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The effect of memory cue duration on performance in the directed forgetting task in healthy aging

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ABSTRACT

Although forgetting is usually considered a memory error, intentional forgetting can function as an adaptive mechanism. The current study examined the effect of increased processing time on directed forgetting in aging as a mechanism to compensate for age-related forgetting. Specifically, an item-method directed forgetting paradigm was used in conjunction with Remember/Know/New responding to examine the effect of cue duration (1, 3, 5 s) on directed forgetting and remembering in younger and older adults. Results indicated that increased processing time improved performance in both age groups. Critically, older adults exhibited a linear increase in directed remembering performance across all cue durations which was related to individual differences in cognitive reserve. Specifically, those older adults with the highest levels of cognitive functioning showed the greatest memory benefit in the longest cue duration condition. These findings indicate the importance of processing time in accounting for intentional memory performance in older adults.

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Directed forgetting; aging; cue durations; processing speed; memory

Introduction

In an age where we are besieged with information, often times it is just as important to forget information as it is to remember it. While incidental forgetting may simply be a by-product of poor encoding, intentional or goal-directed forgetting represents an active, strategic process that is resource demanding. Mechanistically, intentional forgetting has been theorized to occur through inhibition, a cognitive control process that works to prevent information from gaining access to long-term memory stores (Fawcett & Taylor, 2008; Zacks & Hasher, 1994; Zacks et al., 1996). Research has shown that older adults experience age-related deficits in intentional forgetting tasks and has posited that these deficits stem from age-related deficits in inhibitory processes. However, lab-based intentional forgetting paradigms often include a limited window for executing cognitive control processes necessary for directing memory processing. Such a time limit may disproportionately affect older adults who incur cognitive slowing costs (i.e., Salthouse, 1996). In addition, a large literature in cognitive aging has shown that individual differences in baseline cognitive functioning (i.e., cognitive reserve)

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impacts an individual's ability to benefit from environmental support in cognitive tasks (Frankenmolen et al., 2018; Opdebeeck et al., 2016). To examine the impact of cognitive slowing and individual differences on intentional forgetting, the current study used an item-method Directed Forgetting (DF) paradigm to investigate whether older adults' intentional forgetting benefits from additional processing time and how differences in baseline cognition interact with processing time.

In item-method DF, participants are presented with a series of items, each followed by a short delay and a cue instructing the individual to either remember (i.e., the to-be-remembered (TBR) cue) or forget (i.e., the to-be-forgotten (TBF) cue) the item. Participants, however, are ultimately asked to remember all of the items, regardless of the original cue (Basden & Basden, 1996; Bjork, 1970, 1972; Bjork & Woodward, 1973). One's ability to intentionally forget information is typically operationalized as the difference in forgetting for *intentionally* forgotten, or TBF items, compared to *incidentally* forgotten, or TBR items. This difference is termed the DF-effect. The DF-effect is posited to occur based on both enhanced encoding of TBR compared to TBF items (Basden et al., 1993; Bjork, 1970; Paller, 1990) and active inhibition of TBF items that prevents information from gaining access to long-term memory stores (Fawcett & Taylor, 2008; Zacks & Hasher, 1994; Zacks et al., 1996). In addition to behavioral evidence, the contribution of both processes to intentional encoding and intentional forgetting in the DF paradigm is well supported by neuroimaging studies (Bastin et al., 2012; Nowicka et al., 2011; Paz-Caballero et al., 2004; Rizio & Dennis, 2013; Ullsperger et al., 2000; Wylie et al., 2008). Specifically, research shows that, compared to a TBF cue, a TBR cues elicits increased activity in encoding-related brain regions including left inferior and middle frontal gyri and hippocampus. Conversely, compared to a TBR cue, a TBF cue elicits increased activity in right superior and middle frontal gyri, regions associated with cognitive inhibition (Anderson & Huddleston, 2012; Anderson et al., 2004; Benoit & Anderson, 2012; Depue et al., 2007; Levy & Anderson, 2012). Additionally, this increased activity in prefrontal regions during intentional forgetting is negatively correlated with activity in the medial temporal lobe (MTL), further supporting the conclusion that this neural activity is actively inhibiting memory-success activity (Anderson & Hanslmayr, 2014; Anderson et al., 2004; Rizio & Dennis, 2013). Taken together past research highlights the importance of both intentional remembering and intentional forgetting to performance in the DF paradigm, and the intentional control of memory more generally.

With regard to aging, past research has found a reduced DF-effect in older compared to younger adults (e.g., Feyereisen & Charlot, 2008; Foster & Giovanello, 2020; Hasher et al., 1997; Titz & Verhaeghen, 2010; Zacks et al., 1996), as well as reduced visual cortex activity during intentional remembering and reduced prefrontal activity during intentional forgetting instructions (Rizio et al., 2014). Researchers have suggested that age deficits in DF arise from declines in both differential encoding and inhibition mechanisms (see Hogge et al., 2008; Zacks et al., 2000, 1996). This conclusion is supported by studies showing that older adults have difficultly initiating deep encoding (for review, see Craik & Rose, 2012) as well as inhibiting irrelevant material (e.g., Lawo et al., 2012; Troyer et al., 2006). The latter finding is supported by the Inhibition Deficit Theory of Aging, which attributes age-related cognitive deficits to a decline in inhibitory control of working memory contents (Hasher & Zacks, 1988; Zacks et al., 2000).

While age-related reductions in intentional forgetting are well supported by the Inhibition Deficit Theory, one aspect of the DF task that has not been fully considered is the timing allotted to execute both encoding and inhibitory processes. That is, participants are typically only given a few seconds (on average about 3 s; see Titz & Verhaeghen, 2010 for a meta-analysis) to either encode or inhibit a presented item. This could be problematic for older adults, as one of the foremost theories of cognitive aging posits that age-related decline in cognitive processing is due to age-related slowing of mental operations (Salthouse, 1996). Specifically, the Processing Speed Theory of Aging posits that older adults exhibit poorer cognitive performance compared to younger adults due, in part, to the fact that the time required by early operations (e.g., processing of the memory cue) reduces the time available for later operations (e.g., execution of deep encoding or inhibition) operations (Salthouse, 1996). Consequently, older adults may not have sufficient time to both process the cue directing them to either remember or forget the item *and* execute encoding/inhibition processes as effectively as younger adults within the typical time allotted in the DF paradigm. Indeed, previous work by Hogge et al. (2008) suggests that processing speed may contribute to older adults' performance difficulties during the DF task. Thus, while these two explanations of age differences in DF are not necessarily incompatible, taken together they suggest that observed DF deficits in older adults may be a result of the combined effect of age-related deficits in inhibition and age-related deficits in processing speed. To investigate the influence of processing speed on intentional forgetting, we propose that additional time may afford older adults the needed resources to more fully engage in encoding and inhibitory processes, thereby enhancing their DF performance beyond what has been seen using the more typical 3-s instructional duration.

While the length of cue duration in the DF paradigm has been examined previously, results have been mixed. With respect to young adults, some research finds that increases in cue duration results in a reduced DF-effect (Lee et al., 2007), while others observe no effect of duration (Allen & Vokey, 1998; Bancroft et al., 2013). Most relevant to the current investigation is a study by Dulaney and colleagues (Exp. 2; Dulaney et al., 2004) which examined cue duration in older adults. Using cue durations of 1500, 3000, and 5000 ms researchers observed a significant DF-effect in young adults at the two shorter cue durations, but failed to find a statistically significant DF-effect at 5000 ms. The study also failed to find a significant DF-effect in older adults at any cue duration. The lack of DF-effect in older adults notwithstanding, the study design included a random intermixing of cue durations that may have precluded the authors' ability to truly test the effect of cue duration. That is, the unpredictable cue duration may have hindered participants' ability to utilize the longer processing time effectively. The current study aims to address this methodological concern by blocking trials by cue duration, thus allowing participants to use this knowledge when executing memory processes.

In addition, the current study aimed to expand our understanding of age-related differences in directed forgetting by including in the analysis individual difference measures of cognitive reserve. There exists wide individual heterogeneity in cognition in aging populations (e.g., Ardila, 2007; Christensen et al., 1999; Morse, 1993; Schaie, 1988) including individual differences in both memory and executive functioning (e.g., Mejia et al., 1998; Mungas et al., 2010; Ostrosky-Solis et al., 1998; Rhodes & Kelley, 2005). Differences in cognitive reserve have also shown to influence one's ability to take advantage of environmental support during cognitive tasks (Le Carret et al., 2003; Park & Bischof, 2013; Vance et al., 2010). For example, Le Carret et al. (2003) found that older adults with greater education performed better on cognitive tasks requiring control and conceptualization processes. Thus, with respect to the increased cue duration proposed in the current study, it may be that only those individuals with higher levels of cognitive functioning are able to take advantage of additional processing time.

Finally, the current study aims to expand our understanding of age-related differences in directed forgetting by examining the effect of cue duration on recollection processes supporting memory. That is, the majority of DF studies have used a yes/no recognition paradigm (but see Gardiner et al., 1994; Rizio & Dennis, 2013; Rizio et al., 2014). As such, the memory test collapses across qualitative different types of memory (i.e., recollection and familiarity), which are known to be mediated by distinct subsystems of the MTL (e.g., Diana et al., 2007; Yonelinas, 2005) and show differential effects in aging, with recollection showing greater age-related decline than familiarity (Bastin & Van der Linden, 2003; Davidson & Glisky, 2002; Howard et al., 2006; Java, 1996; Jennings & Jacoby, 1993; Mantyla, 1993; Parkin & Walter, 1992; Yonelinas, 2002). Given age deficits in recollection, it may be that the added time provided by longer cue duration will differentially affect older adults' ability to execute recollection-related remembering as well as inhibition-based forgetting associated with subsequent recollection. To this end, Gardiner et al. (1994) observed that the DF-effect was primarily driven by a drop in subsequent recollection, with familiarity-based recognition being unaffected by the memory cues. To the best of our knowledge, no study has examined the effect of cue duration in combination with recollection-based responding in aging. To examine this issue, the current study made use of Remember/Know/New response options at retrieval which allowed for the calculation of both the traditional DF-effect as well as a directed remembering (DR) effect, which allowed for the examination of differences between intentional and incidental recollection.

With respect to the influence of processing time on directed forgetting in aging, we predict that increased cue duration will lead to an increase in the both the DR and DF-effects in older adults, as it allows individuals more time to execute intentional encoding and forgetting. This will be tested by examining a linear increase in both effects across cue durations. The alternative is that age-related slowing does not contribute to age differences in directed forgetting performance, which would be observed as no increase in remembering or forgetting rates with additional time on task. Additionally, we posit that, while older adults will exhibit age deficits in the directed forgetting performance across all cue durations, this age difference will be reduced at longer cue durations. We also posit that those individuals with higher cognitive reserve will show the greatest benefits of cue duration compared to those with lower cognitive reserve.

Methods

Participants

Thirty young adults and 33 older adults participated in the study. All participants, including older adults, were run at a time that was convenient to, and chosen by, them. Three older adults were excluded from all analyses due to a failure to use all response options (1), a high depression score as measured by the Geriatric Depression Scale (see below) (1), and a MATLAB error resulting in a failure to record data (1), leaving 30 older adults in the final analysis. Young adults were Pennsylvania State University undergraduates between the ages of 18 and 23 years (*M* = 19.13, *SD* = 1.41; 25 females) and received class credit for their participation. Older adults were Centre County residents between the ages of 61 and 80 years (*M* = 69.47, *SD* = 5.14; 21 female) and were financially compensated for their particiption (see Table 1). All participants provided informed consent for the ethical treatment of human participants, and all procedures were approved by the Pennsylvania State University Institutional Review Board.

Materials

Stimuli consisted of 364 words obtained from the MRC Psycholinguistic Database (Coltheart, 1981). The stimuli had a mean Kučera and Francis (1967) written frequency of 108.65 (*SD* = 56.41), and a mean word concreteness (Gilhooly & Logie, 1980; Spreen & Schulz, 1966) of 420.49 (*SD* = 101.73). Two hundred and forty words were used during encoding, separated equally into three duration conditions (1000, 3000, and 5000 ms). One hundred and twenty words were used as foils during the recognition test. All words were presented in the center of the computer screen in uppercase white letters on a black background. Memory cues were also presented centrally on a black background. To-Be-Remembered (TBR) cues consisted of five green pound signs, while To-Be-Forgotten (TBF) cues consisted of five red pound signs. The remaining four words were used to practice the task prior to the encoding phase.

Table 1. Participant demographics.

Measure	Younger adults[a]	Old adults
N	30	30
AGE	19.13 (1.41)	69.47 (5.14)
FEMALE	25	21
EDUCATION	12.93 (1.12)	16.5 (2.5)
MMSE	NA[b]	29.43 (0.77)
SYMBOLSEARCH	12.89 (2.57)	12.57 (2.53)
DIGITSYMBOL	12.11 (2.3)	12.77 (3.21)
DIGITSPAN	10.79 (2.87)	12 (2.94)
ARITHMETIC	8.75 (3.26)	10.9 (3.72)
LNSEQUENCING	10.39 (3.1)	11.93 (3.16)
VOCAB	11.82 (2.93)	12.8 (2.83)
COMPOSITE SCORE	11.12 (1.48)	12.16 (2.14)

Mean (sd). N = size of sample, AGE = age in years, FEMALE = number of female participants, EDUCATION = years of education. See text for description of the cognitive assessment measures and the calculation of the composite score.

[a]Two younger adults did not complete the cognitive assessment battery. Means and standard deviations based on the Cognitive Assessment battery reflect 28 complete datasets.

[b]Younger adults were not required to complete the MMSE as part of the cognitive assessment battery.

Table 2. Behavioral response rates.

Age-group		TBR 1 s	TBR 3 s	TBR 5 s	TBF 1 s	TBF 3 s	TBF 5 s
Young	Remember	0.48 (0.21)	0.54 (0.22)	0.58 (0.23)	0.41 (0.18)	0.37 (0.17)	0.41 (0.16)
	Know	0.28 (0.14)	0.24 (0.17)	0.22 (0.16)	0.29 (0.15)	0.31 (0.15)	0.28 (0.15)
	New	0.22 (0.17)	0.2 (0.15)	0.18 (0.13)	0.29 (0.17)	0.3 (0.16)	0.3 (0.16)
Old	Remember	0.39 (0.21)	0.46 (0.23)	0.51 (0.22)	0.34 (0.2)	0.33 (0.2)	0.33 (0.2)
	Know	0.32 (0.2)	0.28 (0.19)	0.27 (0.17)	0.29 (0.18)	0.31 (0.18)	0.33 (0.19)
	New	0.29 (0.18)	0.26 (0.16)	0.21 (0.13)	0.37 (0.17)	0.36 (0.19)	0.34 (0.18)

Note: Mean (SE). TBF = To Be Forgotten, TBR = To Be Remembered.

Procedure

Cognitive assessment

Prior to participation in the experimental protocol, all participants completed a battery of neuropsychological tests designed to measure general cognitive functioning and cognitive reserve (see Table 1). The tests included Symbol Search, Digit-Symbol Coding, Symbol Copy, Digit Span, Athematic, Letter-Number Sequencing (Wechsler Adult Intelligence Scale-III) and Vocabulary (Weschler Memory Scale-III) (Wechsler, 1997). Additionally, the Mini-Mental State Examination (MMSE) (Folstein, 1983), the Beck Depression Scale (Beck et al., 1996), and the Geriatric Depression Scale (GDS) (Sheikh & Yesavage, 1986) were used to screen individuals for signs of early Mild Cognitive Impairment and depression, which has been shown to affect cognitive abilities in older adults (Beaudreau & O'Hara, 2009; Calero & Navarro, 2004). A composite cognitive assessment score was calculated by averaging each individual's Symbol Search, Digit-Symbol, Arithmetic, Letter-Number Sequencing, and Vocabulary scores.

Encoding

In the encoding task, participants were presented with a series of words, displayed one-at -a-time on the computer screen for 1000 ms (see Figure 1). Each word was followed by

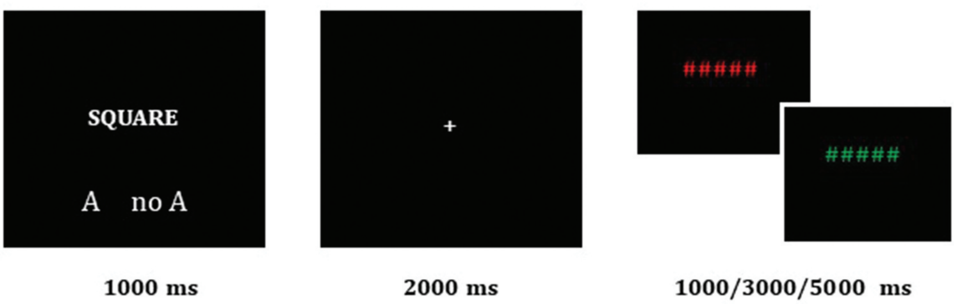

Figure 1. A visual summary of the item-method directed forgetting encoding task for each memory cue duration. Participants first completed a shallow encoding task for each word (Does the word contain the letter 'A' or not?). The task was followed by a two second delay prior to the presentation of the memory cue (#####) instructing participants to either remember (green) or forget (red) the previous word. In accordance with the three cue duration conditions, the cue remained on the screen for either one, three of five seconds.

a brief 2000 ms delay, during which a white fixation cross was presented. To ensure that participants were attending to stimulus presentation, participants were further instructed to indicate whether or not each word contained the letter "A." After this period, a memory cue was presented in the center of the screen indicating whether the word was to-be-remembered or to-be-forgotten. Cues consisted of a group of five colored pound signs. Participants were instructed that words followed by green pound signs should be remembered (TBR items), as they would appear on an upcoming memory test, whereas words followed by red pound signs should be forgotten (TBF items), as they would not be on the memory test. The order of TBR and TBF cues was pseudo-random such that no more than three of each trial-type was presented in a row. Equal numbers of TBR and TBF cues were presented in each cue duration condition. A 2000 ms inter-trial interval preceded the next item, during which a blue fixation cross appeared on the screen. Trials were further broken down into three blocks corresponding to cue duration [1000, 3000, or 5000 ms]. Each encoding block contained 80 items: 40 TBR and 40 TBF words, resulting in total of 120 TBR and 120 TBF words presented during encoding. The presentation order of the three encoding blocks was counterbalanced across participants.

Retrieval

Following a 10-min interference task [Arithmetic Test for young adults and Matrix Reasoning for older adults], participants completed a retrieval task for the words they had previously studied. The retrieval task included 360 words: 120 TBR targets, 120 TBF targets, and 120 novel lures. Each word appeared individually on the screen for 2500 ms during which time participants were asked to make a remember/know/new (R/K/N) memory decision (Yonelinas & Jacoby, 1995). It was stressed to participants that their memory response should not depend on whether the word had been associated with a TBR or TBF cue during encoding, but should instead depend only on whether the word was old or new. The retrieval task was divided into five runs of 72 words each, with short breaks allotted between runs.

RESULTS

False alarms

Prior to the assessment of veridical memory, we tested for age differences in false alarms. Older and younger participants did not differ in their false alarm rates (Old: $M = 0.4178$, Young: $M = 0.4661$; $t(58) = -0.99$, $p =$ ns).

Directed forgetting

First, we examined whether our younger and older participants exhibited a greater-than-zero DF-effect, which is operationalized as the proportion of TBF targets receiving a "New" response minus the proportion of TBR targets receiving a "New" response. (Basden & Basden, 1996). All statistical tests were calculated using R (R Core Team, 2016). One-tailed *t*-tests of the marginal means averaged over the levels of Cue Duration revealed that both our younger and older adult samples displayed DF-effects that were significantly greater than zero (Old: $M = 0.102$, $t(29) = 5.281$, $p < .0001$; Young: $M = 0.098$, $t(29) = 5.794$, $p < .0001$).

Probing for the presence of the DF-effect within each cue duration for both age groups, Bonferroni corrected, one-tailed *t*-tests of the marginal means of the entire design revealed there was a significant DF-effect present at each Cue Duration for both younger and older adults (all $ts > 2.823$, all $ps < .01$) (see Figure 2). This suggests that both our younger and older adults were able to implement directed forgetting both overall and at all cue durations.

In order to examine the influence of age and cue duration on the DF-effect, a 3 (Cue Duration: 1000, 3000, 5000 ms) by 2 (Age Group: young, old) analysis of variance (ANOVA) was performed. The ANOVA revealed a significant main effect of Cue Duration ($F(2, 116) = 4.96, p < .01$). The main effect of Age Group ($F(1, 58) = .02, p =$ ns) and the Age Group x Cue Duration ($F(2, 116) = .06, p =$ ns) interaction did not approach statistical significance. We next performed two pairs of planned contrasts on the marginal means to further examine the main effect of Cue Duration within each age group – a pair of orthogonal polynomial contrasts examining linear and quadratic trends across the cue durations (i.e., contrast weights = –1, 0, 1 and –.5, 1, –.5) and another pair examining a "plateau" effect across the cue durations (i.e., contrast weights = –1, .5, .5 and 0, 1, –1). Noted above, we expected the DF-effect to increase linearly in older adults with each cue duration reflecting a benefit of longer cue durations. The other contrasts were calculated to test the alternative hypotheses that the extra time on task did not improve performance beyond what is observed in the typical item-method directed forgetting design. Further, as slowing of processing speed occurs in aging, there was no expectation that increased time would affect performance in younger adults. The results of these planned contrasts showed that the linear trend was marginally significant in the older adults (contrast = [–1, 0, 1], $F(1,58) = 3.83, p = 0.055$) and neither the quadratic trend, (contrast = [–.5, 1, –.5], $F(1,58) = 0.04, p =$ ns), nor the "plateau" contrasts, (contrast = [–1, .5, .5], $F(1,58) = 2.55, p =$ ns; contrast = [0, 1, –1], $F(1,58) = 1.32, p =$ ns), were statistically significant for the older adults. In young adults, the results showed that the linear trend was statistically significant (contrast = [–1, 0, 1], $F(1,58) = 6.39, p =.014$), while the quadratic trend was not (contrast = [–.5, 1, –.5], $F(1,58) = 0.02, p =$ ns). The planned "plateau" contrasts showed a statistically significant difference between the 1-s and the 3- and 5-s cue durations (contrast = [–1, .5, .5], $F(1, 58) = 5.08, p < .05$) and a nonsignificant difference between the 3- and 5-s cue durations (contrast = [0, 1, –1], $F(1, 58) = 1.33, p =$ ns). Taken together, these results suggest that

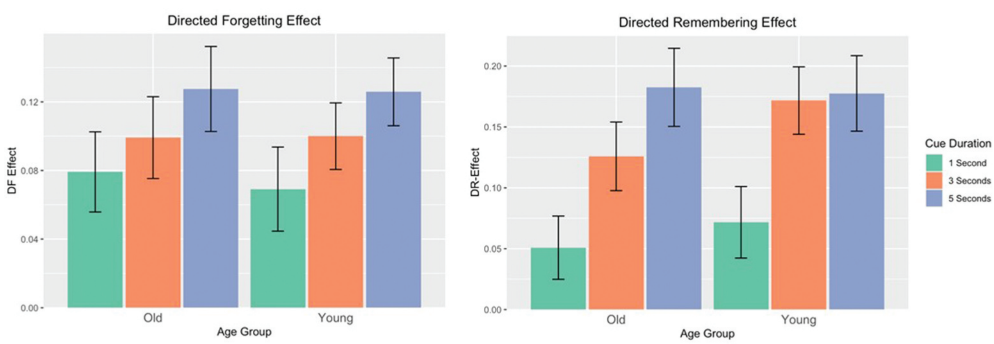

Figure 2. Directed forgetting and remembering effects, broken down by Age Group (Young, Old) and Cue Duration (1, 3, 5 seconds). DF = directed forgetting, DR = directed remembering. Error bars represent +/- 1 standard error of the mean.

increased cue duration results in a similar, linear increase in directed forgetting performance for both younger and older adults.

At the helpful suggestion of a reviewer, and in order to characterize if the effect of Cue Duration was driven by changes in the intentional or incidental forgetting rates, we also ran a Cue Duration x Age Group x Cue Type ANOVA on forgetting rates. The ANOVA revealed a revealed a significant main effect of Cue Duration ($F(2, 116) = 4.486$, $p < .05$), a significant main effect of Cue Type ($F(1, 58) = 60.703$, $p < .05$), and a significant Cue Type x Cue Duration interaction ($F(2, 116) = 4.956$, $p < .05$). Follow up ANOVAs showed that this interaction was driven primarily by a linear decrease in forgetting of TBR items with longer cue durations for both young and older adults. Specifically, an ANOVA on forgetting rates for Older Adults in the TBR condition revealed a significant effect of Cue Duration ($F(2, 58) = 6.84$, $p < .01$), which manifested itself primarily as a linear decrease in miss rates over the Cue Duration conditions (contrast = [–1, 0, 1], $F(1, 58) = 13.58$, $p < .001$). A similar ANOVA on forgetting rates for Young Adults in the TBR condition was marginally significant ($F(2, 58) = 3.09$, $p = 0.053$), which manifested itself as a linear decrease in miss rates over the Cue Duration conditions (contrast = [–1, 0, 1], $F(1, 58) = 6.1195$, $p < .05$). No other result was significant (see Table 2 for all forgetting rates).

Directed remembering

As noted, we were also interested in examining the effect of age and cue duration on recollection rates, which have been shown to be most affected in directed forgetting

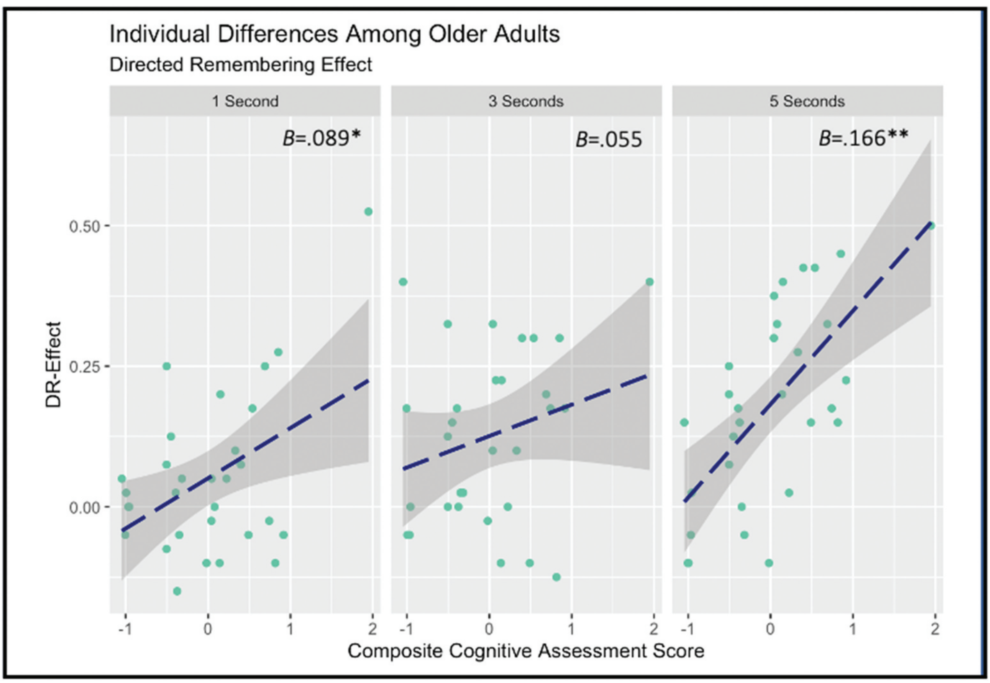

Figure 3. Relationship between directed remembering and composite cognitive assessment score (z-scored on the x-axis) as a function of cue duration. DR = directed remembering. Blue dashed line represents linear regression line. Shaded area represents standard error of the regression line.

(Gardiner et al., 1994). Whereas the DF-effect, or difference in forgetting rates between the TBF and TBR conditions, may best identify the contribution of goal-directed forgetting (i.e., inhibition) to the memory task at hand, examining differences in the remembering rates between conditions may allow us to focus on the role of goal-directed encoding in the memory task. In accordance with previous work in our lab (Rizio & Dennis, 2013; Rizio et al., 2014), a Directed Remembering Effect (DR-effect) was operationalized as the proportion of TBR targets receiving a "remember" response minus the proportion of TBF targets receiving a "remember" response. One-tailed *t*-tests of the marginal means averaged over the levels of Cue Duration revealed that both our younger and older adult samples displayed DR-effects (Old: $M = 0.1197$, $t(29) = 4.91$ $p < .0001$; Young: $M = 0.1403$, $t(29) = 5.51$, $p < .0001$). Probing for the presence of the effect within each cue duration for both age groups, Bonferroni corrected, one-tailed *t*-tests of the marginal means of the entire design revealed that there was an above zero DR-effect present at each cue duration for both younger and older adults (all *t*s > 1.8, all *p*s < .05) (see Figure 2). This suggests that both our younger and older adults were able to implement directed remembering at all cue durations. Figure 3

A similar ANOVA to the one conducted for the DF-effect was conducted for the DR-effect. This ANOVA also revealed a significant effect of Cue Duration ($F(2, 116) = 22.35$, $p < .001$). The main effect of Age Group ($F(1, 58) = .34$, p = ns) and Age Group × Cue Duration ($F(2, 116) = .95$, p = ns) interaction did not approach statistical significance. Echoing the analyses above, we next performed two pairs of orthogonal contrasts to examine polynomial trends and to examine an alternative "plateau" pattern of results for the older and younger adults separately. The results of the polynomial contrasts showed that the linear trend was statistically significant in the older adults (contrast = [−1, 0, 1], $F(1, 58) = 24.44$, $p < .001$) while the quadratic trend was not (contrast = [−.5, 1, −.5], $F(1,58) = 0.16$, p = ns). The results further showed that the linear (contrast = [−1, 0, 1], $F(1, 58) = 17.31$, $p < .001$) and quadratic (contrast = [−.5, 1, −.5], $F(1, 58) = 4.57$, $p < .05$) trends were significant in younger adults. The plateau contrasts revealed a significant difference between the 1-s cue duration condition compared with the 3- and 5-s conditions (contrast = [−1, .5, .5], $F(1, 58) = 20.07$, $p < .001$) and a significant difference between the 3- and 5-s conditions (contrast = [0, 1, −1], $F(1, 58) = 4.53$, $p < .05$)) in the older adults. The younger adults, on the other hand, showed a significant difference between the 1 s and the 3- and 5- conditions (contrast = [−1, .5, .5], $F(1, 58) = 21.82$, $p < .001$) but an nonsignificant difference between the three and five second conditions (contrast = [0, 1, −1], $F(1, 58) = 0.05$, p = ns). Further, in the younger adults, the model using the plateau contrast (AIC = −70.48) fit the data better than the model using the linear contrast (AIC = −68.75). However, the opposite was true in the older adults such that the model using the linear contrast (AIC = −73.72) fit better than the model using the "plateau" contrast (AIC = −71.82). Finally, as the linear trend was significant in both age groups, we tested the fit of the linear contrast in the older adults against the fit of the linear contrast in the younger adults. We found that the linear model was a better fit in older adults than in younger adults ($F(1,1) = 44.69$, $p < 0.001$). Taken together, these results suggest that a linear effect was the best fit for the pattern of results for the older adults, while a nonlinear "plateau" pattern was the best fit for the young adults. Furthermore, the linear fit was a better fit of the data for older compared to younger adults.

At the helpful suggestion of a reviewer, and in order to characterize if the effect of Cue Duration was driven by changes in the intentional or incidental remembering rates, we also ran a Cue Duration × Age × Cue Type ANOVA on recollection rates. The ANOVA revealed a significant main effect of Cue Duration (F(2, 116) = 9.635, $p < .05$), a significant main effect of Cue Type (F(1, 58) = 54.396, $p < .05$) and a significant Cue Type × Cue Duration interaction (F(2, 166) = 22.347, $p < .05$). Follow-up ANOVAs showed that this interaction was driven primarily by a linear increase in recollection of TBR items with longer cue durations for both young and older adults. Specifically, an ANOVA on remember rates for Older Adults in the TBR condition revealed a significant effect of Cue Duration (F(2, 58) = 15.10, $p < .001$), which manifested itself primarily as a linear increase in remembering rates over the Cue Duration conditions (contrast = [−1, 0, 1], F(1, 58) = 30.06, $p < .001$). A similar ANOVA on remember rates for Young Adults in the TBR condition was marginally significant (F(2, 58) = 2.63, $p = 0.08$), which manifested itself as a quadratic effect in remember rates over the Cue Duration conditions (contrast = [1, −2, 1], F(1, 58) = 5.2454, $p < .05$). No other result was significant (see Table 1 for all remember rates).

Individual differences

To explore the effect of individual differences in cognitive function on the ability to utilize longer cue durations, we conducted two ANOVAs of the within-subjects factor Cue Duration (1000/3000/5000 ms) and the between-subjects factor Cognitive Assessment Score on the DF- and DR-effects in older adults.

An ANOVA on the DF-effect resulted in a significant main effect of Cognitive Assessment Score (F(1, 28) = 8.32, $p < .01$) and a nonsignificant effect of Cue Duration (F(2, 56) = 1.95, p = ns) and a nonsignificant interaction effect (F(2, 56) = 1.24, p = ns). These results suggest that there is no relationship between older adults with greater cognitive reserve and directed forgetting performance related to longer cue durations. In contrast to this finding, an ANOVA on the DR-effect resulted in a significant main effect of Cue Duration (F(2, 56) = 13.946, $p < .001$), a significant main effect of Cognitive Assessment Score (F(1, 28) = 11.92, $p < .01$), and a significant interaction effect (F(2, 56) = 4.879, $p < .05$). Further investigation of the interaction effect using contrasts revealed that the effect of Cognitive Assessment Score on the DR-effect was greater in the 5-scondition compared with the 3- and 1-s conditions (contrast = [−.5, −.5, 1], F(1, 56) = 8.90, $p < .01$) whereas there was no statistical difference in the effect between the 3- and 1-s conditions (contrast = [1, −1, 0], F(1, 56) = 0.008, p = ns). This suggests that older adults with a greater cognitive reserve were best able to take advantage of the increased cue duration to implement directed remembering.

Discussion

The current study examined the effect of cue duration and individual differences on performance in the directed forgetting paradigm in aging. While we did not find evidence of an age deficit in memory, consistent with the aims of the study, we did find a significant effect of cue duration on both directed forgetting and directed remembering performance. Planned contrast analyses suggested that cue duration had a systematic effect on directed forgetting and remembering in aging such that more processing time led to better performance on both measures. Also, in our older adults, individual differences in baseline cognitive functioning interacted with cue duration, such that the relationship between cognitive reserve and recollection-related remembering was greatest in the 5-s condition, suggesting that older adults with the greatest cognitive reserve were best able to take advantage of the increased time on task to engage in goal-directed encoding processes. Our results support our hypothesis that longer cue durations improve both DF and DR performance in older adults, as well as speak to the relationship between cognitive reserve and time allotted to execute DR processes. However, while both the DF- and DR-effects increased with cue duration, a follow-up analysis of the memory rates across conditions suggests that both effects were driven by modulation of memory processes associated with the TBR cue, not the TBF cue. Specifically, the results support the idea that longer cue durations benefit performance in the directed forgetting paradigm by allowing individuals greater time to execute remembering-related encoding processes.

Directed forgetting and remembering

Performance in directed forgetting tasks has long been posited to reflect goal-directed forgetting through the process of inhibition associated with the TBF memory cue. However, performance can also be supported by recollection-related remembering associated with the TBR cue. Traditional yes/no recognition instructions in the DF paradigm could not separate these performance differences (as any directed remembering effect would merely be the inverse of the directed forgetting effect). The current design, however, with use of the Remember/Know/New paradigm (Gardiner et al., 1994; Rizio & Dennis, 2013), affords us the ability to examine each separately. Consistent with previous work using the directed forgetting task, both young and older adults exhibited a significant DF-effect, supporting the notion that they can utilize task-related instructions to modulate goal-directed forgetting (Feyereisen & Charlot, 2008; Hasher et al., 1997; Rizio et al., 2014; Titz & Verhaeghen, 2010; Zacks et al., 1996). Our results also revealed a significant DR-effect in both young and older adults, suggesting that both groups can direct cognitive operations in a manner that leads to enhanced remembering associated with TBR trials. Unlike past research in item-method directed forgetting (e.g., Zacks et al., 1996) we did not observe an age deficit in performance. The absence of age differences in the DF paradigm is not without precedence, as previous studies, our lab included, have also not identified age differences in the DF paradigm (Rizio et al., 2014). The results may be indictive of the role individual differences in cognitive reserve may play in executing cognitive operations in this task (see below for more on this point).

Effect of cue duration

Turning to the effect of cue duration, we found a main effect of cue duration in both the DF and DR analyses. Results supported our hypothesis that extra time benefits performance in the DF paradigm and older adults can take advantage of this support to improve in both directed forgetting as well as recollection-related remembering. The absence of an age × cue duration interaction in both analyses further suggested that both groups were able to benefit from longer cue durations in executing both cognitive operations. As such, our analyses support our hypothesis that added time to engage in and execute goal-directed cognitive operations within the DF paradigm will be beneficial to older adults. The increase in DF- and DR-effects across all individuals supports the premise that cognitive control in the directed forgetting task is not an implicit or automated cognitive operation, but one that needs sufficient resources to execute (Cheng et al., 2012; Fawcett & Taylor, 2008). If directed forgetting performance, and the accompanying cognitive control required to engage in these cognitive processes, was reflexive, then performance across all cue durations would be equal. Further, the fact that younger adults show this benefit, not just older adults, speaks to the fact that these operations require sufficient time to execute at any age and are not solely impacted by cognitive slowing in aging.

Despite the absence of any age interaction, our planned contrast analyses within each age group did find that the support associated with extra time to execute goal-directed cognitive operations was not uniformly beneficial to both age groups. Specifically, while younger adults exhibited a significant linear increase in their DF-effect across the three timing conditions, showing the highest directed forgetting performance in the 5-s condition, this effect was only marginally significant in older adults. Such results, in conjunction with the lack of age interactions, suggest that age does not have a systematic impact on one's ability to utilize cue duration for improving goal-directed forgetting. Furthermore, our follow-up analyses examining forgetting rates across all conditions showed that the effect of cue duration on the DF-effect within both age groups was driven by a linear decrease in incidental forgetting across cue durations and not an increase in inhibition related, intentional forgetting. Thus, results suggest that increased time associated with the forget cue does not lead to enhanced goal-directed inhibition of TBF items. Rather, increased time associated with remember cues leads to decreased incidental forgetting.

A slightly different pattern of results emerged when examining the planned contrasts on the DR-effect. Specifically, while a linear trend fit the data in both age groups, a direct contrast between age groups found that the linear trend was a significantly better fit within the older adults than within the younger adults, with the younger adults displaying a "plateau" pattern such that they showed an increased DR-effect between the 1- and 3-s conditions, but no further improvements thereafter (see Figure 2). Such results suggest that older adults systematically benefited from the increased cue durations, while younger adults did not require as much time to incur processing benefits. Additionally, our follow-up analyses examining remembering rates across all conditions showed that foregoing results were driven by increases in intentional recollection across cue durations within both age groups. Thus, results suggest that, unlike goals-directed forgetting, additional time associated with the remember cue can aid in the ability to engage recollection-related remembering of TBR items.

Many other studies have shown similar improvements in older adults' cognitive performance when the older adults are given extended time to execute cognitive operations (e.g., Earles et al., 2004; Foster & Giovanello, 2017, 2020; Pichora-Fuller, 2003). This extended time is proposed to allow for the completion of cognitive operations that may have otherwise been cut short when time constraints are applied to cognitive tasks, forcing older adults to move to subsequent cognitive steps prior to the completion of any one cognitive operation. While the current results support this relationship between increased processing time and task performance in the DF paradigm in older adults, it is unclear from our data what the optimal cue duration may be in this task. That is, while we observed a linear increase in intentional remembering from 1 to 3 to 5 s, it is unclear whether performance in older adults would continue to improve with even longer cue durations. Testing the upper bounds of the benefit of additional time in the DF paradigm for younger and older adults is a question that needs to be explored in future research. At present, this linear increase in older adults supports our hypothesis that aging is associated with difficulty engaging cognitive resources necessary for controlled cognition under time constraints imposed within the directed forgetting paradigm.

With respect to the benefit of additional time on task, the findings are also consistent with other findings from the Processing Speed Theory of aging. The Processing Speed Theory of aging posits that an inevitable reduction in processing speed with age is the fundamental deficit underlying age-related cognitive decline (Salthouse, 1996). This reduction in processing speed impairs performance by preventing the completion of necessary cognitive functions under limited time conditions. As a result, older adults can only access incomplete, partially processed information, a limitation that manifests as cognitive deficits in a variety of tasks. The finding that older adults' recollection-related remembering performance linearly increased with additional time afforded to execute memory-related processing supports our hypothesis that older adults' performance is related to the time allotted to them to carry out cognitive operations (Clarys et al., 2002; Foster & Giovanello, 2020; Salthouse, 2016; Zacks et al., 1996) and impaired by limited time to execute task-related cognitive operations (Salthouse, 1994, 1996, 2016; Salthouse et al., 1999). The fact that younger adults also exhibit a benefit in their performance between the 1- and 3-s, yet showed no greater benefit with 5 s, cue durations further supports the conclusion that while recollection-related remembering requires cognitive effort and resources to execute, aging imposes a limitation related to the ability to carry out such processing.

Noted above, cognitive performance in the DF paradigm involves both directed inhibition of TBF items as well as recollection-related remembering of TBR items. Past work has largely attributed age deficits in the DF-effect to a reduced ability to engage top-down inhibition processes that serve to limit encoding operations, preventing information from being stored in long-term memory (e.g., Fawcett & Taylor, 2008; Rizio & Dennis, 2013; Zacks et al., 1996). Supporting this view, aging has long been associated with deficits in inhibition processes (e.g., the Inhibition Deficit Hypothesis; Hasher et al., 1991; Lustig et al., 2007) and more recently, deficits in inhibition-related neural activity associated with successful directed forgetting of irrelevant information (Gallant et al., 2018; Rizio et al., 2014). While these reductions have been attributed to age-related deficits in frontal mechanisms related to the ability to execute cognitive inhibition (Braver & Barch, 2002; Paxton et al., 2008; Turner & Spreng, 2012; West, 2000), we posited that age-related deficits in processing speed (Deary et al., 2010; Finkel et al., 2007; Salthouse, 1996; Salthouse et al., 2000) also contribute to older adults' difficulties in engaging cognitive mechanisms needed to control memory function. While the differential performance in the DF-effect suggests that both younger and older adults engage goal-directed cognitive inhibition within the DF paradigm, the fact that goal-directed inhibition of TBF words did not increase as a function of cue duration (as the linear increase in the DF-effect was shown to be driven by decreases in incidentally forgetting) suggests that this cognitive operation is a demanding process that is limited with regard to the extent of inhibition possible. Furthermore, our results also suggest inherent differences in difficulty between directed remembering and directed forgetting that cannot be explained by the PROCESSING SPEED TEORY. That is, the fact that both age groups exhibited an increase in directed recollection of TBR words, with increasing cue durations, yet goal-directed inhibition of TBF words did not incur the same benefit, suggests that the latter cognitive process may not be able to be modulated by environmental support factors (e.g., time on task).

Individual differences in older adults

Despite the benefit of increased cue duration on older adults' DR-effect, there was substantial variability within the group's performance overall. These individual differences were explored using a composite score of the cognitive assessment measures as a predictor of both DF and DR performance. The results revealed a significant, positive relationship between the composite cognitive scores and DR-effect that interacted with cue duration, but did not interact with the DF-effect. Follow-up analyses revealed that the relationship between cognitive reserve and directed remembering was larger in the 5-s cue duration than either the 1- or 3-s cue durations. This indicates that older adults with larger cognitive reserve were able to take particular advantage of the longer cue duration afforded in the 5-s condition to implement goal-directed encoding processes necessary for successful recollection-related remembering within the current paradigm.

These results further elucidate the current findings regarding the main effect of cue duration. Specifically, they suggest that the increased performance we observed across cue durations is impacted not by time alone, but also by one's underlying ability to take advantage of the additional resource with respect to the execution of encoding processes. Cognitive reserve has shown to be a factor in previous aging studies where factors such as education, occupation, and general cognition have correlated with performance on cognitive tasks in advanced aging (Alvarado, Zunzunegui, Del Ser & Beland, 2002; Christensen et al., 1994, 2001, 1999; Whalley et al., 2004), with the absence of reserve shown to be a risk factor for developing age-related dementia (Evans et al., 1997; Scarmeas & Stern, 2004; Schmand et al., 1997). Previous work in the field of directed forgetting has also observed a positive relationship between recall within a directed forgetting task and working memory capacity (Marevic et al., 2018). The current study adds to this body of literature by demonstrating that cognitive control and recollection-related processes are impacted by several factors in aging, including both the availability of external resources (i.e., time on task) and internal resources (i.e., cognitive abilities) available to an individual.

Additionally, while the current results exhibit a benefit to directed remembering performance incurred with increased time on task and cognitive reserve in older adults, that relationship was not present in the directed forgetting effect in older adults. Taken together, this suggests that the relationship between reserve and cognition is not ubiquitous across all cognitive operations involved in the cognitive control of memory. In this instance, additional resources benefit control processes involving remembering, but not inhibition. As such, the results may again speak to inherent differences in difficulty between goal-directed inhibition and goal-directed remembering that underlie performance in the DF paradigm. Specifically, results suggest that any difficulties related to the execution of inhibition driven forgetting are not easily mitigated by cognitive reserve in older adults.

Limitations and future direction

With regard to the distractor tasks chosen, our main goal in choosing a task was to use one that involved limited or no semantic processes, as we did not want semantic interference to influence encoding and verbal memory inhibition processes. While we feel we accomplished that by choosing an arithmetic and matrix reasoning task, we inadvertently confounded task with group. While we do not feel the two non-verbal tasks had any differential effect on inhibition processes, a replication of the current study should control for this potential issue. The current study also utilized a commonly applied recognition test within the DF literature, as opposed to a more difficult recall task (e.g., Marevic et al., 2018). Future work could investigate how extended cue duration also influences recall processes in DF, perhaps to a different degree than with recognition. Finally, given our linear increases in performance across the three cue durations used in the current task, it is of interest to extend this processing time to see what upper limits may exist within both age groups with respect to their ability to engage goal-directed memory processes.

Conclusion

Overall, the current study demonstrates that increased processing time within an item-method DF task is directly related to enhanced task performance in older adults, with the results driven primarily by modulation of intentional encoding associated within the TBR condition. Furthermore, the fact that DR performance improved linearly with time on task in older adults suggests that issues related to cognitive slowing and processing speed declines in aging may contribute to age-related deficits previously observed within the DF paradigm. However, the benefit of additional time did not improve performance equally across all individuals. Specifically, we observed a significant relationship between the DR-effect and a composite measure of cognitive functioning in aging, which was greatest in the 5-s cue duration condition. This analysis indicated that older adults with the highest level of cognitive reserve were those that exhibited the highest rates of directed remembering. Taken together, our results support the idea that recollection-related remembering is an effortful process that benefits from extra time to execute in aging, whereas inhibition-related forgetting does not. Additionally, while additional time led to overall improvements in one's ability to direct encoding processes, we did not observe increased inhibition-related forgetting in either age group. This juxtaposition between the two goal-directed cognitive processes and individual abilities may suggest that inhibition is a more difficult process to implement than encoding and is not as easily executed with additional resources such as time on task and enhanced cognitive reserve.

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References

Allen, S. W., & Vokey, J. K. (1998). Directed forgetting and rehearsal on directed and indirect memory tests. In J. Golding & C. M. MacLeod (Eds.), *Intnetional forgetting: Interdisciplinary appoaches* (pp. 173–195). Erlbaum.

Alvarado, B. E., Zunzunegui, M.-V., Del Ser, T., & Beland, F. (2002). Cognitive decline is related to education and occupation in a Spanish elderly cohort. *Aging Clinical and Experimental Research*, *14*(2), 132–142. https://doi.org/10.1007/BF03324426

Anderson, M. C., & Hanslmayr, S. (2014). Neural mechanisms of motivated forgetting. *Trends in Cognitive Sciences*, *18*(6), 279–292. https://doi.org/10.1016/j.tics.2014.03.002

Anderson M.C., Huddleston E. (2012) Towards a Cognitive and Neurobiological Model of Motivated Forgetting. In: Belli R. (eds) True and False Recovered Memories. *Nebraska Symposium on Motivation,* vol 58. Springer, New York, NY. http://www.ncbi.nlm.nih.gov/pubmed/22303764

Anderson, M. C., Ochsner, K. N., Kuhl, B., Cooper, J., Robertson, E., Gabrieli, S. W., . . . Gabrieli, J. D. (2004). Neural systems underlying the suppression of unwanted memories. *Science*, *303* (5655), 232–235. Retrieved from. https://doi.org/10.1126/science.1089504 .

Ardila, A. (2007). Normal aging increases cognitive heterogeneity: Analysis of dispersion in WAIS-III scores across age. *Archives of Clinical Neuropsychology*, *22*(8), 1003–1011. https://doi.org/10.1016/j.acn.2007.08.004

Bancroft, T. D., Hockley, W. E., & Farquhar, R. (2013). The longer we have to forget the more we remember: The ironic effect of postcue duration in item-based directed forgetting. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *39*(3), 691–699. https://doi.org/10.1037/a0029523

Basden, B. H., & Basden, D. R. (1996). Directed forgetting: Further comparisons of the item and list methods. *Memory*, *4* (6), 633–653. Retrieved from. https://doi.org/10.1080/741941000 .

Basden, B. H., Basden, D. R., & Gargano, G. J. (1993). Directed forgetting in implicit and explicit memory tests: A comparison of methods. *Journal of Experimental Psycholgy: Learning, Memory, & Cognition*, *19*(3), 603–616. https://doi.org/10.1037/0278-7393.19.3.603 .

Bastin, C., Feyers, D., Majerus, S., Balteau, E., Degueldre, C., Luxen, A., Salmon, E., Collette, F., & Maquet, P.. (2012). The neural substrates of memory suppression: A FMRI exploration of directed forgetting. *PLoS One*, *7*(1), e29905. https://doi.org/10.1371/journal.pone.0029905

Bastin, C., & Van der Linden, M. (2003). The contribution of recollection and familiarity to recognition memory: A study of the effects of test format and aging. *Neuropsychology*, *17* (1), 14–24. Retrieved from. https://doi.org/10.1037/0894-4105.17.1.14 .

Beaudreau, S. A., & O'Hara, R. (2009). The association of anxiety and depressive symptoms with cognitive performance in community-dwelling older adults. *Psychology and Aging*, *24*(2), 507–512. https://doi.org/10.1037/a0016035

Beck, A. T., Steer, R. A., Ball, R., & Ranieri, W. F. (1996). Comparison of Beck Depression Inventories-IA and-II in psychiatric outpatients. *Journal of Personality Assessment*, *67*(3), 588–597. https://doi.org/10.1207/s15327752jpa6703_13

Benoit, R. G., & Anderson, M. C. (2012). Opposing mechanisms support the voluntary forgetting of unwanted memories. *Neuron*, *76*(2), 450–460. https://doi.org/10.1016/j.neuron.2012.07.025

Bjork, R. A. (1970). Positive Forgetting: The noninterference of items intentionally forgotten. *Journal of Verbal Learning & Verbal Behavior*, *9*(3), 255–268. https://doi.org/10.1016/S0022-5371(70)80059-7

Bjork, R. A. (1972). Theoretical implications of directed forgetting. In A. W. Melton & E. Martin (Eds.), *Coding processes in human memory* (pp. 217–235). V. H. Winston & Sons, Inc.

Bjork, R. A., & Woodward, A. E. (1973). Directed forgetting of individual words in free recall. *Journal of Experimental Psychology*, *99*(1), 22–27. https://doi.org/10.1037/h0034757

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience & Biobehavioral Reviews*, *26* (7), 809–817. Retrieved from. https://doi.org/10.1016/S0149-7634(02)00067-2 .

Calero, M. D., & Navarro, E. (2004). Relationship between plasticity, mild cognitive impairment and cognitive decline. Archives of Clinical Neuropsychology, 19(5), 653–660

Cheng, S.-K., Liu, I.-C., Lee, J. R., Hung, D. L., & Tzeng, O. J. (2012). Intentional forgetting might be more effortful than remembering: An ERP study of item-method directed forgetting. *Biological Psychology*, *89*(2), 283–292. https://doi.org/10.1016/j.biopsycho.2011.10.019

Christensen, H., Mackinnon, A., Jorm, A. F., Henderson, A. S., Scott, L. R., & Korten, A. E. (1994). Age Differences and Interindividual Variation in Cognition in Community-dwelling Elderly. *Psychology and Aging*, *9*(3), 381–390. http://www.ncbi.nlm.nih.gov/pubmed/7999323http://psycnet.apa.org.ezaccess.libraries.psu.edu/journals/pag/9/3/381.pdf

Christensen, H., Mackinnon, A. J., Korten, A., & Jorm, A. F. (2001). The "common cause hypothesis" of cognitive aging: Evidence for not only a common factor but also specific associations of age with vision and grip strength in a cross-sectional analysis. *Psychology and Aging*, *16* (4), 588–599. https://doi.org/10.1037/0882-7974.16.4.588 .

Christensen, H., Mackinnon, A. J., Korten, A. E., Jorm, A. F., Henderson, A. S., Jacomb, P., & Rodgers, B. (1999). An analysis of diversity in the cognitive performance of elderly community dwellers: Individual differences in change scores as a function of age. *Psychology and Aging*, *14* (3), 365–379. https://doi.org/10.1037/0882-7974.14.3.365 .

Clarys, D., Isingrini, M., & Gana, K. (2002). Mediators of age-related differences in recollective experience in recognition memory. *Acta Psychologica*, *109* (3), 315–329. https://doi.org/10.1016/S0001-6918(01)00064-6 .

Coltheart, M. (1981). The MRC psycholinguistic database. *The Quarterly Journal of Experimental Psychology Section A*, *33*(4), 497–505. https://doi.org/10.1080/14640748108400805

Craik, F. I. M., & Rose, N. S. (2012). Memory encoding and aging: A neurocognitive perspective. *Neuroscience & Biobehavioral Reviews*, *36*(7), 1729–1739. https://doi.org/10.1016/j.neubiorev.2011.11.007

Davidson, P. S., & Glisky, E. L. (2002). Neuropsychological correlates of recollection and familiarity in normal aging. *Cognitive, Affective, & Behavioral Neuroscience*, *2* (2), 174–186. https://doi.org/10.3758/CABN.2.2.174 .

Deary, I. J., Johnson, W., & Starr, J. M. (2010). Are processing speed tasks biomarkers of cognitive aging? *Psychology and Aging*, *25*(1), 219–228. https://doi.org/10.1037/a0017750

Depue, B. E., Curran, T., & Banich, M. T. (2007). Prefrontal regions orchestrate suppression of emotional memories via a two-phase process. *Science*, *317*(5835), 215–219. https://doi.org/10.1126/science.1139560

Diana, R. A., Yonelinas, A. P., & Ranganath, C. (2007). Imaging recollection and familiarity in the medial temporal lobe: A three-component model. *Trends in Cognitive Sciences*, *11* (9), 379–386. https://doi.org/10.1016/j.tics.2007.08.001 .

Dulaney, C. L., Marks, W., & Link, K. E. (2004). Aging and directed forgetting: Pre-cue encoding and post-cue rehearsal effects. *Experimental Aging Research*, *30* (1), 95–112. https://doi.org/10.1080/03610730490251504 .

Earles, J. L., Kersten, A. W., Berlin Mas, B., & Miccio, D. M. (2004). Aging and memory for self-performed tasks: Effects of task difficulty and time pressure. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *59*(6), 285–293. https://doi.org/10.1093/geronb/59.6.p285

Evans, D. A., Hebert, L. E., Beckett, L. A., Scherr, P. A., Albert, M. S., Chown, M. J., Pilgrim, D. M., & Taylor, J. O. (1997). Education and other measures of socioeconomic status and risk of incident Alzheimer disease in a defined population of older persons. *Archives of Neurology*, *54*(11), 1399–1405. https://doi.org/10.1001/archneur.1997.00550230066019

Fawcett, J. M., & Taylor, T. L. (2008). Forgetting is effortful: Evidence from reaction time probes in an item-method directed forgetting task. *Memory & Cognition*, *36*(6), 1168–1181. https://doi.org/10.3758/MC.36.6.1168

Feyereisen, P., & Charlot, V. (2008). Are there uniform age-related changes across tasks involving inhibitory control through access, deletion, and restraint functions? A preliminary investigation. *Experimental Aging Research*, *34*(4), 392–418. https://doi.org/10.1080/03610730802271880

Finkel, D., Reynolds, C. A., McArdle, J. J., & Pedersen, N. L. (2007). Age changes in processing speed as a leading indicator of cognitive aging. *Psychology and Aging*, *22*(3), 558–568. https://doi.org/10.1037/0882-7974.22.3.558

Folstein, M. F. (1983). The Mini-Mental State Examination. *Archives of General Psychiatry*, *40* (7), 812. https://doi.org/10.1001/archpsyc.1983.01790060110016 .

Foster, C. M., & Giovanello, K. S. (2017). The effect of presentation rate on implicit sequence learning in aging. *Memory*, *25*(2), 187–200. https://doi.org/10.1080/09658211.2016.1148739

Foster, C. M., & Giovanello, K. S. (2020). Domain general processes moderate age-related performance differences on the mnemonic similarity task. *Memory*, *28*(4), 528–536. https://doi.org/10.1080/09658211.2020.1743321

Frankenmolen, N. L., Fasotti, L., Kessels, R. P. C., & Oosterman, J. M. (2018). The influence of cognitive reserve and age on the use of memory strategies. *Experimental Aging Research*, *44*(2), 117–134. https://doi.org/10.1080/0361073X.2017.1422472

Gallant, S. N., Pun, C., & Yang, L. (2018). Age differences in the neural correlates underlying control of emotional memory: An event-related potential study. *Brain Research*, *1697*, 83–92. https://doi.org/10.1016/j.brainres.2018.06.019

Gardiner, J. M., Gawlik, B., & Richardson-Klavehn, A. (1994). Maintenance rehearsal affects knowing, not remembering; elaborative rehearsal affects remembering, not knowing. *Psychonomic Bulletin & Review*, *1*(1), 107–110. https://doi.org/10.3758/BF03200764

Gilhooly, K. J., & Logie, R. H. (1980). Age-of-acquisition, imagery, concreteness, familiarity, and ambiguity measures for 1,944 words. *Behavior Research Methods & Instrumentation*, *12*(4), 195–427. https://doi.org/10.3758/BF03201693

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation* (Vol. 22, pp. 193–225). Academic Press.

Hasher, L., Quig, M. B., & May, C. P. (1997). Inhibitory control over no-longer-relevant information: Adult age differences. *Memory and Cognition*, *25* (3), 286–295. https://doi.org/10.3758/BF03211284 .

Hasher, L., Stoltzfus, E. R., Zacks, R. T., & Rypma, B. (1991). Age and inhibition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17* (1), 163–169. https://doi.org/10.1037/0278-7393.17.1.163 .

Hogge, M., Adam, S., & Collette, F. (2008). Directed forgetting and aging: The role of retrieval processes, processing speed, and proactive interference. *Aging, Neuropsychology, and Cognition*, *15*(4), 471–491. https://doi.org/10.1080/13825580701878065

Howard, M. W., Bessette-Symons, B., Zhang, Y., & Hoyer, W. J. (2006). Aging selectively impairs recollection in recognition memory for pictures: Evidence from modeling and receiver operating characteristic curves. *Psychology and Aging*, *21* (1), 96–106. https://doi.org/10.1037/0882-7974.21.1.96 .

Java, R. I. (1996). Effects of age on state of awareness following implicit and explicit word-association tasks. *Psychology and Aging*, *11* (1), 108–111. https://doi.org/10.1037/0882-7974.11.1.108 .

Jennings, J. M., & Jacoby, L. L. (1993). Automatic versus intentional uses of memory: Aging, attention, and control. *Psychology and Aging*, *8*(2), 283–293. https://doi.org/10.1037/0882-7974.8.2.283

Kučera, H., & Francis, W. N. (1967). *Computational analysis of present-day American English*. Brown University Press.

Lawo, V., Philipp, A. M., Schuch, S., & Koch, I. (2012). The role of task preparation and task inhibition in age-related task-switching deficits. *Psychology and Aging*, *27*(4), 1130. https://doi.org/10.1037/a0027455

Le Carret, N., Lafont, S., Letenneur, L., Dartigues, J.-F., Mayo, W., & Fabrigoule, C. (2003). The effect of education on cognitive performances and its implication for the constitution of the cognitive reserve. *Developmental Neuropsychology*, *23*(3), 317–337. https://doi.org/10.1207/S15326942DN2303_1

Lee, Y.-S., Lee, H.-M., & Tsai, S.-H.. (2007). Effects of post-cue interval on intentional forgetting. *British Journal of Psychology*, *98* (2), 257–272. https://doi.org/10.1348/000712606X120410 .

Levy, B. J., & Anderson, M. C. (2012). Purging of memories from conscious awareness tracked in the human brain. *The Journal of Neuroscience*, *32*(47), 16785–16794. https://doi.org/10.1523/JNEUROSCI.2640-12.2012

Lustig, C., Hasher, L., & Zacks, R. T. (2007). Inhibitory deficit theory: Recent developments in a "new view." In D. S. Gorfein & C. M. MacLeod (Eds.), *The place of inhibition in cognition* (pp. 145–162). American Psychological Association.

Mantyla, T. (1993). Knowing but not remembering: Adult age differences in recollective experience. *Memory & Cognition*, *21*(3), 379–388. https://doi.org/10.3758/BF03208271

Marevic, I., Arnold, N. R., & Rummel, J. (2018). Item-method directed forgetting and working memory capacity: A hierarchical multinomial modeling approach. *Quarterly Journal of Experimental Psychology*, *71*(5), 1070–1080. https://doi.org/10.1080/17470218.2017.1310270

Mejia, S., Pineda, D., Alvarez, L. M., & Ardila, A. (1998). Individual Differences in Memory Anid Executive Function Abilities During Normal Aging. *International Journal of Neuroscience*, *95*(3–4), 271–284. https://doi.org/10.3109/00207459809003345

Morse, C. K. (1993). Does variability increase with age? An archival study of cognitive measures. *Psychology and Aging*, *8* (2), 156–164. https://doi.org/10.1037/0882-7974.8.2.156 .

Mungas, D., Beckett, L., Harvey, D., Farias, S. T., Reed, B., Carmichael, O., Olichney, J., Miller, J., & DeCarli, C. (2010). Heterogeneity of cognitive trajectories in diverse older persons. *Psychology and Aging*, *25*(3), 606–619. https://doi.org/10.1037/a0019502

Nowicka, A., Marchewka, A., Jednorog, K., Tacikowski, P., & Brechmann, A. (2011). Forgetting of emotional information is hard: An fMRI study of directed forgetting. *Cerebral Cortex*, *21*(3), 539–549. https://doi.org/10.1093/cercor/bhq117

Opdebeeck, C., Martyr, A., & Clare, L. (2016). Cognitive reserve and cognitive function in healthy older people: A meta-analysis. *Aging, Neuropsychology, and Cognition*, *23*(1), 40–60. https://doi.org/10.1080/13825585.2015.1041450

Ostrosky-Solis, F., Jaime, R. M., & Ardila, A. (1998). Memory abilities during normal aging. *International Journal of Neuroscience*, *93*(1–2), 151–162. https://doi.org/10.3109/00207459808986420

Paller, K. A. (1990). Recall and stem-completion priming have different electrophysiological correlates and are modified differentially by directed forgetting. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16* (6), 1021–1032. https://doi.org/10.1037/0278-7393.16.6.1021 .

Park, D. C., & Bischof, G. N. (2013). The aging mind: Neuroplasticity in response to cognitive training. *Dialogues Clin Neurosci*, *15* (1), 109–119. https://www.ncbi.nlm.nih.gov/pubmed/23576894

Parkin, A. J., & Walter, B. M. (1992). Recollective experience, normal aging, and frontal dysfunction. *Psychology and Aging*, *7*(2), 290–298. https://doi.org/10.1037/0882-7974.7.2.290

Paxton, J. L., Barch, D. M., Racine, C. A., & Braver, T. S. (2008). Cognitive control, goal maintenance, and prefrontal function in healthy aging. *Cerebral Cortex*, *18*(5),1010–1028. Retrieved from <Go to ISI>://000254955100004. . https://doi.org/10.1093/cercor/bhm135

Paz-Caballero, M. D., Menor, J., & Jimenez, J. M. (2004). Predictive Validity of Event-related Potentials (Erps) in Relation to the Directed Forgetting, *Effects. Clinical Neurophysiology*, *115*(2), 369–377. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=14744579

Pichora-Fuller, M. K. (2003). Cognitive aging and auditory information processing. *International Journal of Audiology*, *42* (Suppl 2), 2S26–S32. Retrieved from http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=12918626

Rhodes, M. G., & Kelley, C. M. (2005). Executive processes, memory accuracy, and memory monitoring: An aging and individual difference analysis. *Journal of Memory & Language*, *52*(4), 578–594. https://doi.org/10.1016/j.jml.2005.01.014

Rizio, A. A., & Dennis, N. A. (2013). The neural correlates of cognitive control: Successful remembering and intentional forgetting. *Journal of Cognitive Neuroscience*, *25*(2), 297–312. https://doi.org/10.1162/jocn_a_00310

Rizio, A. A., Dennis, N. A., & Sathian, K.. (2014). The cognitive control of memory: Age differences in the neural correlates of successful remembering and intentional forgetting. *PLoS One*, *9*(1), e87010. https://doi.org/10.1371/journal.pone.0087010

Salthouse, T. A. (1994). The nature of the influence of speed on adult age differences in cognition. *Developmental Psychology*, *30*(2), 240. https://doi.org/10.1037/0012-1649.30.2.240

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103* (3), 403–428

Salthouse, T. A. (2016). Contributions of the Individual Differences Approach to Cognitive Aging. *J Gerontol B Psychol Sci Soc Sci*. https://doi.org/10.1093/geronb/gbw069

Salthouse, T. A., McGuthry, K. E., & Hambrick, D. Z. (1999). A framework for analyzing and interpreting differential aging patterns: Application to three measures of implicit learning. *Aging, Neuropsychology, & Cognition*, *6*(1), 1–18. https://doi.org/10.1076/anec.6.1.1.789

Salthouse, T. A., Toth, J., Daniels, K., Parks, C., Pak, R., Wolbrette, M., & Hocking, K. J. (2000). Effects of aging on efficiency of task switching in a variant of the Trail Making Test. *Neuropsychology*, *14* (1), 102–111. https://doi.org/10.1037/0894-4105.14.1.102 .

Scarmeas, N., & Stern, Y. (2004). Cognitive reserve: Implications for diagnosis and prevention of Alzheimer's disease. *Current Neurology and Neuroscience Reports*, *4*(5), 374–380. https://doi.org/10.1007/s11910-004-0084-7

Schaie, K. W. (1988). Variability in cognitive function in the elderly: Implications for societal participation. *Basic Life sciences*, *43*, 191–211. https://doi.org/10.1007/978-1-4684-5460-4_20

Schmand, B., Smit, J. H., Geerlings, M. I., & Lindeboom, J. (1997). The effects of intelligence and education on the development of dementia. A test of the brain reserve hypothesis. *Psychological Medicine*, *27*(6), 1337–1344. https://doi.org/10.1017/s0033291797005461

Sheikh, J. I., & Yesavage, J. A. (1986). Geriatric Depression Scale (GDS): Recent evidence and development of a shorter version. *Clinical Gerontologist: The Journal of Aging and Mental Health*, *5*(1-2), 165–173. https://doi.org/10.1300/J018v05n01_09 .

Spreen, O., & Schulz, R. W. (1966). Parameters of abstraction, meaningfulness, and pronunciability for 329 nouns. *Journal of Verbal Learning and Verbal Behavior*, *5*(5), 459–468. https://doi.org/10.1016/S0022-5371(66)80061-0

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/ .

Titz, C., & Verhaeghen, P. (2010). Aging and directed forgetting in episodic memory: A meta-analysis. *Psychology and Aging*, *25*(2), 405–411. https://doi.org/10.1037/a0017225

Troyer, A. K., Leach, L., & Strauss, E. (2006). Aging and response inhibition: Normative data for the Victoria Stroop Test. *Aging, Neuropsychology, and Cognition*, *13*(1), 20–35. https://doi.org/10.1080/138255890968187

Turner, G. R., & Spreng, R. N. (2012). Executive functions and neurocognitive aging: Dissociable patterns of brain activity. *Neurobiology of Aging*, *33*(4), 826 e821–813. https://doi.org/10.1016/j.neurobiolaging.2011.06.005

Ullsperger, M., Mecklinger, A., & Muller, U. (2000). An electrophysiological test of directed forgetting: The role of retrieval inhibition. *Journal of Cognitive Neuroscience*, *12* (6), 924–940. https://doi.org/10.1162/08989290051137477 .

Vance, D. E., Roberson, A. J., McGuinness, T. M., & Fazeli, P. L. (2010). How neuroplasticity and cognitive reserve protect cognitive functioning. *Journal of Psychosocial Nursing and Mental Health Services*, *48*(4), 23–30. https://doi.org/10.3928/02793695-20100302-01

Wechsler, D. (1997). *Wechsler Adult Intelligence Scale–Third Edition*. The Psychological Corporation.

West, R. (2000). In defense of the frontal lobe hypothesis of cognitive aging. *Journal of the International Neuropsychological Society*, *6*(6), 727–729. discussion 730. https://doi.org/10.1017/S1355617700666109

Whalley, L. J., Deary, I. J., Appleton, C. L., & Starr, J. M. (2004). Cognitive reserve and the neurobiology of cognitive aging. *Ageing Research Reviews*, *3*(4), 369–382. https://doi.org/10.1016/j.arr.2004.05.001

Wylie, G. R., Foxe, J. J., & Taylor, T. L. (2008). Forgetting as an active process: An FMRI investigation of item-method-directed forgetting. *Cerebral Cortex*, *18* (3), 670–682. https://doi.org/10.1093/cercor/bhm101 .

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Memory and Language*, *46*(3), 441–517. https://doi.org/10.1006/jmla.2002.2864 .

Yonelinas, A. P. (2005). Separating the brain regions involved in recollection and familiarity in recognition memory. *Journal of Neuroscience*, *25* (11), 3002–3008. https://doi.org/10.1523/JNEUROSCI.5295-04.2005 .

Yonelinas, A. P., & Jacoby, L. L. (1995). Dissociating automatic and controlled processes in a memory-search task: Beyond implicit memory. *Psychological Research*, *57* (3–4), 156–165. https://doi.org/10.1007/BF00431277 .

Zacks, R. T., & Hasher, L. (1994). Directed ignoring: Inhibitory regulation of working memory. In D. D. T. H. Carr (Ed.), *Inhibitory mechanisms in attention, memory, and language*. Academic Press, (pp. 241–264).

Zacks, R. T., Hasher, L., & Li, K. Z. H. (2000). Human memory. In F. I. M. Craik & T. A. Salthouse (Eds.), *The Handbook of Aging and Cognition* (second ed., pp. 293–358). Lawrence Erlbaum Associates..

Zacks, R. T., Radvansky, G., & Hasher, L. (1996). Studies of directed forgetting in older adults. *Journal of Experimental Psycholology: Learning, Memory, & Cognition*, *22* (1), 143–156. Retrieved from http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=8648283