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Intentional Suppression of Unwanted Memories Grows More Difficult as We Age

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People often encounter reminders to memories that they would prefer not to think about. When this happens, they often try to exclude the unwanted memory from awareness, a process that relies upon inhibitory control. We propose that the ability to regulate awareness of unwanted memories through inhibition declines with advancing age. In two experiments, we examined younger and older adults' ability to intentionally suppress retrieval when repeatedly confronted with reminders to an experience they were instructed to not think about. Older adults exhibited significantly less forgetting of the suppressed items compared to younger adults on a later independent probe test of recall, indicating that older adults failed to inhibit the to-be-avoided memories. These findings demonstrate that the ability to intentionally regulate conscious awareness of unwanted memories through inhibitory control declines with age, highlighting differences in memory control that may be of clinical relevance in the aftermath of unpleasant life events.

Keywords: memory control, inhibition, forgetting, executive control, emotion regulation

Inevitably, the years of our lives bring memories that we would rather forget. The passage of time gradually makes such experiences less accessible, but there are clearly moments when we seek to facilitate forgetting. These moments arise when, during chance encounters with reminders, a brief flash of experience and feeling invades awareness: an object in a drawer may trigger memories of a loved one lost to death or to a broken relationship; the face of a friend may evoke memories of an argument we would prefer to get past; or an envelope on our desk may call to mind a noxious task we must do. In response to these intrusions, we often expel the memory from awareness, to regain footing in our mental landscape. Recent work suggests that in situations such as this, people control awareness of unwanted memories in part by engaging inhibitory processes that suppress the intruding experience, impairing its later retention (Anderson & Green, 2001; Anderson & Levy, 2009; Anderson et al., 2004; Bergstrom, de Fockert, & Richardson-Klavehn, 2010; Depue, Banich, & Curran, 2006; Depue, Curran, & Banich, 2007; Hansylmayr, Leipold, & Bauml, 2010; Hanslmayr, Leipold, Pastotter, & Bauml, 2010; Joorman, Hertel, Brozovich, & Gotleib, 2005; Lambert, Good, & Kirk, 2010; Paz-Alonso, Ghetti, Matlen, Anderson, & Bunge, 2009; see Bulevich, Roediger, Balota, & Butler, 2006, for an exception). In this article, we examine the hypothesis that, in our advancing years, people decline in their ability to regulate conscious awareness through inhibition. Such a finding would have implications not only for theoretical models of cognitive aging (Hasher & Zacks, 1988), but also for understanding clinically relevant differences in how older adults control their memories in the aftermath of unpleasant life events.

Controlling awareness of an unwanted memory when a reminder is encountered requires people to stop the reminder from evoking the memory. To study this form of retrieval stopping, Anderson and Green (2001) introduced the Think/No-Think paradigm. In this procedure, participants are trained on cue-target word pairs (e.g., Ordeal-Roach) until they can provide the second word, when given the first as a reminder. People are then given the Think/No-Think task. In this task, people receive reminder cues, one at a time for several seconds (e.g., Ordeal), along with an instruction either to retrieve the associated memory ("Think" items) or instead to prevent it from entering awareness ("No-Think" items). The aftereffects of people's efforts to control memory are then assessed after the Think/No-Think phase has ended, on a test for all of the previously learned pairs. Interestingly, in this final phase, people's memory is much better for Think than for No-Think items, illustrating that cue-driven retrieval can be willfully controlled. Even more revealing, however, is a second result: final recall of No-Think items typically decreases as more No-Think repetitions are given (0, 1, 8, or 16 times). This pattern is

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exactly what one would predict if people engage inhibition to control awareness: inhibition diminishes activation of the unwanted memories, keeping them out of mind, rendering them less accessible.

Several considerations suggest that the form of retrieval suppression modeled by the Think/No-Think paradigm engages inhibitory processes that are compromised by aging. First, one of the primary functions of inhibitory control is to override prepotent responses when they are inappropriate (Luria, 1966; MacDonald, Cohen, Andrew-Stenger, & Carter, 2000; Norman & Shallice, 1986), a situation that arises in many cognitive domains. Stopping the automatic retrieval of an associated memory arguably presents a special case of this broader demand (Anderson & Green, 2001; Anderson et al., 2004). Indeed, the forgetting of No-Think items exhibits properties taken to reflect inhibition. For instance, Anderson and Green (2001) observed impaired recall for No-Think items (e.g., Ordeal-Roach) regardless of whether they tested final recall of the response (Roach) with the originally trained cue (e.g., Ordeal; hereinafter, the "Same Probe" condition) or with a novel, extralist category with a letter stem (e.g., Insect R____; hereinafter, the "Independent Probe" condition). Thus, suppression often makes items less accessible generally (Anderson & Green, 2001; Anderson et al., 2004; Levy & Anderson, 2008; Paz-Alonso et al., 2009; Bergstrom et al., 2009). The fact that independent test probes reveal forgetting shows that impairment suffered by suppressed items in part reflects reduced accessibility of the item itself (e.g., Roach), and not merely interference from diversionary thoughts that might have grown attached to the original cue (Ordeal) during efforts to suppress retrieval. Independent Probe (IP) impairment is exactly what would be expected if the excluded memory's activation had been lowered by inhibition (Anderson & Green, 2001; Anderson & Spellman, 1995). These findings provide theoretically targeted evidence that inhibition contributes to overriding retrieval.

The role of response override mechanisms in suppressing retrieval receives further support from neuroimaging research. In the Think/No-Think paradigm, suppressing awareness of unwanted memories engages the dorsolateral prefrontal cortex (DLPFC), an area involved in overriding prepotent responses (Anderson et al., 2004; Anderson & Weaver, 2009). Increased engagement of DLPFC reduces later retention of suppressed memories. Not only is DLPFC more activated during No-think than during Think trials, individual differences in activation strongly predict memory impairment for No-Think items. In contrast, retrieval suppression reduces activation in the hippocampus, a structure associated with episodic memory (Anderson et al., 2004). Thus, control processes may suppress retrieval by down-regulating activation in structures that support conscious recollection. Hippocampal activation also is reduced by the DLPFC when people suppress retrieval of aversive scenes, with the corresponding memory deficits for those scenes predicted by individual differences in DLPFC activation (Depue et al., 2007). Taken together, behavioral and imaging findings indicate that suppressing retrieval induces memory deficits that have the characteristics of inhibition, and that are produced by brain systems involved in overriding prepotent responses, consistent with the involvement of inhibitory control in suppressing mnemonic awareness.

If we suppress awareness of unwanted memories by inhibitory control, then controlling unwanted memories may grow more difficult as we age because of declines in inhibitory control function. Neurobiological and behavioral evidence points towards a decline in at least some inhibitory functions with age (Hasher & Zacks, 1988). On the neurobiological level, aging brings a pronounced decline in DLPFC structure and function. For example, DLPFC shows more volume reduction with age than most other brain areas (e.g., Raz et al., 2005) and the availability of dopamine, a neuromodulator important in the prefrontal cortex, declines substantially with age (e.g., Erixon-Lindroth et al., 2005). Assuming that these changes in the DLPFC are accompanied by changes in its functional efficiency, older adults should be less able to engage DLPFC to regulate awareness. Consistent with this possibility, older adults show impaired down-regulation of activation in neocortical areas that represent distracting, task-irrelevant information in working memory tasks, and correspondingly impaired performance (Gazzaley, Cooney, Rissman, & D'Esposito, 2005; see also Jost, Bryck, Vogel, & Mayr, in press). Because individual differences in the engagement of DLPFC have been linked specifically to the efficiency of memory inhibition in younger subjects (Anderson et al., 2004; Depue et al., 2007), as have differences in dopamine metabolism (Wimber, Wendler, Schott, Bauml, & Richardson-Klavehn, 2010), diminished functionality of DLPFC in older adults may also be accompanied by deficits in the ability to regulate awareness of long-term memories. If so, unwanted memories ought to be more distracting and persistent for older adults.

On the behavioral level, aging brings increased susceptibility to interference in perceptual, semantic, or episodic tasks consistent with changes in frontal function (for overviews, see Lustig, Hasher, & Tonev, 2001). For example, older adults are impaired compared to younger adults when reading text interspersed with differently colored, irrelevant words, they show greater effects of context in remote association tasks, and also show greater proactive interference in episodic memory. Heightened interference is exactly what one would expect if older adults were less able to engage inhibition to combat distraction. Nevertheless, although consistent with the inhibition deficit view, these instances of greater interference may instead reflect a weakened ability to maintain focus on relevant information (e.g., Engle, Kane, & Tuholski, 1999). In episodic memory tasks, age differences in the susceptibility to interference might also arise from impaired encoding of context, heightening confusion between relevant and irrelevant information (e.g., Burke, 1997). These ambiguities arise in part because the indicators of inhibitory function—the level of interference—are indirect. In few of these paradigms, for example, has it been shown that inhibition resolves interference in younger populations, by demonstrating that interfering representations are measurably inhibited after interference has been overcome.

A less common approach to establishing the existence of inhibitory deficits in older adults has sought to measure behavioral aftereffects that might be taken to reflect the effects of inhibition, much like the memory deficits of interest in the Think/No-Think paradigm. If, for example, an interfering memory is inhibited, then that inhibited representation should be less accessible when it later becomes task relevant, an outcome that should be measurable as impaired accuracy or reaction time to recall or recognize that memory. This approach has the theoretical advantage that it does not assume that a task involves inhibition on an a priori basis, but requires measurable evidence for lingering effects of inhibition.

Research using the inhibitory aftereffects approach has yielded some promising evidence for inhibitory deficits in older adults. For instance, May and Hasher (1998) found that younger adults were significantly less likely to complete a medium-cloze sentence (e.g., "The baby was fascinated by the bright ____") with a target completion (e.g., "light") if that same target completion had previously been generated in response to a high-cloze sentence (e.g., "Before you go to bed, turn off the ____") and then had been disconfirmed with an unexpected completion (e.g., "stove"). May and Hasher argued that this reduced completion rate reflected persisting inhibition of the target ("light") induced when participants had to encode the unexpected target ("stove"). Older adults, by contrast, did not show such reduced accessibility, consistent with an inhibitory deficit. In a similar vein, Radvansky, Zacks, and Hasher (2005) found that older adults showed reduced inhibitory aftereffects arising after memory retrieval in a speeded fact recognition procedure. Unfortunately, however, the evidence for reduced inhibitory aftereffects in memory in older adults has not been entirely consistent, with some authors reporting clear age-equivalence (e.g., Aslan, Bäuml, & Pastötter, 2007).

Many of the foregoing tasks used to assess inhibitory aftereffects in memory share a common, and potentially important characteristic that may limit their relevance to the question of central interest to the present study. Whereas many previous paradigms measure inhibition aftereffects induced unintentionally as an incidental by-product of retrieval or encoding, we are here concerned with whether people can intentionally engage inhibition to keep a particular memory out of awareness. Intentional retrieval suppression may put particularly strong demands on inhibitory control or may even require inhibitory functions that are qualitatively distinct from inhibition engaged as a by-product of successful retrieval. Thus, intentional inhibition of retrieval may be sensitive to the effects of aging, even if other less demanding forms of inhibition are not. If so, then the Think/No-Think paradigm may provide a useful window into hypothesized inhibitory control deficits in older adults. This procedure provides a metric of the predicted aftereffects of engaging inhibition on the inhibited memories themselves. Importantly, because forgetting of No-Think items has been explicitly linked to the engagement of DLPFC, the grounds for inferring frontally mediated inhibitory control processes are strong. Thus, if older adults suffer from an inhibition deficit, then forgetting of No-Think items should be diminished in older adults.

Whether older adults show reduced forgetting of No-Think item should depend, however, on the manner in which No-Think items are tested. In particular, forgetting deficits should be especially apparent when final recall of No-Think items is tested with IPs, because this type of test provides a purer measure of inhibitory aftereffects, uncontaminated by associative interference (Anderson & Levy, 2007). The contribution of associative interference to final recall comes about on the Same-Probe test because of mental activity that participants engaged in during the No-Think trials to keep the unwanted memory out of awareness (e.g., diversionary thoughts); these diversionary thoughts may become associated with the No-Think reminder and later interfere with attempts to retrieve the suppressed memory from that reminder (Anderson & Green, 2001). For example, if participants are given "Ordeal" and asked to suppress the previously associated item (Roach), they might attempt to do so by inhibiting Roach, but also by diverting themselves with related thoughts about other "Ordeals" they have experienced (e.g., Ordeal-Flood). On the later Same Probe (SP) test (i.e., when they are cued with Ordeal), they may fail to recall Roach either because it's inhibition persists or because Ordeal persistently elicits the alternate thought "Flood," blocking retrieval of Roach. If older adults are deficient in inhibition, Roach may not be forgotten because of inhibition; Roach might be forgotten, however, because older adults cannot contend, on the final test, with persistent intrusion of Flood, precisely because inhibition cannot be recruited for that purpose. In contrast, such interference can be circumvented when Roach is tested with a novel cue, unrelated to the SP cue (e.g., Insect R____), providing a purer estimate of any persisting inhibition of Roach. Thus, evidence for deficits in inhibitory aftereffects should be most apparent on the IP test.

We report two experiments in which we tested older and younger adults' ability to intentionally suppress retrieval of unwanted memories in the Think/No-Think paradigm. Experiment 1 is modeled after the original procedure introduced by Anderson and Green (2001). Experiment 2 is modeled after the adapted Think/No-Think paradigm introduced by Anderson et al. (2004), which differs principally in how participants are cued as to which items to suppress. Given their highly similar methods and results, we report the two experiments together. In both experiments, we measured final recall with both SP and IP tests. However, given that the IP is the purer measure of inhibition, we expect inhibitory deficits to be most evident on this test.

Method

Participants

Participants included 32 younger ($M = 20.6$ years, $SD = 3.1$; 18 females) and 32 older adults ($M = 73.5$ years, $SD = 4.8$; 26 females) in Experiment 1 and 32 younger ($M = 22.2$ years, $SD = 3.1$; 23 females) and 32 older adults ($M = 74.8$ years, $SD = 5.4$; 21 females) in Experiment 2. All subjects were screened for verbal reports of attention deficit disorder, learning disabilities, color blindness, or brain damage or disease and only participants without these conditions were included. In addition, because work on memory suppression was a lecture subject for younger subjects, all participants were screened for knowledge of the procedure, and excluded if they reported such knowledge. Younger adults were undergraduates who received either course credit or were paid $7 per hour. Older adults were recruited through newspaper advertisements and received $10 per hour. All subjects reported themselves to be in good health. In Experiment 1, younger adults scored higher on the Digit Symbol Substitution test (Wechsler, 1981), which measures psychomotor speed [younger: 61.79, older: 42.68; $F(1, 58) = 42.06$, $p < .001$], but there was no difference on a vocabulary test [younger: 39.41, older: 41.13, $F < 1$]. Digit Symbol performance also differed in Experiment 2 [younger: 79.75, older: 51.45; $F(1, 61) = 61.51$, $p < .001$], but there was no difference on a vocabulary test [younger: 41.97, older: 42.03, $F < 1$].

Younger and older subjects were replaced with new participants for the following reasons. Older participants were replaced if they (a) failed to reach the learning criterion (Experiment 1, $N = 9$; Experiment 2, $N = 6$), or (b) reported, after the experiment, that they did not comply with the No-Think instructions and intentionally thought of No-Think items ($N = 1$, Experiment 1). Younger participants were replaced if they (a) failed to reach the learning criterion ($N = 2$, Experiment 1), (b) reported that they did not comply with No-Think instructions ($N = 4$, Experiment 1, $N = 2$, Experiment 2), (c) got fewer than 4 hours sleep the night before ($N = 1$, Experiment 1), or (d) had recall more than 2.7 *SD* from the mean ($N = 1$) or were at ceiling in all conditions ($N = 1$, Experiment 2). In addition, older and younger participants who responded overtly to suppression cues in excess of 2 *SD*s beyond the mean accidental responding rate for their respective group were excluded (In Experiment 1, $N = 2$ younger adults, and 2 older adults; in Experiment 2, $N = 1$ older adult). In the latter instance, participants were not replaced, yielding a final sample of 30 young and 30 old in Experiment 1, and 32 young and 31 old in Experiment 2.

Design and Materials

In Experiments 1 and 2, item type (suppress vs. respond), number of repetitions during the Think/No-Think phase (0, 1, 8, or 16 presentations), and final test type (SP vs. IP) were varied within subjects, whereas age group (young vs. old), counterbalancing, and test order varied between subjects. In addition, half of the participants in each age group in each experiment participated in the morning (8-10 a.m.) and half, in the afternoon (3-5 p.m.) to ensure age related differences in circadian arousal pattern did not influence our findings. The percentage of items recalled was measured.

The two sets of 40 critical (and 12 filler) word pairs used in Experiments 1 and 2 were identical to those reported in Anderson and Green (2001) and Anderson et al. (2004), respectively. The stimulus and response members were designed to be relatable (e.g., Banner-Football), and were unrelated to other pairs in the set. The critical pairs were counterbalanced so that each item participated in every condition equally often. Responses were exemplars (e.g., Football) of different categories (e.g., Sports) and the categories later served as IPs, with a single letter stem for the response (e.g., Sports F_____).

Procedure

The procedure consisted of three phases: a learning phase, the Think/No-Think phase, and the final test. Afterwards, subjects completed the vocabulary and digit symbol tasks.

Learning phase

Subjects first studied each of the 52 pairs for 6 s, so that they could recall the response word when presented with the lefthand member (hereinafter the “hint word”). Test-feedback cycles followed in which subjects recalled the response given its hint word. On each test trial, the correct answer was provided as feedback. Test-feedback cycles continued until a minimum of 50% correct answers was accomplished for the younger subjects, and 70% for the older subjects. Subjects received up to a maximum of seven cycles through the list to achieve this criterion. Different learning criterions were chosen for younger and older subjects to achieve similar baseline recall.

Think/No-Think phase

During the Think/No-Think phase, subjects received Suppression and Respond trials. On Suppression trials, subjects were asked to focus attention on the hint word, but to suppress retrieval of the associated response for the entire 3 s that the hint was presented. The instructions emphasized that it was insufficient to simply withhold the vocal response, and that they should avoid awareness of the response. If the subject accidentally spoke an answer on suppress trials, a loud beep sounded signaling an error. On Respond trials, hint words were presented for 3 s or until the subject gave an answer. If they did not respond, the correct answer appeared in blue color for 500 ms.

Experiments 1 and 2 differed in the manner by which participants were signaled as to which hint words were in the Suppression and Respond conditions. Experiment 1 followed the “hint training” protocol developed by Anderson and Green (2001). Essentially, participants were trained until they could recognize all of the suppression hint words before the Think/No-Think phase. Experiment 2 followed the protocol developed in Anderson et al. (2004), which replaced hint-training with color cuing: during the Think/No-Think phase, Suppression hint words appeared in red letters, whereas Respond hint words appeared in green letters.

Final Test Phase

After the Think/No-Think phase, subjects completed the SP and the IP tests. The SP test cued participants with the original hint word (e.g., Banner-___) whereas the IP test cued them with a category and the first letter of the item (e.g., Sport-F__). Subjects were given 5 s for each item and asked to think of the response that fit each cue and say it aloud. The average serial position of all conditions (i.e., all baseline, Think, and No-Think repetition conditions) was matched within each test type (SP or IP) by blocked randomization. Every item was tested twice—once on the SP test, and once on the IP test. The order of these tests was counterbalanced across subjects.

Results and Discussion

Given the similar procedures and results across the experiments (there were no reliable experiment effects), we report statistics both across the experiments combined and for each individually.

Learning Phase

In Experiment 1, younger adults required fewer trials to reach their learning criterion of 50% correct ($M = 1.27$) than older adults took to reach their criterion of 70% ($M = 3.83$), $t(58) = 8.26$, $p < .0001$. Similarly, in Experiment 2 younger subjects required only 1.3 cycles, whereas older adults required 3.0 cycles, $t(61) = 6.97$, $p < .0001$. The higher learning standard for older adults succeeded in raising performance of older adults to that of younger adults. In Experiment 1, recall on the final training cycle was similar in the two groups ($M = .70$ and .77 for younger and older adults respectively), as it was in Experiment 2 (.72 and .77 for younger and older adults, respectively).

Final Test Phase

Facilitation for Think Items. As can be seen in Table 1, repeatedly retrieving Think items facilitated later recall performance in both Experiments 1 and 2 for both SP and IP tests. Older adults started from a somewhat lower baseline than did younger adults, but age differences decreased with repetitions. These observations were confirmed in separate ANOVAs for SP and IP tests using the factor of age, and the contrast between baseline and 16 repetitions. For SP we obtained significant effects for age, Experiment 1: $F(1, 58) = 10.20$, $MSE = .02$, $p < .01$, Experiment 2: $F(1, 61) = 25.20$, $MSE = .01$, $p < .01$, overall: $F(1, 119) = 32.42$, $MSE = .01$, $p < .01$, and repetitions, Experiment 1: $F(1, 58) = 74.99$, $MSE = .01$, $p < .01$, Experiment 2: $F(1, 61) = 137.70$, $MSE = .01$, $p < .01$, overall: $F(1, 119) = 201$, $MSE = .01$, $p < .01$. The age by repetition interaction was not significant for Experiment 1, $F(1, 58) = 1.31$, $MSE = .01$, $p > .2$, but it was for Experiment 2, $F(1, 61) = 8.86$, $MSE = .01$, $p < .01$, and overall, $F(1, 119) = 7.68$, $MSE = .01$, $p < .01$. There were no reliable interactions with the Experiment factor in the overall analyses. For IP there again were reliable main effects for age, Experiment 1, $F(1, 58) = 6.24$, $MSE = .03$, $p < .05$, Experiment 2: $F(1, 61) = 5.02$, $MSE = .02$, $p < .01$, overall: $F(1, 119) = 11.32$, $MSE = .02$, $p < .01$, for repetitions, Experiment 1, $F(1, 58) = 25.87$, $MSE = .02$, $p < .05$, Experiment 2: $F(1, 61) = 6.49$, $MSE = .02$, $p < .02$, overall: $F(1, 119) = 28.06$, $MSE = .02$, $p < .01$, and either reliable or almost reliable age by repetition interactions, $F(1, 58) = 4.04$, $MSE = .02$, $p < .05$, Experiment 2: $F(1, 61) = 3.84$, $MSE = .02$, $p < .06$, overall: $F(1, 119) = 7.82$, $MSE = .02$, $p < .01$. The greater benefit for older adults on the SP test may simply reflect ceiling effects on measurement for younger adults, though it is unclear why this advantage would occur on the IP test. These findings establish, at a minimum, that older adults do not have a measurable deficit in the benefits of retrieval in the current experiments.

Impairment for No-Think Items. Turning now to the theoretically important suppress trials, Figure 1 shows older and younger adults' inhibition scores, that is the difference between 16 suppression repetitions and the 0-repetition baseline condition; Table 1 presents the percent correct recall across all relevant conditions. As is evident in the critical IP test, younger adults showed inhibition scores in the typical range across both experiments whereas older adults showed, if anything, small facilitation effects. The interaction of age with inhibition was reliable both across experiments, $F(1, 91) = 8.67$, $MSE = .03$, $p < .01$, and for each of the individual experiments, Experiment 1: $F(1, 44) = 5.29$, $MSE = .02$, $p < .05$, Experiment 2: $F(1, 47) = 4.25$, $MSE = .02$, $p < .05$. Inhibition scores for younger adults were reliable overall, $F(1, 46) = 9.51$, $MSE = .02$, $p < .01$, Experiment 1: $F(1, 22) = 4.91$, $MSE = .02$, $p < .05$, Experiment 2: $F(1, 24) = 4.61$, $MSE = .02$, $p < .05$, whereas for older adults the trend towards facilitation was not reliable, overall: $F(1, 45) = 2.16$, $MSE = .03$, $p > .1$, Experiment 1: $F(1, 22) = 1.33$, $MSE = .03$, $p > .2$, Experiment 2: $F(1, 23) = .89$, $MSE = .03$, $p > .3$. Thus, consistent with a deficit in the ability to regulate the content of awareness through inhibition, younger adults exhibited a larger inhibition effect than older adults.[1]

Interestingly, we obtained a different pattern on the SP test. Here, we found a reliable inhibition score across both experiments,

Table 1
Percentage Correctly Recalled on the Final Same and Independent Probe Tests as a Function of Age and Number of Repetitions in the Think Conditions of Experiments 1 and 2 (SDs in Parentheses)

Number of Think repetitions				
Condition	0	1	8	16
Experiment 1				
SP test				
Young adults	83 (15)	94 (09)	98 (06)	98 (06)
Older adults	73 (12)	83 (15)	91 (13)	93 (12)
IP test				
Young adults	84 (14)	86 (19)	89 (15)	91 (14)
Older adults	71 (17)	84 (15)	87 (15)	89 (14)
Experiment 2				
SP test				
Young adults	86 (13)	93 (17)	98 (20)	100 (20)
Older adults	71 (13)	81 (21)	97 (10)	97 (12)
IP test				
Young adults	85 (13)	83 (19)	91 (17)	86 (21)
Older adults	74 (16)	80 (17)	87 (16)	87 (17)

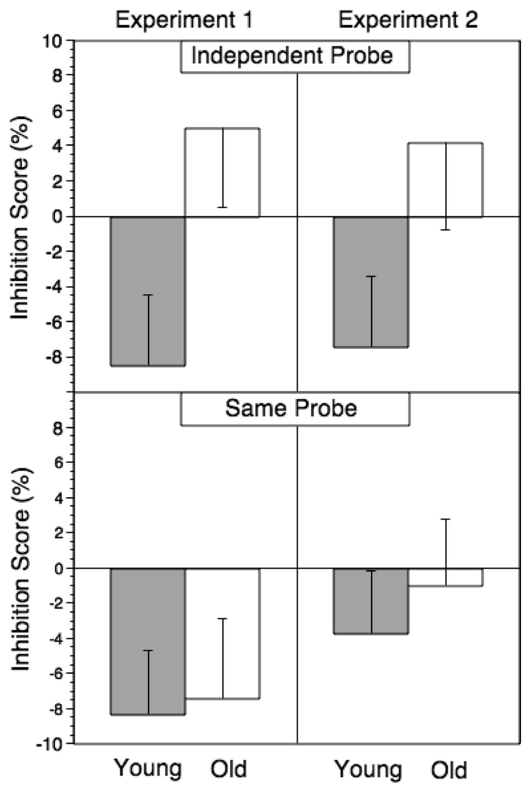

Figure 1. Memory impairment scores (16 No-Think Repetitions 0 No-Think repetitions) plus *SE*s on the IP and SP tests of Experiments 1 and 2 for younger and older adults. The IP test is more sensitive to older adults' inhibition deficit.

[1] Test order (IP vs. SP) was counterbalanced across subjects and therefore it is possible that the critical pattern of age effects was modulated by this factor, for example, because of proactive interference across successive tests. However, the age by inhibition by test order interaction was far from reliable, $F(1, 115) = .14$, $p > .7$, $MSE = .03$; the four-way interaction including experiment was also nonsignificant, $F(1, 115) = .00$, $p > .9$, $MSE = .03$.

$F(1, 91) = 9.17$, $MSE = .02$, $p < .01$, and in Experiment 1 $F(1, 44) = 13.07$, $MSE = .02$, $p < .01$, but not in Experiment 2: $F(1, 47) = .64$, $MSE = .02$, $p < .4$. Though the older adults show numerically less forgetting, this difference was not reliable (F < 1). Importantly, the three-way interaction between age, inhibition and test type (IP versus SP) was reliable, overall $F(1, 91) = 5.42$, $MSE = .02$, $p < .05$, and in Experiment 1: $F(1, 44) = 4.47$, $MSE = .01$, $p < .05$, though not in Experiment 2: $F(1, 47) = 1.57$, $MSE = .02$, $p > .2$. As noted in the Introduction, the IP is the purer measure of inhibition whereas the SP is susceptible to associative interference effects that may inflate the inhibition score in subjects with an inhibitory deficit (Anderson & Levy, 2007). Thus, these results affirm the importance of using pure measures of inhibition when testing for inhibitory deficits.

Although we have focused our analyses on the contrast between our baseline conditions and the highest level of suppression we measured (16 repetitions), the amount of inhibition over repetitions is also of interest. Inspection of Table 2 reveals that whereas performance generally went down with increasing numbers of suppression attempts for younger adults, there was some variability in this relationship. In some cases, for example, performance after a single suppression attempt was lower than after 8. It is unclear what produces this variability, though it seems likely to arise from random variation in lapses of control over repetitions, resulting in intrusions. It is worth noting, however, than when all younger adults are considered from the two experiments, suppression effects decline monotonically with suppression attempts for both the IP test (*Ms* = .84, .81, .79, and .76 for the 0, 1, 8 and 16 repetitions conditions), and the SP test (*Ms* = .84, .83, .83, and .78). In contrast, older adults show more variability, and a general increase in performance on the IP test (*Ms* = .73, .79, .75, .77 for the 0, 1, 8, and 16 repetitions conditions) and a nonmonotonic pattern on the SP test (.72, .77, .70, .68). These findings are generally consistent with inhibitory control that is increasingly effective with repetition for younger adults, but a variable, and less effective inhibition process for older adults.

Notably, younger adults in the present experiments showed SP and IP test effects that were statistically equivalent (across both experiments, the young SP effect = 6%, and the young IP effect = 8%). This pattern has been reported previously (Anderson & Green, 2001; Anderson et al., 2004; Bergstrom et al., 2009; Lambert et al., 2010; Paz-Alonso et al., 2009). Given the potential joint contribution of inhibition and associative interference to the SP test, however, one might have expected a larger memory deficit on the SP test, compared to the IP test, to which only inhibition contributes. Although this expectation makes sense, it assumes that associative interference and inhibition are independent and additive components that contribute to the size of the forgetting effect. This may not be true. We have argued elsewhere, for example, that increasing efficacy at inhibiting distracting traces in a population ought to be accompanied by a concomitant decrease in associative interference at test, owing to the possibility that the ability to overcome interference from distracting thoughts at test is supported by the very same inhibition process that is involved in the initial suppression of the item (Anderson & Levy, 2007). Thus, for younger adults at the peak of inhibitory function, associative interference may be minimal, rendering SP and IP inhibition similar. Older adults, by contrast, ought to suffer more interference on the SP test, precisely because inhibition is deficient and they cannot counter interference.

Table 2
Percentage Correctly Recalled on the Final Same and Independent Probe Tests as a Function of Age and Number of Repetitions in the No-Think Conditions of Experiments 1 and 2 (SDs in Parentheses)

Number of No-Think repetitions				
Condition	0	1	8	16
Experiment 1				
SP test				
Young adults	83 (15)	78 (24)	84 (17)	74 (17)
Older adults	73 (12)	76 (26)	64 (28)	66 (20)
IP test				
Young adults	84 (14)	83 (22)	77 (22)	75 (21)
Older adults	71 (17)	77 (19)	70 (18)	76 (24)
Experiment 2				
SP test				
Young adults	86 (13)	87 (17)	81 (20)	82 (20)
Older adults	71 (13)	79 (19)	76 (16)	70 (22)
IP test				
Young adults	85 (13)	78 (19)	80 (17)	77 (21)
Older adults	74 (16)	81 (21)	81 (17)	78 (21)

One possible concern is that despite receiving more learning opportunities than younger adults and having similar initial learning levels, older adults had somewhat lower final baseline recall overall, $F(1, 119) = 33.3$, $p < .001$ (SP test, $F(1, 119) = 18.46$, $p < .001$, and for the IP test, $F(1, 119) = 25.6$, $p < .001$) as can be seen in Tables 1 and 2. Generally, it seems unlikely that the relatively small baseline difference would be responsible for the cross-over interaction pattern obtained in the IP test. One could argue though that based on overall lower memory, there may be a smaller tendency for cues to activate the associated words during Suppression trials and less need for inhibition. However, when looking at performance across the Think/No-Think phase, we actually found that older adults experienced more unwanted retrievals of the to-be-suppressed words on Suppress trials, Experiment 1: younger = 2.2%, older = 9.8%, $t(32.8) = -3.79$, $p = .001$; Experiment 2: younger = .2%, older = .8%, $t(36.1) = -2.84$, $p = .007$. Thus, if anything, there would have been more need for inhibition in older adults than in younger adults.

Finally, Hasher, Zacks, and May (2000) have reported age differences in time-of-day effects on inhibitory processing: older adults seem to be relatively intact in the morning but low in inhibitory control in the afternoon; younger adults, on the other hand, are worse off in the morning than in the afternoon. We included time-of-testing as an additional between-subject factor, mainly to control for possible time-of-day effects. However, even though this was not the main goal of our study, we can test for the presence of such effects in the current context. For the IP, the age by inhibition by time-of-day interaction was not reliable, $F(1, 115) = 1.28$, $p = .26$, $MSE = .03$. Interestingly, for the SP this interaction was highly significant, $F(1, 115) = 11.17$, $p = .001$, $MSE = .02$. Younger adults showed a larger reduction in recall from 0 to 16 repetitions in the afternoon (−8.6%) than in the morning (−3.2%). For older adults, there was a very strong reduction of recall in the morning (−12.6%), but an increase in the afternoon (5.8%). Thus, we replicate the pattern time-of-day effects obtained in the literature for SP, but not for IP. On the one hand the dissociation between IP and SP results supports the view that these do not represent the same underlying construct. On the other hand, the specific pattern is unexpected given that (a) May et al. proposed that time-of-day affects inhibitory control and that (b) we argue here that IPs can serve as a relatively pure manifestation of inhibitory control whereas SP effects can be affected by interference. Given that this is an unexpected and so far un-replicated finding we need to be cautious with our interpretations. However, it is worth noting that in our data, the typical time-of-day pattern was present in the measure that is presumably contaminated by interference, but not for the measure that served as a pure indicator of inhibition. Therefore, we believe it is worth further examining whether circadian rhythm modulates processes that affect proneness to interference as opposed to inhibition, per se.

Suppression Strategies

A postexperimental questionnaire was included for Experiment 1 that inquired, for each individual word pair serving in the No-Think condition, what strategies participants adopted (strategy data were not available for Experiment 2). Reported strategies were classified into one of the following categories: Image (generated a distracting image), Thought (generated a distracting thought), Word (generated a distracting word), Sound (thought of a distracting sound), perceptual (perceptually analyzed the hint word), and gaze avert (looked away from the word). In addition, participants were asked to rate, for each hint, whether the corresponding response word came into mind when it should not have. The percentage of hint words on which participants reported a given strategy was computed. In addition, the percentage of hint words on which any strategy was reported was examined to see whether there was any overall difference in strategy use, as older adults are less prone to adopt any particular forgetting strategy (Sahakyan, Delaney, & Goodmon, 2008).

Overall, the percentage of words on which younger (59%) and older adults (47%) reported using any strategy did not differ reliably, $t(58) = .74$, $p = .46$, though older adults in general reported numerically fewer strategies. Care must be taken in interpreting this result, however, as the ability to remember a particular strategy after the experiment had ended would likely be subject to overall differences in memory evident in the data set. These findings suggest that in the Think/No-Think procedure older adults do spontaneously engage in strategy use to a similar extent as do younger subjects. This finding may differ from that reported by Sahakyan et al. (2008) with the directed forgetting procedure, perhaps because the Think/No-Think task confronts participants with strong cues to well learned responses that may create a more challenging control task. Of the particular strategies coded, there were no reliable differences between age groups in their frequency of use, except for the tendency to divert oneself with an alternative word, which was more prevalent for younger ($M = 13\%$) than for older adults ($M = 2\%$), $t(58) = 2.6$, $p = .01$. However, the use of this strategy did not correlate with either SP or IP inhibition in younger adults (in fact, it correlated nonsignificantly in the wrong direction, $r = -.28$, and $r = -.006$, for SP and IP inhibition, respectively). For older adults, this strategy did not correlate with SP inhibition ($r = -.06$), but it did correlate with IP inhibition ($r = .45$). The latter correlation, however, is driven by an outlier subject, who, once removed, reduces the correlation to −.06. No subjects in either age group reported averting their gaze away from the hint word. Interestingly, older adults were more likely to report that the associated response word came into mind inappropriately during suppression trials ($M = 24\%$) than were younger adults ($M = 10\%$), $p = .04$, consistent with the hypothesized difficulty in inhibiting unwanted memories.

Discussion

The results of Experiments 1 and 2 strongly favor the hypothesis that the ability to engage inhibition to intentionally suppress retrieval declines with age. Even after 16 attempts to suppress No-Think items, older adults showed numerically better recall for those items than for baseline items on an IP test. In contrast, younger adults showed significant impairment for No-Think items, which increased with the number of suppression attempts, in line with previous work (Anderson & Green, 2001; Anderson et al., 2004). This difference in memory inhibition across age groups was observed in both experiments, despite differences in materials and in the particulars of the procedures. Because the IP measure circumvents associative interference that might otherwise contaminate test performance (Anderson & Spellman, 1995; Anderson & Green, 2001; Anderson & Levy, 2007), reduced impairment on this test provides especially strong and focused evidence for a deficit in inhibitory control in older adults, consistent with the inhibitory deficit hypothesis of cognitive aging (Hasher & Zacks, 1988).

The clear separation of older and younger adults with respect to inhibitory function observed on the IP test contrasts with the pattern observed on the SP test. As can be seen in Figure 1, the SP test in both Experiments yields a pattern similar to that observed on the IP test, but the age difference in inhibition is muted. In fact, the age difference was reliably greater on the IP test. As argued in the Introduction, however, reduced recall on the SP test may reflect the joint contributions of inhibition and associative interference (Anderson & Levy, 2007). Because interference from competing associations ought to be difficult to manage given weakened inhibition, older adults would be expected to exhibit impairment for No-Think items on the SP test. Thus, older adults' memory deficits would appear deceptively similar to those observed for younger adults, as they do in Figure 1. When associative interference is circumvented with an IP test, however, the apparent inhibitory effect disappears for older but not for younger adults. These findings thus suggest that noninhibitory interference processes produce the SP effect for older adults, and confirms the expectation that the IP method is a purer and more diagnostic measure of inhibition (Anderson & Levy, 2007).

The present findings are theoretically important, especially when juxtaposed to recent work reported by Aslan et al. (2007). Aslan et al. found retrieval-induced forgetting in both older and younger adults' episodic memory, with no evidence for an age difference. This held, regardless of whether participants were tested with a SP or an IP test. Given that the present experiments used a comparable standard for measuring inhibition (the IP method), our findings suggest that there is something crucially different between intentionally suppressing retrieval and engaging inhibition to resolve retrieval competition, as occurs in the retrieval-induced forgetting procedure. This may reflect a fundamental difference between controlled and automatic inhibition. Alternatively, the crucial difference may prove to be the overall challenge posed by the inhibition task: suppressing a single, highly trained association when repeatedly confronted with a reminder places significant demands on inhibitory control, perhaps more than typically arise in studies of retrieval-induced forgetting, or even in list-method directed forgetting (Zellner & Bäuml, 2006). Regardless of which account is correct, the present findings establish that intentional retrieval suppression engages an inhibitory process that is compromised with age.

Research indicates that inhibitory processes measured by the Think/No-Think task extend to the control of emotionally aversive stimuli, such as highly negative scenes (Depue et al., 2006, 2007). Such findings suggest that retrieval suppression may provide a model for understanding how people suppress retrieval of emotionally unpleasant experiences (Anderson & Green 2001; Anderson et al., 2004; Depue et al., 2006, 2007; see also, Joorman et al., 2005), reducing their tendency to intrude into awareness. If so, the present findings suggest that as we age, we may grow less able to forget upsetting experiences. Consistent with the existence of a forgetting deficit, evidence from the directed forgetting procedure indicates that older adults sometimes are less able to intentionally forget a first list of memory items when given an instruction to forget followed by a second list (Sahakyan et al., 2008; Zacks, Radvanksy, & Hasher, 1996; however, see Zellner & Bäuml, 2006; Sego, Goldin, & Gottlob, 2006). It remains unclear, however, whether the reduced forgetting for older adults observed in the directed forgetting procedure reflects an inhibition deficit, or a tendency, on the part of older adults, to simply not try to forget because they feel they do not need to (Sahakyan et al., 2008). The present findings suggest, however, that even when older subjects do engage forgetting strategies, they show forgetting deficits in an experimental paradigm that provides focused evidence for the involvement of inhibitory control. As such, the mechanistic tools that might support forgetting in the interests of emotion regulation may be compromised.

Yet, when it comes to the question how cognitive control functions are related to life-span differences in emotion regulation, matters become surprisingly complicated. Specifically, older adults generally experience less negative affect, at least up to the mid-70s (e.g., Carstensen, Pasupathi, Mayr, & Nesselroade, 2000; Mroczek & Kolarz, 1998), and there is evidence that older adults exhibit an attention and memory bias towards positive and away from negative information. Furthermore, it seems that this bias becomes manifest in controlled rather than in automatic attentional and memory processes (for a review see Mather & Carstensen, 2005). Obviously, such a pattern is difficult to reconcile with the observation of reduced suppression ability in older age. One possible scenario, suggested by Mather and Carstensen, is that the changes in emotion regulation reflect an across-life-span motivational change that affects how control resources are allocated and that can at least partially override the decline in control functionality. In fact, recent evidence also suggests that the positivity bias in memory functioning is found only in older adults with high levels of executive control ability (Mather & Knight, 2005). Thus, it is possible that declines in emotion regulation in very old age, or in low executive control subgroups is moderated by reduced retrieval suppression. Instances in which suppression ability is reduced may also explain late-life onsets of posttraumatic stress disorder (Floyd, Rice, & Black, 2002; Hamilton & Workman, 1998; Ruzich, Looi, & Robertson, 2005).

While clearly further work is needed to examine the complex relationship between cognitive control processes and emotion regulation in old age we believe that advances in understanding the cognitive and neural underpinnings of memory control provide targeted hypotheses about the mechanistic basis of such deficits. The finding of diminishing capacity to control the influence of unwanted memories with advancing age is thus not merely of theoretical interest, but of relevance to understanding clinically important issues faced by our aging population.

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