhibition affords control over the momentary contents of working memory. In particular, poor inhibitory control results in enriched or cluttered contents in working memory (that is, time-sharing between relevant and nonrelevant information), and in the inappropriate production of strong but incorrect responses. Reductions in inhibitory control can have consequences for a variety of cognitive processes including learning, retrieval, and comprehension. Such reductions can make a person highly distractible, forgetful, inappropriately absorbed in either thought or the external world and less able to satisfy personal goals. The data reviewed here suggest that reductions in inhibitory control are associated with aging and, for both younger and older adults, with performing tasks that require inhibitory control at an individual's non-optimal time of day.

Imagine yourself late one night, reading a good mystery.<sup>1</sup> It has been a long day, and several of today's unresolved problems will have to be added to tomorrow's "to do" list. You are too tired to work—and too wound up to sleep. After a few minutes, you might find yourself at the bottom of a page without any idea of what you have read, despite the clear impression that your eyes followed the text. This is a mental control failure in which goals may have controlled eye movements, but they did not control thoughts, which were focused on personal concerns rather than on the book.

Such failures of control are probably more common at some times and under some circumstances than others, and they may be more common for some individuals—and even for some groups—than for others. The research described here is an attempt to understand mental control. Our approach was to formulate a general theory and then study that theory's usefulness by exploring failures of control. We begin with the theory.

From our perspective (Hasher and Zacks 1988; Stoltzfus, Hasher, and Zacks 1996; Zacks and Hasher 1994), control is the degree to which an activated goal determines the contents of consciousness. Indeed, our central interest has been in the key processes that enable goals to control the contents of consciousness. From the start, our approach to these control processes has been heavily influenced by two closely related sets of ideas: ones deriving from recent accounts of selective attention that focus on selection for action

(Allport 1989; Navon 1989a,b; Neill 1989; Neumann 1987; Norman and Shallice 1986; Tipper 1992); and others deriving from current approaches to short-term or working memory (Baddeley 1992, 1993; Cowan 1988, 1993). Proceeding from these views (though not entirely agreeing with any one of them), we assume that familiar stimuli in the environment automatically activate, in parallel, their representations in memory, and that this activation can spread via well-established linkages to associated information. The outcome of this initial activation phase is modulated by attentional control processes that operate in the service of goals and expectancies. This modulation process involves both excitatory mechanisms, which enhance the activation of goal-relevant, expected information and inhibitory mechanisms, which suppress the activation of extraneous, goal-irrelevant information. We also assume that among representations receiving some degree of activation, conscious awareness is restricted to the most highly activated subset (cf. Cowan 1988, 1993), which we refer to as "items at the focus of attention" or as the "conscious contents of working memory." This line of argument implies that efficient operation of both excitatory and inhibitory attentional mechanisms is essential to the goal of keeping the contents of consciousness free of extraneous information.

Inhibition has three functions, all directed at the contents of working memory: access, deletion, and restraint. Inhibition controls *access* to working memory by preventing any activated but goal-irrelevant information (triggered automatically by familiar stimuli in the physical or mental environment) from entering working memory. Inhibition thus enables activated, goal-relevant representations to enter the focus of attention with reduced cross talk from irrelevant representations. Inhibition also controls what is active in working memory by *deleting* or *suppressing* the activation of any marginally relevant or irrelevant information, along with the activation of any information that becomes irrelevant because (to use examples from language processing) the topic or main character has shifted, because there has been a misunderstanding, or because goals have shifted. Together, the access and deletion functions of inhibition serve to clear working memory of irrelevant information, so that items concurrently active there are relevant to one another. The deletion function also prevents recently rejected items from having sustained cross talk with focal attention items, which allows these items to recruit the activation necessary to establish cohesion among successively occurring ideas (Stoltzfus et al. 1993). Inhibitory mechanisms also serve a *restraining* function by preventing prepotent candidates for response from immediately seizing control of the thought and action effectors, so that other, less probable response candidates can be considered. Inhibition thus enables variation in behavior even in situations where there is a dominant response.

There are intellectual, social, and interpersonal consequences of poor inhibitory control over the conscious contents of working memory. We focus on the intellectual ones. In addition to the obvious ease with which thoughts

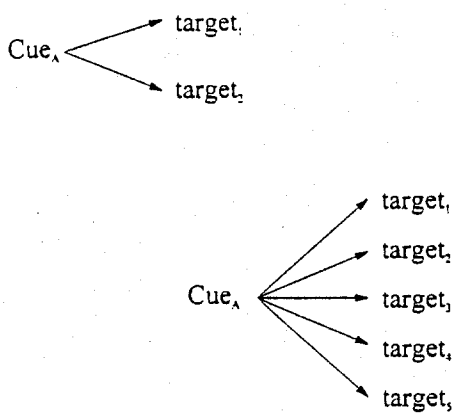


Figure 23.1 Example of spare (left) and cluttered (right) fans.

will drift from topic to topic and distracting stimuli will disrupt ongoing work, we begin with lapses of retrieval, a consequence of poor inhibitory control that in the long run is particularly damaging to coherent thought and action. Retrieval lapses are the downstream consequence of inhibitory failures that enable goal-relevant and -irrelevant information to time-share in working memory. Because information that co-occurs in mental time is stored together in memory units (Logan and Etherton 1994; Postman and Underwood 1973), the units stored when inhibition is deficient will be richer (or more cluttered) than those stored when inhibition is effective. When inhibition is efficient, memory bundles are more likely to include only mutually relevant information. Figure 23.1 depicts the spare and cluttered memory bundles (or "fans") that are, respectively, the consequences of efficient inhibition (seen on left) and inefficient inhibition (seen on right).

Although mental clutter (or time-sharing) has cross talk consequences for ongoing cognition, its more profound consequence is for downstream (or subsequent) cognition: the loss of rapid and accurate access to past records in memory. A rich research domain in human memory shows that the momentary probability of retrieving an element from a large fan is less than the probability of retrieving the same element from a small fan and that retrieval from a large fan, if successful, is slower than retrieval from a small fan (e.g., Anderson 1983). Thus lack of inhibitory control over the contents of active memory can have consequences triggered by retrieval failures. Such lapses occur most often in time-limited situations including the vast majority of all externally controlled events (e.g., watching a movie or listening to a colloquium speaker). Such situations are probably not rare even in interpersonal communication: speakers may fail to attend to cues from listeners, suggesting they are having retrieval problems; listeners may themselves fail to provide the critical cues to avoid being mistaken for not being interested or smart. Time-limited situations probably include many self-initiated events as well because people are likely to have a subjectively determined amount of time they are willing to allot to a retrieval attempt before quitting.

Thus people with poor inhibitory control over the contents of consciousness are people who are distractible<sup>2</sup>, who have difficulties with retrieval of details, including, for example, those needed to form the on-line inferences critical to comprehension. Because of retrieval problems, they are forced to rely either on the highly practiced or general information that comes to mind most quickly (including, for example, schemas) or on cues present in the external world. Loss of control over the contents of consciousness will, in some instances, enable automatic processes to play a larger role in behavior, make it difficult to avoid dwelling on current personal concerns, or make it difficult to refocus the cognitive system onto goal-relevant tasks and information when it is dominated by the external world. To some degree, this is a description of key aspects of the cognitive lives of older adults. However, young adults vary in the degree to which they resemble this description, and across the day, we may all, as well.

We make the case for this general model of cognition by showing that (1) as a group, older adults have less inhibitory control over the current contents of working memory than younger adults and that (2) people of all ages probably have more control at some times of day than at other times. We turn now to evidence that supports the model. We first consider evidence on the deletion function of inhibition, followed by the access function. Before discussing the restraining function, we make the case, for a "less is more" view of the operation of working memory. In sections 23.5 and 23.6, we consider inhibitory control under conditions of optimal and nonoptimal circadian arousal.

### 23.1 INHIBITION: THE DELETION FUNCTION

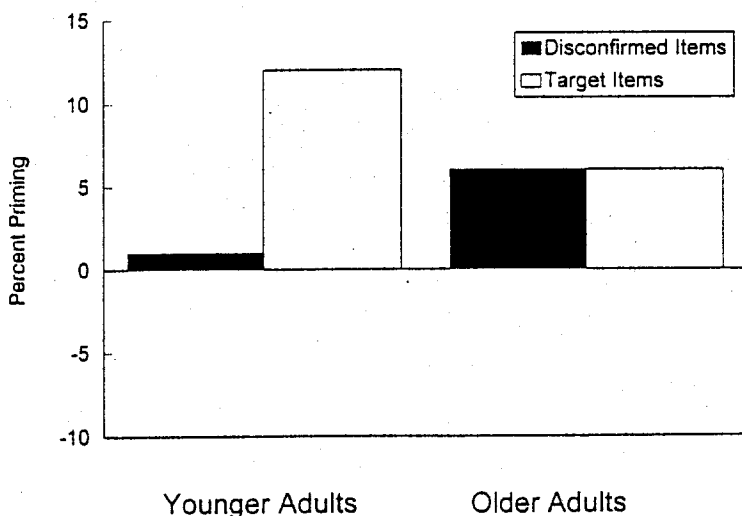
One task that assesses inhibitory control over the contents of working memory is a "garden path" sentence-processing task in which the *deletion* function of inhibition is engaged by an experimenter-created switch from a highly probable ending of a sentence to a less probable one that participants are instructed to remember. We assess the effectiveness of inhibitory control by testing for accessibility in memory of the original and final endings using a conceptually based, implicit memory task (Hartman and Hasher 1991). The assumption is that efficient inhibition should leave only the final target items accessible in memory.

In the initial phase of this experiment, people generate the last word for each of a series of sentences that were selected for their highly predictable endings. Most participants produce the word "lights" as the completion to "Before you go to bed, be sure to turn off the \_\_\_\_\_." (Across all sentences and multiple studies, approximately 88% of participants produce expected endings.) After participants generate an ending, a target word appears, and participants are instructed to remember only that target item for a later memory test. For half of the sentences (fillers), the target item matches the participant-generated ending. For the other half of the sentences (critical gar-

den path sentences), the participant-generated ending is replaced by a new, less probable target word, for example "stove." Thus for half of the sentences, the participant-generated ending is disconfirmed, and participants must remember a new, experimenter-provided target item.

After a series of such sentences and a brief filled interval, we implicitly test for memory access to the target words (e.g., "stove") and to the disconfirmed words (e.g., "lights") of critical sentences by asking people to complete a series of sentences with the first word that comes to mind. (Our cover story was that we needed these completions for use in another study.) The test phase sentences were tied to the initial phase as follows. For each of the critical garden path input sentences, two sentences were written, one to test for access to the to-be-remembered target word (e.g., for "stove": "She remodeled her kitchen and replaced the old \_\_\_\_\_") and one to test for access to the self-generated but disconfirmed word (e.g., for "lights": "The baby was fascinated by the bright \_\_\_\_\_").<sup>3</sup> The test sentences were completed with a 50% probability by naive participants who had not been exposed to our input materials; norms internal to the study showed approximately a 50% completion rate when critical items served as fillers for the test phase.

If inhibitory mechanisms are efficient, people should have access to the to-be-remembered target information, but not to their initial, highly probable, but disconfirmed ending. The disconfirmed items would have been deleted and made less accessible than the target items—at least in the momentary context of the experiment. And indeed, this describes the performance of younger adults who have access to the target endings only. The generated, but disconfirmed endings have retreated to a baseline level of activation (see figure 23.2). Note, by contrast, though, that older adults have reliable access



**Figure 23.2** Percentage of priming for disconfirmed and target words for younger and older adults. Data from Hartman and Hasher 1991.

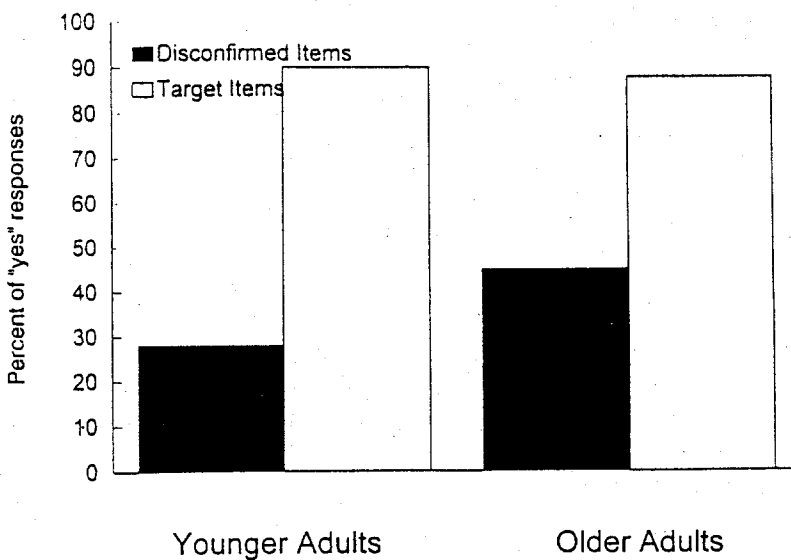
to both endings. Inefficient inhibition did not fully clear working memory of no longer relevant information.<sup>4</sup>

To support the view that inhibitory processes are engaged to delete no longer relevant information from working memory, and that inhibitory processes are indeed less efficient for older adults than for younger adults in general, we have used a converging operations approach. Included among the different tasks is one that used speeded decisions to determine the interpretation of the central situation held by readers at different points in a passage. Critical passages have a garden path structure in that they initially mislead people to an interpretation that subsequently turns out to be incorrect (Hamm and Hasher 1992). For example, one story in this study deliberately misleads people to believe that an object discussed in the context of a hunter's taking a shot while on a safari is a gun, when actually the object is a camera (because the trip, as it turns out, is a photographic safari, not a hunting one). Understanding the nature of the object being used is absolutely critical to understanding this passage. We assess understanding by having people make speeded judgments as to whether target words (e.g., gun) are consistent with their interpretation of the passage, either midway through the passage (before the initial, garden path interpretation has been disconfirmed) or at the end of the passage (when the garden path interpretation is no longer appropriate and a new interpretation is evident).

Our series of experiments (e.g., Zacks and Hasher 1988) with such materials shows that older adults do indeed understand the passages and that by the end of each, most have the correct interpretation (in this example, camera) in mind, just as most younger adults do. There is, however, a difference between younger and older adults with respect to the initially generated, but incorrect interpretation (gun): younger adults have abandoned this interpretation, while older adults have not (see figure 23.3).

The materials in these two sets of studies simulate a fundamental occurrence in discourse: topics, settings, protagonists, and even speakers shift, and each of these requires (to some extent) the ability to focus on the new and, frequently, to delete from the contents of working memory topics no longer relevant. As in our garden path passage and sentence studies, the instruction to suppress no longer relevant information in natural language situations is implicit in most communications. Perhaps, one might argue, there are age differences in sensitivity to implicit suggestions. Across their life span, adults may become less proficient at detecting such cues. Thus, although our interpretation of these studies is that inhibitory mechanisms critical for the deletion of no longer relevant information from working memory become less efficient with age, an alternative interpretation is possible. That is, older adults may require *explicit* instructions to accomplish the suppression that younger adults can do under *implicit* instructions.

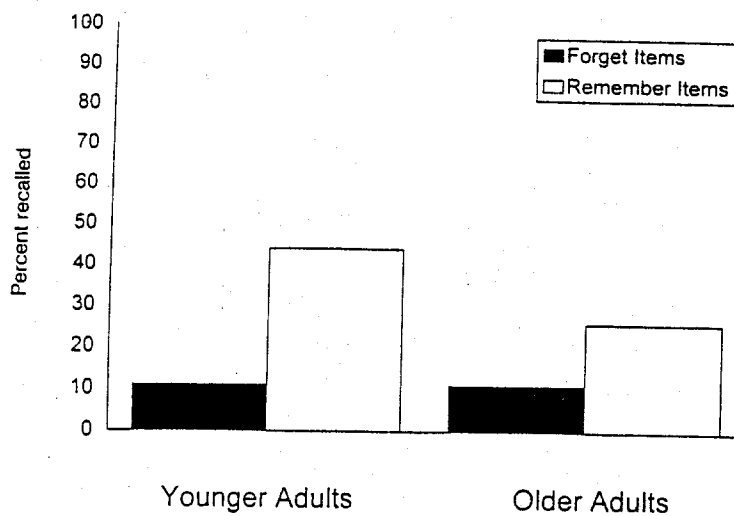
A series of studies on directed forgetting, a family of tasks that uses explicit instructions to forget no longer relevant information, suggests that this alternative interpretation is not correct. Even with explicit instructions



**Figure 23.3** Percentage of yes (agreement) responses to disconfirmed interpretations and to target interpretations, shown for younger and older adults. Data from Hamm and Hasher 1992.

to forget, older adults still have more no longer relevant information accessible in memory than do younger adults (see Zacks, Radvansky, and Hasher 1996). Directed forgetting studies typically expose participants to many lists of unrelated items, with information regarding which items to remember and which to forget being presented either after each item or after a block of items. The diminished ability of explicit "forget" instructions to engage the delete function can be seen on a surprise, final recall test, in which participants are asked to recall not only the "remember" items from each list, but also the "forget" items from the lists. A critical difference here is in the composition of recall, with (see figure 23.4) older adults recalling far fewer *remember* items than younger adults—but as many *forget* items. Thus it seems that the inhibitory mechanism that deletes no longer relevant information from its active state in working memory is indeed impaired with age, whether the selection "instruction" is implicit, as in the earlier studies, or explicit, as in directed forgetting tasks.

Taken together then, these data suggest that, on average, older adults have less control over the contents of working memory than do younger adults, especially with respect to the deletion function. We note here that Gernsbacher (1990; Gernsbacher and Faust 1991) has been exploring a similar mechanism in her "structure-building" framework of language comprehension. Those findings show that efficient comprehension requires the deletion of no longer relevant information from working memory and, like ours, implicates an inhibitory mechanism as key in that process. We note as well, that Gernsbacher has reported that young adults vary in their inhibitory efficiency and that good readers are particularly effective inhibitors. Together, these data suggest that older adults, (and younger adults who are poor readers) are, on average, more likely to have enriched working



**Figure 23.4** Percentage of Forget and Remember words recalled by younger and older adults. Data from Zacks, Radvansky, and Hasher 1996.

memories, in that the contents will, at any given moment, be “cluttered” with information that is no longer relevant (or that is marginally relevant or even totally irrelevant).

### 23.2 INHIBITION: THE ACCESS FUNCTION

Our view predicts that deficient inhibition should permit more irrelevant information to enter the focus of attention. The evidence on this prediction can be simplified considerably if one distinguishes between two sources of information; the external world and the mind. In general, external distraction has a greater negative impact on older than on younger adults because more activated information, cued by the environment, gains access to working memory for older adults than for younger adults. This is seen, for example, in selective attention tasks and in activities such as driving that require the person to interact with a complex environment (see Hasher and Zacks 1988 for a brief review). There are exceptions to the general conclusion that older adults are more distracted by extraneous environmental stimuli; these involve situations in which the target and distraction are easily distinguishable on the basis of salient perceptual cues (e.g., color or spatial location). So, for example, older adults are far more disrupted than are younger adults by the presence of distraction in unpredictable locations in a reading-aloud task (Carlson et al. 1995; Connelly, Hasher, and Zacks 1991; Li, et al. in press). On the other hand, when the distracting text appears in predictable locations, older adults are no more disrupted by irrelevant stimuli than are younger adults (Carlson et al. 1995). Thus, except when there are salient cues to direct attention to target stimuli, older adults have greater difficulty denying extraneous information access to working memory.



Examples of goal-irrelevant information from internal sources include off-track associations to task information, unrelated personal concerns, context-irrelevant interpretations of ambiguous words, and so on. The evidence that older adults are likely to show greater working-memory access to such thoughts and associations than are younger adults is not, at first glance, strong. For example, older adults do not seem to show an elevated incidence of idiosyncratic associations on free association tests or increased difficulty disregarding context-irrelevant meanings of ambiguous words (Burke 1997). In interpreting such findings, however, it is important to consider that in many situations, the contextual cues are such that the first thought or association that comes to mind is likely to meet the goals of the task at hand. If so, one would not expect to see evidence of broadcast activation (see section 23.6; see also Zacks and Hasher 1997).

Evidence that decreased attentional inhibition is associated with broader access of extraneous associations and ideas to working memory is most easily seen in situations that involve weak cues as to the most appropriate interpretation. So, for example, in the garden path passage study of Hamm and Hasher (1992) there were "control" passages that weakly supported, from the beginning, the final interpretation that the experimental garden path passages eventually implied. Thus, in its control version, the safari passage initially referred to a photographic trip. Despite this, there was clear evidence that older adults, early on in the passage, considered two alternative interpretations for the object with which a shot was to be taken, a camera and a gun. For the most part, younger adults considered only camera. Similarly, there is evidence in the semantic priming literature that older adults show hyperpriming relative to younger adults (Laver and Burke 1993), even in situations in which responses of younger and older adults occur at equal points in time (Laver 1992, 1994). Hyperpriming can be taken to suggest that with very little context (a single word), more ideas come to mind for older adults than for younger adults.

When inhibitory control is weak, thought processes will range more broadly than when it is not. Consider evaluating the following sentences: "A bride and groom often fight at their wedding. Children often play with handguns and grenades on a playground." Young adults quickly respond "no" to these sentences when asked to verify them; older adults engage in expansive justifications, looking at multiple interpretations of these situations (May 1997). Profound examples of topic wandering among ideas that are only loosely connected have been reported by Arbuckle and Gold (1993) for older adults whose inhibitory controls are severely damaged.

### 23.3 INHIBITION: THE RETRIEVAL COST

A major cost of the working-memory clutter that is the product of inefficient access and deletion functions of inhibition is reduced access to target information at retrieval. One of the hallmarks of aging is an increased tendency

to forget, and the empirical literature, with very few exceptions (e.g., Levy and Langer 1994) confirms this widely made observation (e.g., Craik and Jennings 1992; Light 1991). Here, we call special attention to age differences in interference as measured in the "fan effect" (Anderson 1983) because of its critical role in determining the downstream consequences of a cluttered working memory. Older adults show bigger fan effects than younger adults (Gerard et al. 1991; Radvansky, Zacks, and Hasher 1996). In the latter study, we taught younger and older adults a series of facts (e.g., "The pay phone is in the laundromat") of varying fan sizes until they knew them extremely well. A participant might learn three facts about "the pay phone" (large fan of three), and learn only one fact about "the potted palm" (small fan of one). After learning to criterion, participants made verification judgments for test sentences (e.g., "The potted palm is in the laundromat"). The indices of retrieval efficiency of the learned facts were the speed and accuracy of verifying statements that participants had actually learned and in rejecting statements that were foils created by repairing the subjects and predicates of original sentences.

The findings were clear (see figure 23.5). Both younger and older participants showed fan effects, with slower and less accurate retrieval for information in larger fans than for information in smaller fans. And, as expected for a group we assumed would spontaneously create larger functional fan

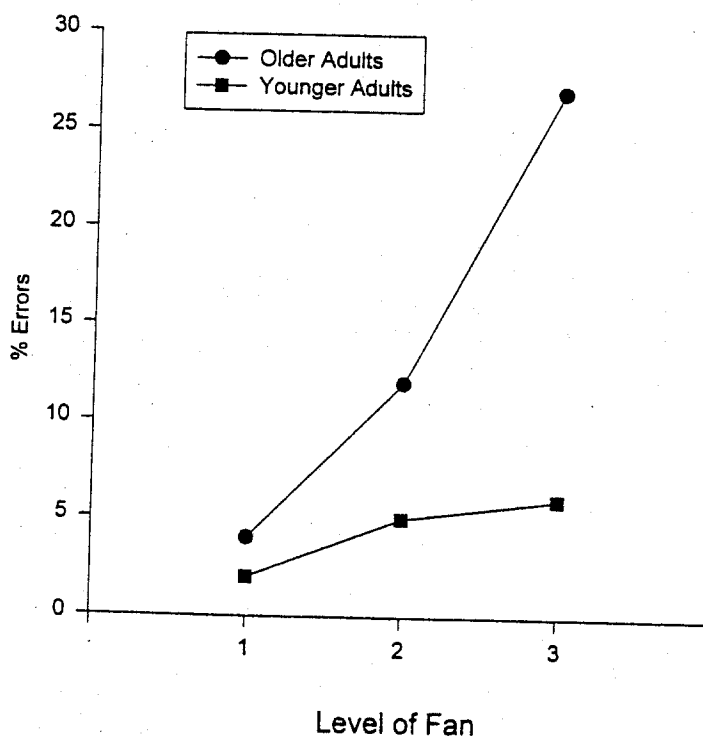


Figure 23.5 Percentage of errors at each of three levels of fan size for younger and older adults. Data from Radvansky, Zacks, and Hasher 1996.

sizes for themselves while learning, older adults showed larger fan effects than did younger adults.

The fan effect is actually one of a variety of tasks that measures the tendency for multiple "facts" associated with a single cue to compete with each other, and to block retrieval of one or more of the associated facts (Anderson 1983; Nelson, Schreiber, and McEvoy 1992; Watkins and Watkins 1975). Indeed, competition at retrieval is a major mechanism underlying proactive interference (PI), one of two classic paradigms used to simulate real-world forgetting. In the PI paradigm, participants typically learn two or more successive lists of items in which the same set of cues ("A" terms) is associated with successive sets of responses ("B", "C," and so on across the lists). The task for experimental participants is to retrieve, when cued by the A items, either the final set of response terms (e.g., the Cs), or all response terms (e.g., Bs and Cs).

The typical finding for experimental participants, compared to controls (who either learned only the last list, or else who learned successive lists having no cue-overlap relationship to one another), is poorer retrieval. We make three arguments here: (1) people with poorer inhibitory control over the contents of working memory will spontaneously generate more facts to a single cue during learning (because they fail to prevent unrelated items from entering working memory); (2) people with poorer inhibitory control over the contents of working memory will not entirely delete from working memory items from the just-recalled list when the next list is presented, creating memory representations for a current list that are cluttered with information from more than one list; and (3) people with poorer inhibitory control may also search more pathways during retrieval. Greater amounts of PI can result from each of these. Indeed, a recent reread of the classic proactive inhibition literature suggests that older adults are far more vulnerable to PI than was previously thought and that, in general, they show larger PI effects than do younger adults (see Kane and Hasher 1995).

#### 23.4 INHIBITION AND THE UNCLUTTERED MIND

To summarize, the theory outlined here specifies that goal-driven inhibitory control mechanisms, when efficient, constrain the contents of working memory to those most relevant at the current moment. This is a "minimalist" aesthetic, which suggests that less (in working memory, anyway) is more (in cognitive efficiency). Why? Because a spare working memory (one whose contents are limited to goal-driven, interrelated information) produces memory bundles whose fans include only relevant information, making each specific fact more likely to be retrieved, and retrieved more quickly, than otherwise. A spare working memory thus enables solutions to comprehension problems to be calculated "on the fly" because of rapid, accurate access to the past.

Note, however, that this view of an efficient working memory as one that is relatively sparsely occupied contrasts with the widely held view that being able to hold a large amount of information in working memory is optimal (Just and Carpenter 1992). From our perspective, the efficiency of a relatively spare working memory is seen in real time—as when information at the focus of attention is not disrupted by cross talk from other, irrelevant information; and in downstream time—as when information no longer in the focus of attention can be quickly and accurately retrieved on demand.

Indeed, based on the early work of Daneman and Carpenter (1980), we earlier laid out a framework suggesting that age differences in “mental-capacity” might best be thought of in terms of capacity to operate on information while simultaneously holding information (Zacks and Hasher 1988; see Just and Carpenter 1992). However, our own work only substantiated these suggestions at a heuristic level, not at the level of detail (Zacks and Hasher 1988; Hasher and Zacks 1988). Nonetheless, there is a good deal of support for such a viewpoint in the developmental literatures, in part because measures of capacity based on Daneman and Carpenter 1980 do a reasonable job of explaining age-related variance (e.g., Just and Carpenter 1992; Carpenter, Miyake, and Just 1994; Siegel 1994).

On the other hand, a consideration of working-memory span measures (indeed, most span measures) suggests all may be vulnerable to proactive interference because such tasks involve repeated tests on the same person with either identical materials (e.g., the digit span) or very similar materials (word and sentence span tasks) being used across multiple retrieval trials. Note that similarity among a set of items or tasks is a major determinant of the amount of PI, with greater similarity resulting in reduced retrieval (Postman and Underwood 1973). A second and standard aspect of span tasks makes them particularly problematic for those, like older adults, who may be differentially susceptible to interference (Kane and Hasher 1995). Virtually all span tasks use a procedure in which participants recall from many lists (each with similar items) in succession, and virtually all tasks also begin with short lists and proceed to longer lists. Because interference is known to increase across successive lists (reducing later list recall relative to earlier list recall; Keppel and Underwood 1962), such procedures virtually guarantee lower estimates of memory (or capacity) for those more vulnerable to interference than for those who are less so. From the present perspective, then, lowered working-memory capacity—as indexed by span tasks—may well be the by-product of reductions in inhibitory control.

Our recent work shows that the standard ascending span tasks indeed underestimate the span for older adults more than for younger adults. This conclusion stems from span estimates obtained by presenting span lists in a *descending* order, rather than in the standard ascending order (May, Hasher and Kane 1998). This work also suggests that procedures designed to reduce interference between lists will considerably increase the size of the span estimate for older adults. Indeed, for people more vulnerable to interference,

span measures might be a better index of individual differences in interference susceptibility than of general "capacity." Thus span measures may predict the comprehension performance of older adults (and of children as well, see, for example, Siegel 1994) because both span and comprehension are determined to some substantial degree by the amount of proactive interference present in the testing situation. People who cannot effectively use inhibition to shut off the no longer relevant past create larger bundles of information in working memory, and are subsequently unable to quickly and accurately retrieve information needed to form inferences or to quickly resolve any initial misunderstandings of syntax or meaning. As a result of such on-line failures, comprehension will be compromised.

### 23.5 INHIBITION, CIRCADIAN AROUSAL, AND INTRA-INDIVIDUAL DIFFERENCES

Consider the late-night reading example from the beginning of the chapter: Many people report that they are better able to focus, to ignore distraction, to retrieve more of what they know with greater speed and more accuracy at some times of day than at others. Although there are probably many factors that contribute to our ability to control cognition, a powerful one appears to be tied to circadian arousal rhythms.

Circadian patterns of arousal may be seen in a number of physiological events, including body temperature, heart rate, and hormone secretion, with each process showing regular peaks and declines across the day (Horne and Ostberg 1976, 1977; Hrushesky 1994). Recent research suggests that certain cognitive processes also follow a circadian rhythm, with peak performance periods correlating with individual patterns of physiological arousal (e.g., Bodenhausen 1990; May, Hasher and Stoltzfus 1993). For example, memory for prose is more accurate (May, Hasher, and Stoltzfus 1993; Petros, Beckwith, and Anderson 1990), and decisions are more analytic (Bodenhausen 1990) when testing times match an individual's peak period in circadian arousal than when testing times occur at other times of day.

Our own work on this problem began with the consideration that there may very well be age differences in circadian arousal patterns between the well-educated, healthy older adults we typically test in our studies and the younger adults currently enrolled in college, where social patterns (at least) dictate late nights. Using the Horne-Ostberg "Morningness-Eveningness Questionnaire" (Horne and Ostberg 1976), a paper-and-pencil inventory with excellent reliability and validity, our work confirms this observation (see May, Hasher, and Stoltzfus 1993; May and Hasher 1998): About 70–75% of older adults in our samples have their peak arousal period early in the day (and are termed *morning-type* people), while fewer than 5% of college students do. By contrast, about 35% of college students in our samples have their peak late in the day (and are termed *evening-type* people), while under 2% of older adults do (see figure 23.6).

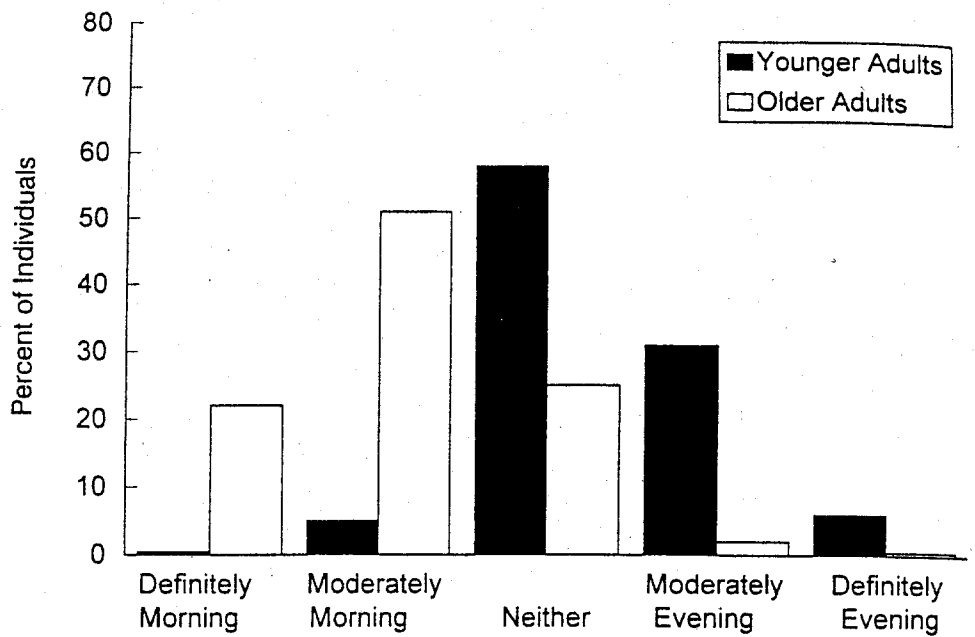


Figure 23.6 Percentage of younger and older adults in each of five categories of circadian arousal, as determined by the "Morningness-Eveningness Questionnaire." Norms collected on 1,362 younger adults and 563 older adults.

We have begun to explore whether these differences in arousal patterns influence inhibitory control. Of particular relevance here is a set of findings on two aspects of inhibitory control, *deletion* and *restraining*. For both thought and action, our findings clearly support the following conclusions: (1) inhibitory control diminishes with age; and (2) inhibitory control varies with circadian arousal for both younger and older adults.

### Control over Thought

Our garden path sentence-processing task (Hartman and Hasher 1991) described earlier uses an implicit measure of memory to index control over thought, in this instance over no longer relevant (disconfirmed) words and of targets. Using the same materials and procedures as in Hartman and Hasher 1991, but with morning-type older adults and evening-type younger adults, individuals were tested at 0800 or at 1700 hours.<sup>5</sup> The data, again shown (as in figure 23.2) as priming scores, can be seen in figure 23.7.

Consider the performance of the younger adults first (on the left). At their optimal time, there is priming only for the target items; younger adults show *below-baseline suppression* for the disconfirmed items. That is, when younger adults are operating at or near their peak performance times and once-relevant information becomes irrelevant, it is momentarily less accessible than it would have been had the word not occurred in the context of the experiment. For a sharp contrast, see the performance of younger adults at

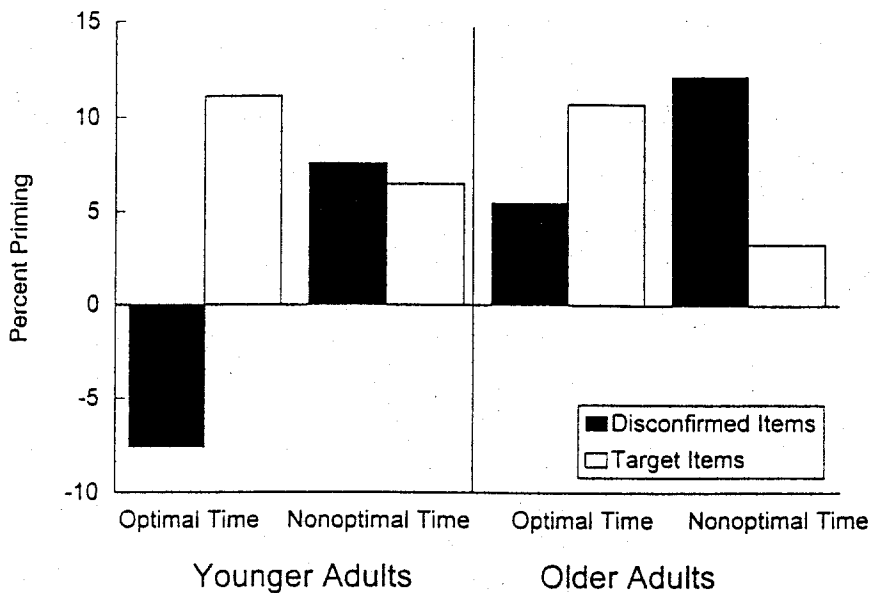


Figure 23.7 Percentage of priming for disconfirmed and target items shown at optimal and nonoptimal times of day for younger and older adults. Data from May and Hasher 1998.

their nonoptimal time (the morning), where there is reliable priming for both target and disconfirmed items, suggesting reduced inhibitory deletion control at nonoptimal testing times. Thus younger adults show substantial differences in inhibitory control efficiency across the day.

The same conclusion can be seen by looking at the performance of older adults across the day (on the right): Operating at or near their peak efficiency time, older adults show priming for both target and disconfirmed items, suggesting that by contrast with young adults, the inhibitory mechanisms of older adults are indeed inefficient. Operating at a nonoptimal time, this age difference becomes even more dramatic: Now older adults have reliable access *only* to the disconfirmed item, priming for the to-be-remembered target does not differ from access to items that were *never presented*. Thus, when a highly probable response occurs to older adults at their nonoptimal times, it is not only difficult for them to suppress that item, it appears to be extremely difficult to encode or acquire a replacement term. New patterns of responding may be very difficult to acquire if they need to replace a pre-existing one—especially for older adults who might try to learn at nonoptimal times. There is a complementary point to be made here (and we elaborate on this point later). If a strong response is the appropriate one for the situation (i.e., if inhibitory control is not needed), no time-of-day differences are to be expected.

### Control over Overt Responses

In addition to control over the contents of consciousness, inhibitory mechanisms also enable control over strong or prepotent overt responses (see, e.g.,

Butler, Zacks, and Henderson 1996). That is, the *restraining* function of inhibition prevents powerful responses from being produced before they can be evaluated for their appropriateness in a situation, or before less likely but potentially appropriate responses can be retrieved from memory. Thus it is the failure of inhibition over the usual strong response of turning right at the first corner out of the parking lot that, at the end of the working day, prevents you from doing an unaccustomed errand requiring a left turn. To investigate inhibitory control of prepotent, but unwanted motor responses, we tested evening-type younger adults and morning-type older adults in a task that required, on occasion, the withholding of an otherwise well practiced response.

Using the stop signal paradigm (see Logan 1994), we first trained participants on a simple categorization task in which they indicated, with a keypress, whether a given exemplar (e.g., chair) was a member of a specific category (e.g., furniture). After training on the categorization task, participants were informed that a tone would sound on some trials as a signal *not* to make a categorization response. During the test phase, the stop signal occurred on one-third of the trials, and its onset varied across those trials, with compensation made for individual differences in categorization response items. Control was measured as the ability to prevent a categorization response when the tone sounded.

As seen in the figure 23.8, the data from the stop signal task generally mirror our findings regarding control over thought: inhibitory control over practiced actions diminishes both with age and with being asked to perform at off-peak times of day. Both age and circadian arousal affect the ability to stop an undesired, but strong action, with younger adults generally showing greater inhibitory control than older adults and with both age groups demonstrating enhanced ability to prevent unwanted actions at peak relative to off-peak times. As in some other instances, the falloff from peak to nonpeak times is greater for older than for younger adults.

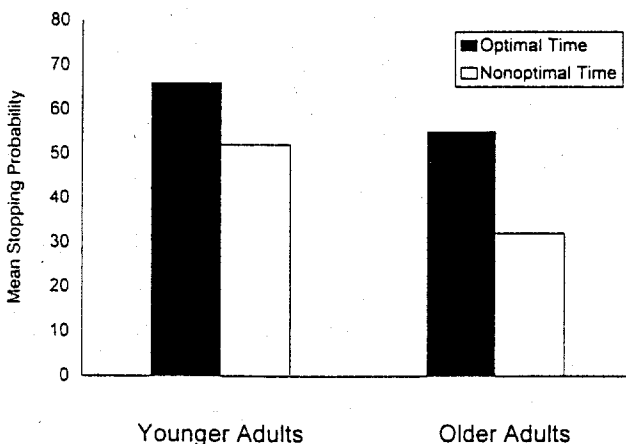


Figure 23.8 Mean stopping probability for younger and older adults tested at optimal and nonoptimal times of day. Data from May and Hasher 1998.



Control over strong thoughts and actions is clearly impaired with age and with performing at nonoptimal times. Thoughts are difficult to delete from working memory and actions are difficult to stop. As our late-night example suggests, both worrying and skilled eye movements will be difficult to stop at nonoptimal times of day. We turn now to the strong responses themselves to address the question of the impact of age and time of day on such responses.

### 23.6 INHIBITORY CONTROL, CIRCADIAN RHYTHMS, AND THE SPARING OF FUNCTION

Consider domains such as vocabulary and general knowledge, in which the knowledge of older adults is at least the equal of that of younger adults (Salthouse 1982). In the circadian arousal studies, there were several opportunities for us to observe the use of such knowledge across the day. In all studies, participants receive a very difficult vocabulary test, the "Extended Range Vocabulary Test" (Educational Testing Service 1976). In one study (May and Hasher 1998, experiment 1), participants provide completions for sentence frames that are missing their final word; they do this for the high-probability sentences in the initial phase of the study and again for the medium-probability sentences used as control items in the test phase. A final semantic knowledge task is in the stop signal experiment (May and Hasher 1998, experiment 2), in which participants make category decisions about exemplars. We have also given a test of general knowledge by asking people to respond to a wide range of trivia questions (May). A test of reading skill has also been administered (Li et al. forthcoming).

Neither age nor testing time influences performance on any of these tasks (see table 23.1). The absence of age differences may reflect the superior gen-

**Table 23.1** Performance of Younger and Older Adults Tested in the Morning or Afternoon on Vocabulary, Sentence Completion, Categorization, and General-Information Tasks

	Younger Adults		Older Adults	
	AM	PM	AM	PM
Vocabulary <sup>a</sup>	22	23	26	29
Vocabulary <sup>b</sup>	18	17	28	23
Sentence endings (high-cloze) <sup>a</sup>	.89	.89	.88	.87
Sentence endings (medium-cloze) <sup>a</sup>	.52	.52	.49	.51
Categorization <sup>b</sup>	.91	.92	.89	.91
Knowledge questions <sup>c</sup>	.78	.78	.79	.81
Passage reading time <sup>d</sup>	34.1	34.8	44.0	45.3

a. Data from May and Hasher 1998, experiment 1 (48-item test)

b. Data from May and Hasher 1998, experiment 2 (36-item test)

c. Data from May 1997

d. Data (in sec) from Li et al., forthcoming

eral knowledge of older adults. The absence of time-of-day differences, however, suggests that retrieval of well-learned information occurs as easily at nonoptimal as at optimal times. Thus what is impaired by age and by testing at nonoptimal times is the suppression of strong responses, not their retrieval.

Thus, too, one source of sparing performance, across age and times of testing, stems from expertise and high levels of practice. Of course, this may only be true when the knowledge that comes to mind quickly is the correct answer to the problem. Life probably offers many such situations, and these enable experts such as teachers, physicians, and jurists to do reasonable jobs, even at nonoptimal times of day.

### 23.7 ALTERNATIVE EXPLANATIONS

Although we have used an inhibitory framework to account for the data reviewed here, some of the results we reported are consistent with an encoding deficit explanation of age-related deficits in cognitive functioning. According to this view, cognitive failures such as poor acquisition of new associations and diminished retrieval result not from an inability to inhibit inappropriate alternative candidates, but rather from inefficient encoding of new associations in episodic memory (Gilbert 1941; MacKay and Burke 1990; Speiler and Balota 1996). Individuals who are less effective at encoding information will form fewer cue-item associations, will be less efficient at encoding distinguishing attributes of stimuli, and will have fewer discriminative cues available at retrieval.

A subset of the data in this chapter is consistent with such a view. We highlight here critical findings that are not. For example, if older adults have difficulty forming new associations, they should show poorer memory for target information than do younger adults. Although this is often the case, we note that in the implicit retrieval of targets from the garden path sentence task (Hartman and Hasher 1991; Hasher, Quig, and May 1997; May and Hasher 1998), there are several conditions in which this finding does not obtain. Indeed, the implicit memory literature often fails to find age differences (e.g., Howard 1988). There are also findings in explicit memory tests that fail to show age differences. If younger adults encode more elaborative associations for all stimuli than older adults (rather than inhibiting irrelevant stimuli), they should have greater access both to relevant and to irrelevant information at retrieval. In the directed forgetting paradigm, however, younger adults did not recall more "forget" items than older adults, although they did recall more "remember" items (Zacks, Radvansky, and Hasher 1996). Recent evidence suggests that older adults can have greater access to irrelevant information than younger adults, at least when access is measured using a conceptually based implicit task (Multhaup, Hasher, and Zacks 1998), and that they can use mental models as effectively as younger adults (Radvansky and Curiel 1998; Radvansky, Zacks, and Hasher 1996). Note, as well, the sparing of well-learned knowledge seen in table 23.1.

There are also a number of findings that can only be accommodated by an inhibitory perspective. These include the below-baseline priming in the garden path sentence study shown by younger adults tested at their peak times, and the inability of older adults, generally, and younger adults tested at nonoptimal times, to stop actions that are strongly expected in a context. Indeed, the inability of older adults to stop thinking about a strong response at their nonoptimal time (the expected ending of high-cloze sentences, see figure 23.7) suggests one inhibition-based reason older adults may have trouble hooking new responses to old stimuli: if a strong response is triggered by that cue, they may have difficulty suppressing it so that a new response can also be hooked to it. Although at least one alternative interpretation is available for some of the studies reported here, the inhibitory control hypothesis not only provides a unique explanation for some of the data, it seems a plausible and parsimonious account of a complete set of findings (see Zacks & Hasher 1998, for further discussion).

### 23.8 CONCLUSION

Our work explores inhibitory control problems across a range of behavioral domains including attentional control (see May, Kane, and Hasher 1996; Kane et al. 1997), working-memory control (e.g., Hamm and Hasher 1992; May, Hasher, and Kane 1997; Zacks, Radavanski, and Hasher 1996), forgetting (e.g., Kane and Hasher 1996; Zacks and Hasher 1994; Radvansky, Zacks, and Hasher 1996), and language comprehension (e.g., Zacks and Hasher 1988). Our findings suggest that inhibitory control over the contents of working memory is a powerful determinant of behavioral efficiency (Zacks and Hasher 1998). The model joins with the work of others (e.g., Dempster 1992; Gernsbacher and Faust 1991; Kuhl 1992) to show that differences in cognitive functioning across the life span, among individuals, and even across the day within individuals (May and Hasher 1998; Yoon, May and Hasher, forthcoming), can be tied together in a framework that emphasizes the fundamental importance of inhibitory attentional control over the contents of consciousness.

### NOTES

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1. This particular example presumes that you are a morning-type person, rather than an evening-type person, a difference that turns out to be critical for central issues in this chapter.

2. Although in general, distractibility is benign (the "confused professor" type), there are circumstances under which distractibility is dangerous (e.g., city driving during rush hour) and others under which distractibility can give rise to unwise behavior (e.g., being persuaded by weak arguments that might otherwise have little impact; see Rahhal, Abendroth, and Hasher 1996).
3. Note that when participants failed to generate the expected item (e.g., "lights") in the initial phase, the respective test sentences developed for that critical input sentence were omitted from analyses.
4. No data are currently available on the time course of this suppression effect. We suspect that suppression is limited to episodic events and does not impact substantially on semantic memory. There is some suggestion that the clutter is not necessarily permanent, and can be cleared out, for older adults, by providing them with an additional, rich interpretational framework for a change in interpretation (Hasher, Quig and May 1997; see also Stoltzfus 1992, experiment 2).
5. Given the relative rarity of young adults who are morning types and the even greater rarity of older adults who are evening types, we have not been able to test substantial numbers of people in these two categories.

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