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A Dual Mechanisms of Control Account of Age Differences in Working Memory

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Age-related differences in working memory (WM) can be large, but the exact sources are unclear. We hypothesized that young adults outperform older adults on WM tasks because they use controlled attention processes to prioritize the maintenance of relevant information in WM in a proactive mode, whereas older adults tend to rely on the strength of familiarity signals to make memory decisions in a reactive mode. We used a WM task that cued participants to prioritize one item over others and presented repeated lure probes that cause errors when one is engaged in a reactive mode. Results showed that, relative to young adults with full attention available to use proactive control during the delays, older adults with full attention (and young adults with divided attention) during the delays had exaggerated error rates to repeated lure probes compared to control probes. When the amount of proactive interference was increased (by repeating stimuli across trials), older adults were able to engage in proactive control, and this eliminated their exaggerated error rate (while young adults with divided attention could not). These results provide evidence for a dual mechanisms of control account of age differences in WM.

Public Significance Statement
Age-related differences in working memory (WM) underlie various aspects of older adults' cognitive functioning. This study shows that age-related differences are largely due to older adults' difficulties with focusing attention on relevant information and resisting interference from irrelevant information. Older adults made memory decisions in a reactive-mode by responding based on whether a stimulus seemed familiar; however, with practice and feedback, they shifted to using a proactive mode by maintaining their focus on the to-be-remembered items, and this eliminated their age difference. This study helps to explain age differences in WM and identifies cognitive training targets to improve older adults' cognition.

Keywords: working memory, attention, proactive, reactive, aging

Supplemental materials: https://doi.org/10.1037/pag0000817.supp

Working memory (WM) is a central cognitive function that typically declines with age and broadly contributes to cognitive deficits (Bopp & Verhaeghen, 2005; Brockmole & Logie, 2013; Hale et al., 2011; Park, 2000). The source of this age-related decline remains unclear. Past studies suggest that a variety of factors cause deficient WM in older adults, including deficiencies with perception, processing speed, controlled attention, interference resolution, inhibitory control, long-term memory (LTM), and metacognition (Bowles & Salthouse, 2003; Emery et al., 2008; Gazzaley et al., 2007; Jarjat et al., 2019; Lustig et al., 2001, 2007; Lustig & Jantz, 2015; Pichora-Fuller, 2006; Salthouse, 1996; Siegel & Castel, 2019; Wilson et al., 2012). The present study focused on the role of controlled attention in age-related differences in WM.

Here we propose that a prominent theory from the cognitive control literature can account for patterns of age differences in WM. The dual mechanisms of control (DMC) framework posits

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This study's design, hypotheses, and analytic plan were preregistered; all stimuli, experiment, and analysis scripts and deidentified data have been made publicly available and can be accessed at https://osf.io/ztqx8/. The data and results appearing in this article were previously presented at the 2022 Working Memory Symposium and the 2022 and 2023 meetings of the Psychonomic Society.

Chenlingxi Xu and Chang-Mao Chao contributed equally.

Chenlingxi Xu played a lead role in formal analysis and writing–original draft and an equal role in conceptualization, investigation, methodology, and software. Chang-Mao Chao played a supporting role in conceptualization, methodology, and writing–review and editing and an equal role in investigation and software. Nathan S. Rose played a lead role in conceptualization, funding acquisition, project administration, and supervision and an equal role in methodology and writing–review and editing.

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that cognitive control operates via two distinct operating modes: proactive and reactive control (Braver, 2012). In the context of WM, proactive control refers to the anticipatory prioritization of maintenance of the information that is deemed to be most relevant for ongoing cognition; in contrast, reactive control involves more passive maintenance of information and a reliance on the strength of familiarity signals to make memory decisions. In the present study, we examined how potential age differences in the engagement of these two modes of cognitive control might explain age-related differences in WM. We used a task with "retrocues" that directed participants' attention to prioritize maintenance of the item that will be tested first or second on each trial, similar to some recent studies (Jarjat et al., 2019; Loaiza & Souza, 2018, 2019).

Typical retrocue tasks show participants an array of to-be-remembered items followed by a retrocue, that is, a cue indicating the location or feature of the to-be-tested item. Participants should guide their attention to the retrocued item and prioritize its maintenance, and doing so usually benefits memory accuracy or response time (RT) compared to uncued items (Lepsien & Nobre, 2006; Myers et al., 2017; Souza & Oberauer, 2016; Verhaeghen & Basak, 2005; Wallis et al., 2015). If older adults have deficient attention-control processes, they should not show retrocue benefits. However, the literature is mixed. Some studies with single-retrocue tasks showed that older adults showed similar retrocue benefits as younger adults (Gilchrist et al., 2016; Loaiza & Souza, 2018, 2019; Mok et al., 2016; Souza, 2016; Yi & Friedman, 2014), while others revealed an age-related deficit in retrocue benefits (Duarte et al., 2013; Loaiza & Souza, 2019; Newsome et al., 2015). Of those studies that showed similar retrocue benefits for older and younger adults, Loaiza and Souza (2018, 2019) and Souza (2016) employed a single-retrocue WM task with a memory array of colored circles, while Mok et al. (2016) used a similar task with oriented lines. In these studies, participants were asked to precisely recall the retrocued feature. Gilchrist et al. (2016) used a single-retrocue WM task involving a memory array of five colored shapes (which exceeds most older adults' visual WM capacity), drawn from a limited pool of three colors and shapes that are highly overlapping across trials. Similarly, Yi and Friedman (2014) used a closed set of number stimuli (1–9) as memoranda; thus, proactive interference (PI) was high. Of the two studies that found age-related deficits in retrocue benefits (Duarte et al., 2013; Newsome et al., 2015), both used single-retrocue WM tasks that required participants to remember and make recognition decisions about the color of a probed item from arrays of 2, 3, or 4 (Duarte et al., 2013) or 1–6 (Newsome et al., 2015) items. Double-retrocue tasks are even more informative because they also measure the ability to switch attention between items and reactivate initially uncued items (Lewis-Peacock et al., 2012; Rose et al., 2016; Souza & Oberauer, 2017). To date, only one study has examined age differences in double-retrocue tasks, and it found preserved retrocue benefits (Loaiza & Souza, 2018). The variation in study designs prompts an inquiry into which factors influence whether older adults can or cannot benefit from retrocues.

A theoretical account of the source of this variability has not been advanced, until now. We propose that the DMC framework can explain the mixed results (Braver et al., 2007). In the context of a delayed recognition task, reactive responses may be determined by relying on the strength of the familiarity signal triggered by the presentation of an old or new/lure probe (Samrani et al., 2017). Jonides et al. (2000) presented a list of four letters (e.g., G, F, R, M) and an old or new/lure probe (e.g., d) after a 3,000-ms delay on each trial. Repeated recent-negative lures that were an old to-be-remembered item from a previous list (e.g., M, R, K, D) were difficult to reject presumably due to the strong familiarity signal that they evoked (Braver et al., 2007; Jonides & Nee, 2006). Older adults (and younger adults with lower WM capacity) failed to reject such repeated lures compared to young adults with higher WM capacity, suggesting that they were likely responding in a reactive mode (Braver et al., 2007).

Previous research on a variety of cognitive control tasks has shown that older adults and children prefer a reactive over proactive mode of control, and this explains their deficiencies relative to young adults (Barch et al., 2001; Braver et al., 2001; Chatham et al., 2009; for review, see Braver & West, 2011). For example, patterns of RTs in different trial types can reveal both costs and benefits of using a proactive or reactive mode of control (Braver et al., 2007; Bugg, 2014; Paxton et al., 2006).

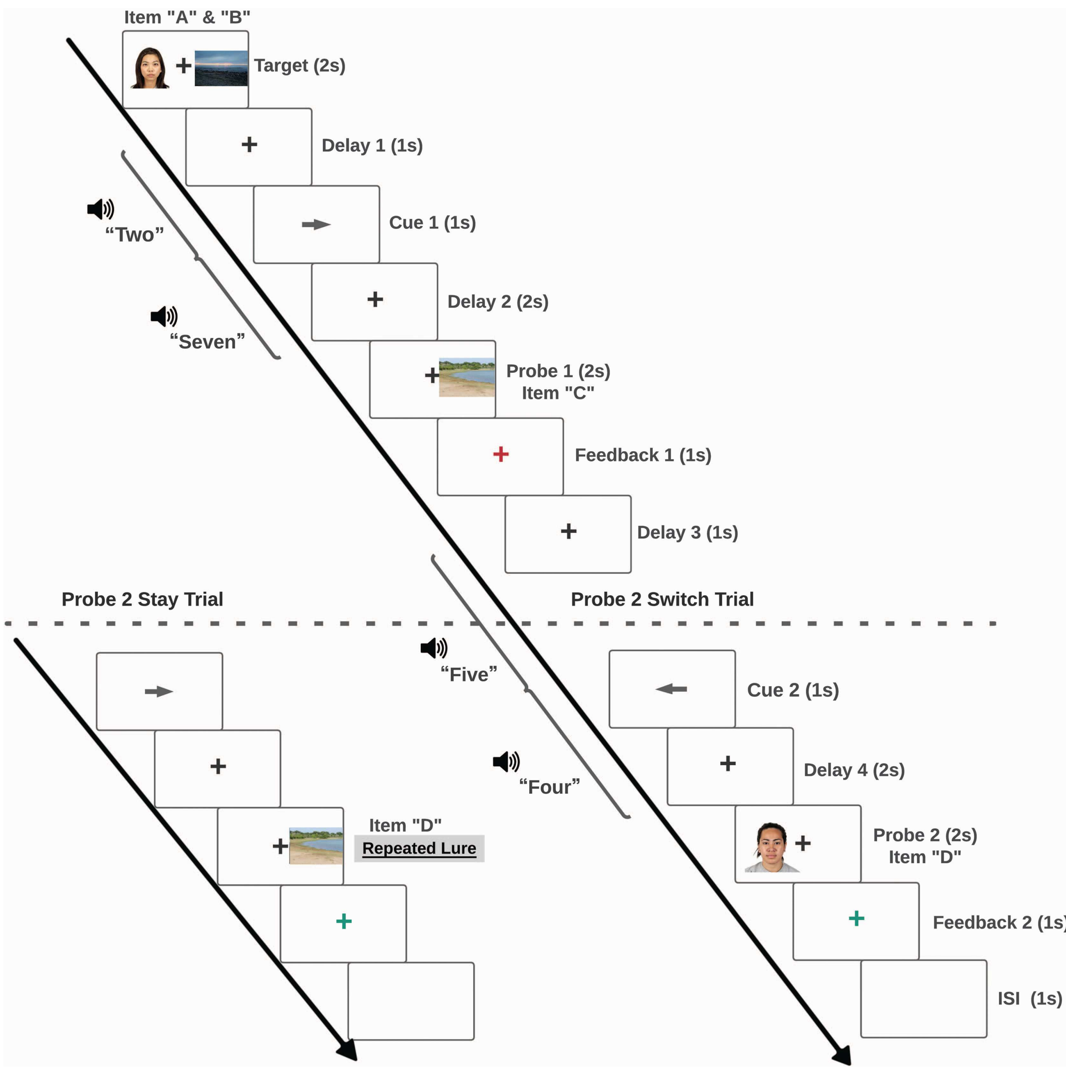
In WM tasks, the extent to which one engages in proactive control likely depends on both the amount of PI (Plancher et al., 2017) and whether feedback is provided. For example, Loosli et al. (2014) tested young ($M = 9$ years) and older ($M = 13.1$ years) children and young ($M = 23.7$ years) and older ($M = 69.9$ years) adults on both a WM task with repeated lure probes similar to Jonides et al. (2000) and an n-back WM updating task, but feedback was not provided. On both tasks, the to-be-remembered stimuli and lures were repeated across trials, so the amount of PI was high. Therefore, proactive control should have been engaged. However, older adults and children had a harder time rejecting the proactively interfering, repeated-lure probes compared to young adults. This could be because feedback was not provided (see also Gonthier et al., 2019). Previous studies found that feedback can modulate WM performance by providing either motivation for improving performance or support for potentially deficient source monitoring or metacognitive processes (K. C. Adam & Vogel, 2016, 2018; Braver, 2012; Yee & Braver, 2018). It is unclear if older adults (or children) knew that "old" responses to repeated lures were errors. Alternatively, even if participants were aware that endorsing repeated lures was erroneous, it may not have been possible for them to sufficiently engage in proactive control to override their strong familiarity signals. That is, did deficient controlled-attention processes render older adults (and children) incapable of engaging in proactive control, or did they prefer to rely on a reactive, familiarity-based mode of responding?

To test the DMC account of age differences in WM, in two preregistered experiments, we administered double-retrocue tasks with feedback and low or high PI to older adults and young adults with either full (Low-PI Experiment A) or divided attention (DA, Low-PI Experiment B).[1] In these Low-PI Experiments, the only stimuli that were repeated were lure probes presented within the same trial, so the amount of PI across trials was low. Therefore,

[1] The Low-PI Experiment A was first preregistered on OSF in February 2021. Following this, we collected and analyzed the data. To elucidate the source of the age-related difference, we proceeded with the Low-PI Experiment B. In October 2021, we updated our preregistration to incorporate results from both Low-PI Experiments A and B and concurrently preregistered our plan for the High-PI Experiment. Note that the initial preregistration also included subsequent long-term memory (LTM) assessments following the Low-PI Experiments to address separate questions about the role of LTM in WM. A separate paper on this topic is published (https://doi.org/10.1177/17470218231217723).

relying on a reactive, familiarity-based mode of responding would result in correct responses on most trials. The exception was on trials with repeated lures. See the task diagram in Figure 1, which includes examples of a trial with a repeated-lure probe and a "switch" trial. Switch trials allow the assessment of cost (in terms of accuracy or RT differences relative to Probe 1 or Probe 2 stay trials) of switching attention away from, and then back to, the initially uncued item (i.e., reactivating it later on in the trial). Therefore, these trials help gauge the extent to which participants used the retrocues to prioritize maintenance of the cued item in focal attention. In the High-PI Experiment, all stimuli were repeatedly presented as both targets and lures across trials, so PI was high, especially on trials with lure probes that were repeated within the same trial.

Figure 1
Examples of the Working Memory Task Procedure



Note. Participants encoded and maintained both items (A and B) during delay 1; then the first arrow (Cue 1) pointed to the side of the screen on which the item that would be tested first was presented, so participants were to prioritize maintenance of that item to prepare for Probe 1. In this example Probe 1 (Item C) is a nonmatch of the tested item (Item B). After the participant responded, feedback was provided, and a 1-s interstimulus interval, a second arrow (Cue 2) pointed to the item that would be tested second. Probe 2 stay trials (left) are when the same item (B) was probed both times. In this example, Probe 2 (Item D) is the same nonmatch probe as Probe 1, so it is a repeated lure that is particularly difficult to reject; Probe 2 switch trials (right) are when different items were probed each time, so these trials measure the extent to which participants used the retrocues to prioritize maintenance of the cued item. Note that the cue and probe conditions were pseudorandomly determined to be equally probable and balanced within each block, and the cues were always 100% valid. Permissions Creative Commons Attribution 4.0 (CC BY 4.0) license: Personal photographs of individuals used with reuse permission from Chicago Face Database (Ma et al., 2015); Landscape photos used with reuse permission from Places365 Database (Zhou et al., 2018). ISI = interstimulus interval.

For the reasons reviewed above, the primary measures of interest for this study are the error rates for lures repeated within the same trial compared to control/baseline error rates for lures that were either never repeated (Low-PI Experiment) or were repeated between trials (High-PI Experiment). This is analogous to the comparison between error rates for recent negative and nonrecent negative probes on the recent probe task (Jonides & Nee, 2006).

Primary Preregistered Hypotheses

Our primary preregistered hypotheses predicted that there would be different effects of performing the tasks in a reactive versus proactive mode on these error rates. When participants were in a reactive mode, we hypothesized that there would be exaggerated error rates for within-trial repeated lures compared to the control/baseline lures. Because feedback was provided, participants should have realized that responding in a reactive mode produces errors on trials with lures repeated within the same trial. Therefore, this should have encouraged participants to use the retrocues to proactively prioritize maintenance of cued over uncued items, which should reduce errors to repeated lures. When participants performed the task in this proactive mode, we hypothesized that there would be no difference in error rates for the within-trial repeated lures compared to the control/baseline lures.

To further test the hypothesis that age-related differences in WM are due to older adults' reduced use of proactive control during WM delay periods, we compared young and older adults' performance with full attention (FA) during the delay and cueing periods to a group of young adults with divided attention (DA) during these periods. Young adults performed a DA task during the delay and cueing periods to disrupt their ability to select and maintain the cued items in focal attention. The logic of this manipulation was to assess the extent to which disrupting young adults' attention caused their performance to approximate that of older adults (Castel & Craik, 2003). If it did, it would support the hypothesis that older adults' deficiencies were due to reduced attentional resources (Craik & Byrd, 1982).[2]

We predicted that, if the source of age-related differences in WM is because of older adults' difficulties with using control processes to focus their attention on the cued item and prioritize its maintenance over an uncued item, then young adults, whose attention was preoccupied by the DA task, should perform the task similar to older adults with FA. Specifically, we predicted that young adults with DA would have difficulties prioritizing the cued over uncued item, so they would rely on a reactive, familiarity-based mode of responding to make their recognition decisions and, therefore, show an exaggerated error rate for the within-trial repeated lures compared to the control/baseline lures.

Additional Preregistered Hypotheses

Three additional preregistered hypotheses about standard effects that should be observed predicted that there would be:

1. a retrocue effect, that is, switching attention away from an uncued item and then reactivating it following a second retrocue should show a cost, evidenced by worse accuracy on Probe 2 switch relative to Probe 1 and Probe 2 stay trials,
2. an age difference in the retrocue effect, that is, if older adults have deficiencies with either controlling attention to cued over uncued items or recovering initially uncued items, then their retrocue cost should be larger than young adults, evidenced by an Age $\times$ Probe Type interaction, due to worse accuracy on Probe 2 switch relative to Probe 1 trials for older adults compared to young adults with FA, and
3. a testing effect, that is, better memory for Probe 2 stay compared to Probe 1 trials because Probe 2 stay trials tested the same item twice with feedback.

The retrocue and testing effect analyses were important because they both provide insight into the nature of age differences in performance (the extent to which older adults used retrocues like young adults) and allow for comparison to previous retrocue studies. If young and older adults used different modes of cognitive control, then age differences in those effects should be observed.

Low-PI Experiments A and B

Method

Transparency and Openness

This study's design, hypotheses, and analytic plan were preregistered; the links to the stimuli, experiment, and analysis scripts and deidentified data for this study are accessible at https://osf.io/ztqx8/.

Participants

An a priori power analysis using G*power (Faul et al., 2007) indicated group minimums of $n = 27$ (power = .95, $\alpha = .05$) to attain an effect size as large as the age effect ($d = 1$) reported by Newsome et al. (2015). However, because many previous studies showed no interaction between retrocueing and age (i.e., Gilchrist et al., 2016; Loaiza & Souza, 2018, 2019; Yi & Friedman, 2014), we tested more participants to ensure that any failure to detect an effect would not be due to having insufficient power from undersampling and in case participants' data needed to be excluded for any reason (e.g., failure to follow instructions, poor accuracy on the DA task). All participants had normal or corrected-to-normal vision and hearing, could discriminate between the green and red feedback colors, and used English as their primary language for at least 15 years. In addition, all participants were screened for neurocognitive dysfunction using the modified Telephone Interview for Cognitive Status (TICS) with a cutoff = 34 (Knopman, 2018). Both the young FA and DA groups scored significantly higher than the older adult group on the TICS, $t(55) = 2.82$, $p = .007$ and $t(54) = 2.96$, $p = .004$, respectively. Sample characteristics are detailed in Table 1.

Participants were compensated with extra course credit or a gift card ($15 per hour) for their participation. The study was approved by the University of Notre Dame's Institutional Review Board (Title: Rehearsal vs. Refreshing and its Effects on Memory, Protocol No. 18-01-4,374).

[2] While definitions of reduced cognitive resources may be unclear, time is presumed to be the critical resource that is reduced by aging because older adults have slower rates of information processing; therefore, they have less time to complete cognitive operations than young adults within the same period of time.

Table 1
Summary of Participant Sample Characteristics for the Low-PI Experiment A and B

Statistic	Low-PI Experiment A		Low-PI Experiment B
	Young adult FA	Older adult FA	Young adult DA
N recruited	30	30	30
N included in analysis	30	27	29
N in-person/virtual testing	10/20	12/18	20/10
N female/male	23/7	16/11	23/6
Mean age (Minimum~Maximum; *SD*)	19.87 (18~21; 1.19)	71.92 (64~81; 3.97)	20.10 (18~24; 1.37)
Mean TICS (*SD*)	40.47 (3.22)	38.15 (2.94)	40.48 (2.95)
Racial composition	50% Caucasian, 17% Hispanic/Latino/ Spanish, 20% multiracial, 7% Asian, 3% American Indian/Alaska Native, 3% Middle Eastern/North African	100% Caucasian	66% Caucasian, 10% Asian, 10% Black/African American, 10% multiracial, 3% Hispanic/Latino/ Spanish

Note. All data were collected in 2021. Participants were recruited from the University of Notre Dame or surrounding community in South Bend, IN, United States, or via Prolific for virtual testing. PI = proactive interference; FA = full attention; DA = divided attention; TICS = Telephone Interview for Cognitive Status.

Materials and Procedure

The Low-PI Experiment used a double-retrocue WM task (Figure 1) programmed with PsychoPy (Peirce et al., 2019). Participants either performed the experiment in person or online (Table 1).[3]

Participants completed a practice block of 12 trials, which were drawn from a different set of stimuli from the actual experiment. The WM task had two blocks of 24 trials each. At the beginning of each trial, participants were instructed to fixate on the central-fixation cross. Two pictures from distinct categories (face, name, or scene[4]) were displayed for 2 s, one to the left of central fixation and the other to the right.[5] Then, a left- or right-pointing arrow appeared at central fixation, indicating which item would be tested first. Participants were instructed to focus their attention on this cued item and prioritize its maintenance; they were also told not to forget the other (uncued) item because 50% of the time that item would be tested second. Then, following a 2-s delay, a probe stimulus was presented; it was either an exact match or a mismatch (an image of a novel item from the same category). Participants were to press either "1" with their left middle finger if the cued item and probe matched or "2" with their left index finger if they did not match, as quickly and as accurately as possible within a 2-s response window.[6] The central-fixation cross either turned green if correct or red if incorrect. Then, to direct participants to the item that would be tested next, another arrow appeared. Participants were told to shift their focus of attention to this item and that the uncued item was no longer relevant to the trial. Following a 2-s delay, participants saw a second probe and indicated whether or not the probe matched the initially presented cued item. The cued location and stimulus category were fully counterbalanced across the experimental trials.

In the Low-PI Experiment B, young adults performed the WM task with DA during the delays.[7] For the DA task, participants listened to a random series of digits (1–9) presented through headphones at a comfortable listening level. They were told to press the "o" key (using their right index finger) for odd digits and the "p" key (using their right middle finger) for even digits without sacrificing speed or accuracy for one task over the other. Note that DA was not required during the stimulus presentation or probe periods so that the effects of disrupting attentional selection and maintenance processes could be assessed independently from any effects on encoding and retrieval processes.

The speed at which the odd–even digit-parity task was to be performed was titrated for each individual during pretesting by adjusting the response window with a one-up, three-down staircase procedure. To start, participants had to respond within 1 s of the auditorily presented digit. Each response was followed by a tone indicating whether it was correct (800 Hz tone) or incorrect (400 Hz tone). Following three consecutive correct responses, the response window was shortened by 20%. Following one incorrect response, the response window was increased by 25%. This proceeded for 10 up/down reversals. The presentation rate for the DA task was the participant's mean RT of their final three reversals plus two standard deviations.[8]

[3] Details of online testing sessions and COVID-19 compliance are described by Chao et al. (2023). A control analysis was conducted to examine the interaction between testing conditions (online vs. offline) and probe type within each age group. For each group, there were no interactions between probe type and location of testing (see Supplemental Material).

[4] The face stimuli were selected from the Chicago Face Database (Ma et al., 2015). All faces were adults with neutral expressions and were balanced for race (White, Black, Latin, Asian) and gender (male and female). Scene stimuli that were unlikely to be identifiable by participants were obtained from the Places365 database (Zhou et al., 2018). The name stimuli were selected from the U.S. First Names Database of common, easily pronounceable names for our American, English-speaking participants.

[5] Note that, for the purposes of a separate report focused on subsequent long-term memory for these items, the participants' subsequent long-term memory for these items, their location, and their associated pair were also tested later on in the session (for details, see Chao et al., 2023).

[6] All participants were asked to respond 1 for match and 2 for nonmatch to help them remember the response mapping. Participants used their left hand to make responses because we could not ensure that all participants (especially the online participants in the Low-PI Experiment) would have a T9 keyboard to make responses. Moreover, as discussed below, participants in the divided attention condition used their right hand for the odd/even digit task.

[7] Data for the Low-PI Experiment A were collected first, in accordance with the preregistered plan. To elucidate the source of age differences found in the Low-PI Experiment A and assess the role of controlled attention during the delays, the Low-PI Experiment B with the divided attention condition was then conducted.

[8] Note that during the WM test, the number of digits presented during the delays depended on this presentation rate. If the titrated presentation rate was over 1.2 s, two digits were presented during the delay periods (n = 28); otherwise, three digits were presented (n = 2). Control analyses were conducted to confirm that the pattern of results did not differ if the participants with three digits were excluded (see Supplemental Material).

Data Analysis

The young and older FA groups were compared first, consistent with the preregistration. Then, to address potential ceiling and floor effects, and to test the hypothesized source of age-related differences, the young DA group was added to compare to the older FA group. The young DA and young FA groups were also compared to assess the extent to which dividing young adults' attention during the delays caused performance to differ.[9] These groups were compared with two-way mixed analyses of variance (ANOVAs); these ANOVAs had group as a between-subjects factor and within-subjects factors to compare the effect of trial type (Probe 1,[10] Probe 2 stay, and Probe 2 switch) on accuracy, as well as the effect of lure type (repeated lures vs. nonrepeated lures) on error rates.[11] Simple tests of main effects and post hoc *t* tests were performed to elucidate interactions or test our a priori preregistered hypotheses. To protect against the potentially inflated Type I error rate due to multiple comparisons, Bonferroni corrections were used unless otherwise stated.

Bayesian analysis of variance and Bayesian *t* tests were conducted with the BayesFactor package (Morey et al., 2015) in R (R Core Team, 2021) to supplement the frequentist analyses. Bayes factors (BFs) were computed to assess the strength of evidence for the null versus alternative hypothesis using the default, weakly informative prior (Rouder et al., 2012). BFs less than 3 and greater than 3 and 10 were considered to be ambiguous, substantial, or strong evidence, respectively (Lee & Wagenmakers, 2014).[12] Unless specified, the BFs generally aligned with the frequentist analyses.

Data Exclusion Criteria

Video of the experiment sessions was recorded to monitor the participants' level of arousal, eye blinks, and movements during the stimulus, cue, and probe presentation periods of the task and also to see if any interruptions or excessively long pauses impacted data collection. No data were excluded based on these criteria. The recorded experimental sessions were also examined to ensure the participants understood and followed the instructions (e.g., they did not reverse the mapping of the response buttons). Three participants from the older adult group in the Low-PI Experiment were excluded because their average WM accuracy in a condition was <55%, and, upon review of the recorded session, it was apparent that they did not understand or follow the instructions. Additionally, if a participant's average accuracy was <70% on the secondary odd–even digit task, suggesting they had sacrificed their DA task performance, the WM data were excluded from the analyses. One participant was excluded due to low accuracy on the DA task.

Results

Primary Preregistered Hypothesis: Repeated Versus Nonrepeated Lures

Low-PI Experiment A: Young FA Versus Older FA. The average performance on the WM task in the Low-PI Experiment for each lure type is shown in Figure 2(A). Omnibus ANOVA results and follow-up *t* tests are summarized in Tables 2 and 3, respectively. The ANOVA comparing the young FA and older FA groups showed a main effect of group, but no main effect of lure type; the interaction between the two factors was not significant. Planned *t* tests showed that the older FA group's error rate for repeated lures was higher than the young FA group, while their error rate for the nonrepeated (control/baseline) lures was not different from the young FA group.[13] That is, older adults were more likely than young adults to erroneously endorse repeated lures as old items, suggesting that older adults relied more on the strength of a familiarity signal than young adults to make their recognition decisions.[14] To clarify the source of age differences and the role of controlled attention during the delays, these results were compared to those of the young adult group with DA during the delays in Experiment B.

Low-PI Experiment B: Older FA Versus Young DA. The ANOVA comparing the older FA and young DA groups showed no significant main effect of group or lure type and no significant interaction. These results indicated that the young DA group showed a similar exaggerated error rate on repeated lures as the older FA group. Additionally, ANOVAs comparing the young FA and young DA groups showed significant main effects of lure type and group, with a significant interaction. Follow-up *t* tests showed a group difference (young FA vs. young DA) on repeated lures, but not on nonrepeated lures. These results suggested that the DA task during the delay likely caused young adults to show an exaggerated error rate.

Additional Preregistered Hypotheses

Additional Hypothesis 1: Retrocue Effects. The average accuracy on the WM task for each probe type is shown in Figure 2(B). Omnibus ANOVA results are summarized in Table 4. ANOVA comparing the young FA and older FA groups showed significant main effects of group and probe type with a significant interaction. *T* tests showed that the older FA group performed worse on Probe 2 switch trials than they did on Probe 1 trials (Table 5). In

[9] We also conducted 2 two-way mixed ANOVAs with all three groups (young FA, older FA, and young DA) as a between-subjects factor and trial type (Probe 1, Probe 2 stay, and Probe 2 switch) as a within-subjects factor to compare the effects on accuracy and lure-type (repeated lures and nonrepeated lures). The conclusions based on these results were the same as the ones reported in the manuscript that compare each pair of groups (young FA vs. older FA, according to the preregistered data analysis plan, as well as young FA vs. young DA, and older FA vs. young DA, for completeness).

[10] It was unnecessary to distinguish between stay and switch trials for Probe 1 responses because, at this point in the trial, participants did not know which item would be cued and tested later on Probe 2, and stay and switch trials were equally probable.

[11] The same analyses were also conducted on the RT data. These results generally aligned with the findings from the accuracy data; detailed RT results are reported in the Supplemental Material.

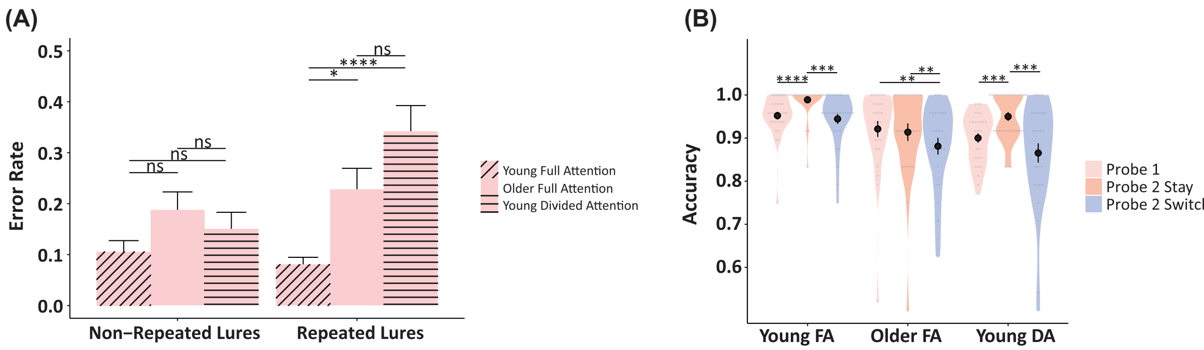
[12] Note that when BF values are lower than 1, it suggests evidence was found supporting the null hypothesis (i.e., BF_{01}). To facilitate understanding and to have the values in a comparable scale for the evidence favoring the null vs. alternative, those BF values were reported in its inverse form ($1/BF_{01}$).

[13] Note that results from these a priori planned *t* tests diverged from the interaction effect perhaps due to insufficient power to detect a subtle or variable interaction effect. Experiment 2 provides a well-powered replication and extension of these analyses.

[14] To rule out a floor effect, one-sample *t* tests comparing error rates to 0 were conducted. Results demonstrated that error rates were significantly above zero for both lure types across both the young and older FA groups ($t >$ 4.31, $p < .001$) and also for the young DA group [see Exp. 1B; $t(28) = 4.31$, $p = .002$].

Figure 2

Low-Proactive Interference Experiments A and B: Mean WM Error Rates on Trials With Nonrepeated and Repeated Lures (A) and Accuracy on Probe 1, Probe 2 Stay, and Probe 2 Switch Trials for the Young FA, Older FA, and Young DA Groups (B)



Note. WM = working memory; FA = full attention; DA = divided attention; ns = not significant; error bars = standard error of mean. * $p < .05$. ** $p < .01$. *** $p < .001$. **** $p < .0001$, ns means nonsignificant ($p > .05$).

contrast, the young FA group did not show a difference in accuracy between Probe 1 and Probe 2 switch trials.

The ANOVA comparing the young DA and young FA groups showed the main effects of both probe type and group, and no significant probe type by group interaction, suggesting that the DA task caused the young adults to perform worse overall. The probe type by group interaction was not significant. The young DA group's performance on Probe 1 trials was not significantly different from Probe 2 switch trials, indicating no difference in retrocue effects between the young DA and FA groups.[15]

The ANOVA on WM accuracy comparing the young DA and older FA groups showed a significant main effect of probe type, but not group, suggesting that the young DA group did not differ from the older FA group overall. The probe type by group interaction was ambiguous. Follow-up *t* tests did not show substantial evidence that the young DA group outperformed the older FA group on any probe type (Table 6).

Additional Hypothesis 2: Age Difference in the Retrocue Effect. Both the ANOVAs (older FA vs. young FA, older FA vs. young DA) on WM accuracy showed a significant group by probe-type interaction. Older adults showed a cost for switching attention away from an uncued item, while both young adult groups did not. This suggests an age-related difference in the retrocue effect.

Additional Hypothesis 3: Testing Effect. Consistent with the hypothesized testing effect, the young FA group's accuracy improved on Probe 2 stay trials compared to Probe 1, likely due to being tested on the same item twice with feedback on Probe 2 stay trials; meanwhile, the older FA group did not benefit from this repeated testing with feedback.[16] The young DA group also showed a testing effect. This suggested that, despite having lower overall performance than the young FA group, the young DA group was still able to both use the retrocues to prioritize the cued item over the uncued item and utilize the feedback from Probe 1 to improve performance on Probe 2 stay trials.

Discussion

Older adults erroneously endorsed repeated lures as old items compared to nonrepeated lures more frequently than young adults with FA. According to our primary hypothesis, this suggested that older adults relied more on the strength of a familiarity signal than young adults to make recognition decisions on this WM task. Additionally, the accuracy data suggested that the groups used the retrocues, but in different ways; older adults showed a cost on Probe 2 switch trials. Moreover, both young adult groups showed testing effects, evidenced by higher accuracy on Probe 2 stay trials than Probe 1 trials, whereas older adults did not. Thus, there were age differences in repeated lure error rates, retrocue, and testing effects.

To clarify if the age differences in the Low-PI Experiment 1A were because the young FA group employed more proactive control to focus attention on the cued item during the delay periods, Experiment B was conducted. Experiment B compared the results of the young and older FA groups to a group of young adults with DA during the delay. This assessed if the DA task would make young adults' performance look like that of the older adults with FA, particularly for errors to repeated versus nonrepeated lures. Findings revealed that dividing young adults' attention during the cueing and maintenance periods resulted in exaggerated error rates similar to the older adults. This suggested that, when their attention during these periods was disrupted, young adults also relied on familiarity signals to make their recognition decisions. Repeating the lure probe within the same trial likely evoked such a strong familiarity signal upon its second presentation that it was difficult for both the older FA and young DA groups to reject it as a nonmatch of the cued, target item.

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[15] Note that the young DA group's performance was also worse on Probe 2 switch than Probe 2 stay trials, $p(29) = 4.26$, $p < .001$, $BF_{10} = 5.50$. Consistent with our preregistered Hypothesis 3, this was likely due to a testing effect. We elaborate on this in Hypothesis 3.

[16] Potential ceiling effects could complicate interpretation of age-related differences. To test for possible ceiling effects, one-sample *t* tests comparing accuracy for each trial type to 1.0 were conducted for each group. Accuracy was significantly off the ceiling for every condition and group ($t > 3.82$, $p < .001$), except for the Probe 2 stay condition for the young FA group, $t(29) = 0.68$, $p = .103$. Therefore, the age-related difference on Probe 2 stay trials (i.e., the testing effect) may be underestimated. Addressing this was one motive for adding the young DA group, whose performance was significantly off the ceiling for each condition.

Table 2

Low-PI Experiments A and B: Results of Two-Way Analysis of Variances and Bayes Factors Comparing the Young FA, Older FA, and Young DA Groups' Error Rates on Repeated and Nonrepeated Lure Trials

Experiment	Analysis	Main effect of group	Main effect of lure type	Group × Lure-Type Interaction
Low-PI Experiment A	2 (Group: Young FA, Older FA) × 2 (Lure Type: repeated lures, nonrepeated lures)	$F(1, 55) = 5.32$, $p = .025$, $\eta_p^2 = 0.088$, $BF_{10} = 1.49$	$F(1, 55) = 0.10$, $p = .749$, $\eta_p^2 = 0.00$, $BF_{01} = 4.90$	$F(1, 55) = 0.80$, $p = .38$, $\eta_p^2 = 0.01$, $BF_{01} = 2.66$
Low-PI experiment B	2 (Group: Young DA, Older FA) × 2 (Lure Type: repeated lures, nonrepeated lures)	$F(1, 54) = 0.40$, $p = .529$, $\eta_p^2 = 0.01$, $BF_{01} = 3.88$	$F(1, 54) = 7.39$, $p = .01$, $\eta_p^2 = 0.12$, $BF_{10} = 11.83$	$F(1, 54) = .03$, $p = .09$, $\eta_p^2 = 0.05$, $BF_{01} = 1.29$
	2 (Group: Young FA, Young DA) × 2 (Lure Type: repeated lures, nonrepeated lures)	$F(1, 57) = 8.69$, $p = .005$, $\eta_p^2 = 0.13$, $BF_{10} = 4.68$	$F(1, 57) = 7.12$, $p = .01$, $\eta_p^2 = 0.13$, $BF_{10} = 3.66$	$F(1, 57) = 10.77$, $p = .002$, $\eta_p^2 = 0.16$, $BF_{10} = 36.68$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; PI = proactive interference; BF_{10} = favors the alternative; FA = full attention; DA = divided attention.

In summary, results from the Low-PI Experiment suggested that older adults and young adults (with FA) adopted different modes of processing on the WM task. Older adults were more likely to use a reactive, familiarity-based mode of responding than young adults with FA, who were more likely to engage in proactive control. When young adults' ability to engage in proactive control during the delays was disrupted by the distracting, secondary task, they appeared to use a reactive mode of responding, which resulted in an exaggerated error rate for repeated lure probes compared to both the nonrepeated (control/baseline) lure probes and the error rates for young adults with FA during the delays.

These results prompted an important question: Can older adults use proactive control to diminish or eliminate the significant age difference in their repeated lure error rates? Research from the cognitive control literature suggests that older adults fail to engage in proactive control to suppress or inhibit no-longer-relevant information, even in situations when they know they should do so to perform well (Braver & Barch, 2002; Paxton et al., 2008). In a second preregistered experiment, we tested competing hypotheses: if healthy older adults cannot engage in proactive control, then age-related differences will remain, even when PI is high and the errors of relying on familiarity are obvious; if they can learn to engage in proactive control, then they should be able to diminish or eliminate their age differences in WM; however, compared to young adults with FA, they might require more practice to learn to stop basing their memory retrieval decisions on the strength of familiarity signals and proactively maintain retrocued items.

High-PI Experiment

In the High-PI Experiment, we increased the level of PI by repeatedly presenting each stimulus multiple times over both the practice and experimental blocks of trials. Considering all stimuli were equally familiar and feedback was provided, we expected participants to learn to discount the no-longer diagnostic familiarity signal and instead engage in proactive control processes, if they could do so. If older adults can engage in proactive control, their performance should resemble the young adults with FA.

Method

Participants

A power analysis based on the age effect ($d = 0.85$) found in the Low-PI Experiment estimated that $N = 31$ (power = .95, $\alpha = .05$) was needed. All participants participated in person and were recruited using the same screening criteria as in the Low-PI Experiment. Mean TICS was worse for the older FA group than both the young FA and young DA groups, $t(65) = 1.96$, $p = .05$ and $t(63) = 2.85$, $p = .006$, respectively. Sample characteristics are detailed in Table 7.

Data Exclusion Criterion

The preregistered data exclusion criteria in the High-PI Experiment were the same as in the Low-PI Experiment. A total of 13 participants were excluded from the analysis: seven because their accuracy in one or more probe conditions was below 55% (one young FA, one older FA, and six young DA), three because their accuracy in the secondary task was below 70% (three young DA),

Table 3

Mean (SE) Error Rates (Top) on Repeated and Nonrepeated Lure Trials for the Young FA, Older FA, and Young DA Groups, and t-Test Comparisons Between Groups for Each Lure Type (Bottom)

Group and comparison	Nonrepeated lure	Repeated lure
Young FA	0.11 (0.02)	0.08 (0.01)
Older FA	0.18 (0.04)	0.23 (0.04)
Young DA	0.15 (0.03)	0.33 (0.05)
Young FA versus older FA	$t(55) = -0.99$, $p = .330$, $BF_{01} = 2.43$	$t(55) = -2.21$, $p = .037$, $BF_{10} = 2.21$
Young DA versus older FA	$t(54) = 0.85$, $p = .410$, $BF_{01} = 2.75$	$t(54) = -1.68$, $p = .10$, $BF_{01} = 1.15$
Young DA versus young FA	$t(57) = -0.01$, $p = .99$, $BF_{01} = 3.78$	$t(57) = -4.53$, $p < .01$, $BF_{10} = 702.37$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} = favors the alternative; *SE* = standard error; FA = full attention; DA = divided attention.

one because their TICS score was below 34 (one older FA), and two because they did not complete the session due to technical issues (two young FA).

Materials and Procedure

The details were identical to that of the Low-PI Experiment except that each stimulus (eight per category) was repeated 32 times throughout the experiment and had an equal chance of being a target or a probe item; stimulus presentation location was also fully counterbalanced across conditions. Participants first completed a practice block of 24 trials, which were drawn from the same set of stimuli for the test blocks so that PI began to accumulate during practice. There were four blocks with 48 test trials per block with each stimulus counterbalanced across conditions so that all stimuli became equally familiar.

Data Analysis

As preregistered, we conducted a two-way mixed ANOVA with a group (young FA, older FA, and young DA) as a between-subjects factor and probe type as a within-subjects factor. Because all stimuli were repeatedly presented throughout, the repeated lures that were most difficult to reject were those that were repeated within a trial. These errors were compared to lures that were repeated between trials. Error rates for within-trial repeated lures and between-trial repeated lures were compared with another two-way mixed ANOVA, with lure type as a within-subjects factor and group as a between-subjects factor. As in the Low-PI Experiment, each analysis was supplemented with Bayesian inferential statistics. Averaging across all blocks of trials did not clearly support either preregistered hypothesis.[17] Thus, we conducted an exploratory analysis to assess moderating factors. The error rates for the lures and WM accuracy for the different trial types averaged over all blocks are reported in Supplemental Figure 5.

To assess if the pattern of performance changed across the four blocks of trials as PI accumulated, we conducted exploratory Bayesian multilevel modeling to test for a potential interaction between the effects of group, probe type, and block. Two models were directly compared. One model included fixed effects of group, probe type, and their interactions. The other model included an additional fixed effect of block, and interactions with group and probe type. Both models allowed random effects of subject-specific variations in both intercepts and slopes associated with the factors included in the fixed effects.

The brms package (Bürkner, 2018) in R was used to fit Bayesian logistic mixed effects models and to conduct leave-one-out cross-validation for assessing the out-of-sample predictive performance for the Bayesian models. As in Loaiza and Lavilla (2021), we specified vague prior distributions for the model parameters, including half-normal distributions with mean 0 and a scale of 2 for the fixed effects and the residual standard deviation. We used four chains of 2,000 iterations each, with a warm-up period of 1,000 iterations (see Supplemental Materials for details).

The model comparison suggested a better fit of the model with block included, $\Delta LOO = 58.5$ ($SE = 11.2$). This suggested that the block significantly interacted with the effects of group and probe type. Consequently, we conducted follow-up ANOVAs to assess the effects of group and probe type for each block separately to elucidate the source(s) of the interaction. In addition to reporting the means in Figure 3, the full set of means, standard error of mean (SEM), *t* values, and BFs for these comparisons are provided in Supplemental Tables 5 and 6 for interested readers.

Reactive–Proactive Response Mode Index. A reactive–proactive index was calculated for each individual in the older FA and young DA groups to capture the change in the difference from the young FA group across blocks in both the within- and between-trial repeated lure error rates. For each block, the index was calculated as follows: (an individual's mean within-trial error rate – the young FA group's mean within-trial error rate) + (the individual's mean between-trial error rate – the young FA group's mean between-trial error rate). The older FA group's average index (i.e., the age effect) was

[17] Our primary preregistered hypotheses predicted that when participants were in a reactive mode, there would be exaggerated error rates for within-trial repeated lures compared to the control/baseline lures; when participants performed the task in a proactive mode, we hypothesized that there would be no difference in error rates for the within-trial repeated lures compared to the control/baseline lures. That is, if older adults' ability to engage proactive control was preserved, their error rates for within-trial repeated lures should be brought down to the level of the young FA group; if they could not, their error rates for within-trial repeated lures should be similar to the young DA group. Average error rates across blocks did not clearly conform to either hypothesis; older adults' error rates changed over blocks. Therefore, the additional factor of block was included in analyses as an exploratory factor. We also reanalyzed the Low-PI Experiment data as a function of block as a control analysis to confirm that a similar shift in older adults' mode of processing was not observed in the Low-PI Experiment (see Supplemental Materials).

Table 4
Low-Proactive Interference Experiments A (Top) and B (Bottom): Two-Way Analysis of Variance and Bayes Factor Results Comparing the Young FA, Older FA, and Young DA Groups' Accuracy on Probe 1, Probe 2 Stay, and Probe 2 Switch Trials

Analysis	Main effect of group	Main effect of probe type	Group × Probe Type Interaction
2 (Group: Young FA, Older FA) × 3 (Probe Type: Probe 1, Probe 2 stay, Probe 2 switch)	$F(1, 55) = 9.83$, $p = .003$, $\eta_p^2 = 0.15$, $BF_{10} = 13.78$	$F(2, 110) = 15.90$, $p < .001$, $\eta_p^2 = 0.22$, $BF_{10} = 7{,}001$	$F(2, 110) = 4.97$, $p = .012$, $\eta_p^2 = 0.08$, $BF_{10} = 4.90$
2 (Group: Young DA, Older FA) × 3 (Probe Type: Probe 1, Probe 2 stay, Probe 2 switch)	$F(1, 54) = 0.07$, $p = .78$, $\eta_p^2 = 0.00$, $BF_{01} = 3.73$	$F(2, 108) = 17.42$, $p < .001$, $\eta_p^2 = 0.24$, $BF_{10} = 35{,}202$	$F(2, 108) = 3.84$, $p = .03$, $\eta_p^2 = 0.07$, $BF_{10} = 2.16$
2 (Group: Young FA, Young DA) × 3 (Probe Type: Probe 1, Probe 2 stay, Probe 2 switch)	$F(1, 57) = 14.70$, $p < .001$, $\eta_p^2 = 0.21$, $BF_{10} = 76.28$	$F(2, 114) = 24.43$, $p < .001$, $\eta_p^2 = 0.29$, $BF_{10} = 2{,}673{,}930$	$F(2, 114) = 1.75$, $p = .19$, $\eta_p^2 = 0.03$, $BF_{01} = 3.27$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} = favors the alternative; FA = full attention; DA = divided attention.

contrasted with the young DA group's average index for each block (i.e., the DA effect). Thus, the index measured the amount of change from a reactive to a proactive mode of responding in both older adults with FA and young adults with DA relative to young adults with FA as PI accumulated over the blocks of trials.

Results

Primary Preregistered Hypothesis: Within-Trial Versus Between-Trial Repeated Lure Error Rates

As discussed in the Data Analysis section, the data were analyzed for each block separately due to the significant interaction with a block. The data are in Figure 3. ANOVAs on error rates showed significant main effects of group on all blocks (Table 8). The main effect of lure type was significant due to higher error rates for within-trial than between-trial (control) repeated lures for all but the last block. The group by lure-type interaction was significant because the difference between within- and between-trial repeated lures was larger for both the older FA and the young DA groups compared to the young FA group on the first two blocks, but not the last two blocks. This was because the difference between within- and between-trial repeated lures was no longer significant for the older FA group.

In Block 1, *t* tests showed that both the older FA and young DA groups had significantly higher error rates for within-trial repeated lures than the young FA group, but not for the between-trial repeated lures (Table 9). This suggested that both the older FA and young DA groups were initially responding in a reactive mode. However, as PI accumulated, these groups' error rates diverged. By Block 3, older adults' error rates for the within-trial repeated lures decreased and were not significantly different from the young adult FA group [the mean difference between the older FA and young FA groups was 0.19 ($SE = 0.03$), 0.13 ($SE = 0.05$), 0.02 ($SE = 0.04$), and 0.01 ($SE = 0.04$) for Blocks 1, 2, 3, and 4, respectively]. Meanwhile, for the young DA group, error rates for within-trial repeated lures remained elevated relative to the young FA group across all blocks; the mean difference between the young DA and young FA groups was 0.22 ($SE = 0.04$), 0.25 ($SE = 0.05$), 0.19 ($SE = 0.05$), and 0.23 ($SE = 0.05$) for Blocks 1, 2, 3, and 4, respectively. Because error rates for the between-trial repeated (control) lures also changed across blocks as PI accumulated, and the rates changed differentially between the groups (see Figure 3A and Table 9), a reactive–proactive response mode index was calculated to capture the change in both error types across blocks.

Reactive–Proactive Response Mode Index

Figure 4 shows the reactive–proactive mode of responding index that captures the older adults' shift from a reactive mode to a more proactive mode of responding as PI accumulated over the blocks of trials. A two-way mixed ANOVA was conducted on the reactive–proactive index, with a between-subjects factor of a group (young DA vs. older FA) and a within-subjects factor of a block. Results

Table 5
Low-Proactive Interference Experiments A and B: Mean (SE) Accuracy (Top) and Comparisons Between the Conditions Within Each Group (Bottom)

Condition	Young full attention	Old full attention	Young divided attention
Probe 1	0.95 (0.01)	0.94 (0.01)	0.90 (0.01)
Probe 2 stay	0.99 (0.01)	0.93 (0.01)	0.95 (0.01)
Probe 2 switch	0.94 (0.01)	0.88 (0.02)	0.88 (0.02)
Probe 1 versus Probe 2 stay	$t(29) = -6.46$, $p < .001$, $BF_{10} = 45{,}499$	$t(26) = 0.58$, $p = .57$, $BF_{01} = 4.26$	$t(28) = -4.82$, $p < .001$, $BF_{10} = 573.49$
Probe 1 versus Probe 2 switch	$t(29) = 0.69$, $p = .50$, $BF_{01} = 4.20$	$t(26) = 3.55$, $p = .005$, $BF_{10} = 25.20$	$t(28) = 1.40$, $p = .17$, $BF_{01} = 2.30$
Probe 2 stay versus Probe 2 switch	$t(29) = 4.57$, $p < .001$, $BF_{10} = 368.55$	$t(26) = 3.26$, $p = .006$, $BF_{10} = 13.57$	$t(28) = 4.20$, $p < .001$, $BF_{10} = 175.57$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} favors the alternative; *SE* = standard error.

Table 6
Low-Proactive Interference Experiments A (Top) and B (Bottom) Comparing Accuracy Between Groups for Each Probe

Group comparison	Probe 1	Probe 2 stay	Probe 2 switch
Young FA versus older FA	$t(55) = 1.10$, $p = .82$, $BF_{01} = 2.21$	$t(55) = 3.86$, $p < .001$, $BF_{10} = 136.90$	$t(55) = 2.76$, $p = .008$, $BF_{10} = 7.18$
Young DA versus older FA	$t(54) = 2.23$, $p = .03$, $BF_{10} = 2.14$	$t(54) = -1.49$, $p = .14$, $BF_{01} = 1.48$	$t(54) = 0.12$, $p = 1.000$, $BF_{01} = 3.68$
Young DA versus young FA	$t(57) = 3.63$, $p = .002$, $BF_{10} = 57.24$	$t(57) = 2.93$, $p = .005$, $BF_{10} = 9.27$	$t(57) = 2.91$, $p = .017$, $BF_{10} = 9.55$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} = favors the alternative; FA = full attention; DA = divided attention.

showed a significant main effect of group, $F(1, 62) = 8.99$, $p = .004$, $BF_{10} = 9.70$, and a significant interaction between block and group, $F(3, 186) = 6.33$, $p < .001$, $BF_{10} = 56.21$; the main effect of block was not significant, $F(3, 186) = 1.07$, $p = .37$, $BF_{01} = 13.40$. Follow-up tests of simple main effects showed that block had a significant effect on the index for the older FA group, $F(3, 96) = 7.53$, $p < .001$, but not the young DA group, $F(3, 90) = 1.22$, $p = .307$]. Follow-up t tests indicated that the older FA group's error rates on within-trial repeated lures relative to the young FA group dropped to essentially zero after Block 2: Block 1 versus Blocks 3 and 4, $ts(32) > 4.21$, $ps < .001$, $BFs_{10} > 140.42$; Block 2 versus Blocks 3 and 4, $ts(32) > 2.62$, $ps < .01$, $BFs_{10} > 3.42$, suggesting that the age-related differences in error rates were fully eliminated by Block 3.

A potential concern regarding the results is that the elimination of age-related differences observed in the last two blocks was due to a ceiling effect on the young FA group's performance. To formally test this, one-sample t tests comparing accuracy for each trial type to 1.0 were conducted for each group. Accuracy was significantly off the ceiling for every condition and group ($ts > -10.7$, $ps < .001$, $BFs_{10} > 425.86$). Similarly, one-sample t tests comparing error rates to the floor demonstrated that error rates were also significantly above zero for both lure types across all groups (between trial, $ts > 5.06$, $ps < .001$, $BFs_{10} > 1283.26$; within trial, $ts > 6.34$, $ps < .001$, $BFs_{10} > 39795.05$). It is plausible that young adults with FA could have further boosted their WM performance if they had more room to improve on the scales. Notably, while older adults were able to eliminate their sizable deficit in error rates relative to the young FA group, the young DA group was not.

Additional Hypothesis 1: Retrocue Effects

The average accuracy for each group and probe type as a function of blocks is shown in Figure 3B. ANOVAs on accuracy showed that in each block, there were main effects of both group and probe type, with no interactions. Follow-up t test comparisons of probe types for each group and block showed that all three groups had significantly worse accuracy on Probe 2 switch than Probe 1 trials in each block (see Figure 3B), except for the young FA group on Block 2 and the young DA group on Block 4.

Additional Hypothesis 2: Age Differences in the Retrocue Effect

There were nonsignificant Group × Probe Type interactions for each block (Table 10). The older FA group was only worse than the young FA group on block one for Probe 1 and Probe 2 switch trials (Tables 11 and 12). Probe 2 switch was worse than Probe 1 for both the older FA and young FA groups for each block (except Block 2, Table 12). Collectively, there was no substantial evidence for age differences in the retrocue effect especially in Blocks 3 and 4.

Additional Hypothesis 3: Testing Effect

Regarding the benefits of testing the same item twice with feedback, responses to Probe 2 stay trials were only better than Probe 1 trials for the young DA group on Blocks 3 and 4 (Table 12).

Response times (RTs) were also analyzed and are reported in the Supplemental Materials to supplement analysis of accuracy.[18] Note that the young FA and older FA groups showed faster RTs to Probe 2 stay than Probe 1 trials in each block (except Block 2 for the young FA group). In contrast, the young DA group did not. Thus, the hypothesized testing effect in the high PI experiment was more evident in RTs for the young and older FA groups.

Discussion

In the High-PI Experiment, by repeatedly presenting the stimuli across trials to increase the amount of PI, we examined whether older adults could adopt a more proactive mode when familiarity signals were no longer diagnostic on most trials. Results showed that in Block 1, even though participants extensively practiced the task to expose them to all of the stimuli, older adults still had difficulties rejecting the within-trial repeated lures. Their error rates on Block 1 were similar to that of the young DA group and significantly higher than the young FA group. This mirrored the pattern observed in the Low-PI Experiment. Starting from Block 2, older adults significantly reduced their error rates and eliminated their age difference relative to the young FA group by Block 3, consistent with the hypothesized shift in the older FA group's processing mode. Figure 4 shows that the older FA group's deficit relative to the young FA group gradually decreased, while the young DA group's deficit appeared to increase across blocks as PI accrued. This was presumably because the young DA group's ability to engage in proactive control during the cueing and maintenance periods was disrupted by the DA task, especially as PI accumulated.

Additionally, by Block 3 the older FA group showed a retrocue effect that was not substantially different from the young FA group. As discussed below, this aligns with our DMC account of age differences in retrocue effects. Thus, the results support our suggestion that increasing PI on a WM task and providing feedback can be effective ways to encourage older adults to engage in a more proactive versus

[18] All response time means, standard errors, t and p values, and BFs are reported in full in Supplemental Table 2 for the interested reader, for transparency, and to support meta-analyses.

Table 7
Summary of Participant Sample Characteristics for the High-Proactive Interference Experiment

Statistic	Young adult FA	Older adult FA	Young adult DA
N recruited	36	35	40
N included in analysis	33	33	31
N in-person/virtual testing	36/36	35/35	40/40
N female/male	29/4	19/14	29/2
Mean age (Minimum~Maximum; *SD*)	18.68 (18~21; 0.97)	72.91 (65~80; 4.81)	19 (18~21; 0.99)
Mean TICS (*SD*)	40.06 (3.06)	38.67 (2.75)	40.53 (2.51)
Racial composition	55% Caucasian; 16% Hispanic/Latino/Spanish; 10% Black/African American; 10% multiracial; 6% Asians; 3% others	97% Caucasian; 3% Black/African American	74% Caucasian; 10% multiracial; 6% Middle Eastern/North Africans; 6% Asians; 3% Black/African American

Note. *All data were collected from* 2021 to 2022. Participants were recruited from the University of Notre Dame or surrounding community in South Bend, IN, United States. All participants completed this experiment at the University of Notre Dame, IN, United States. FA = full attention; DA = divided attention; BF = Bayes Factors; TICS = Telephone Interview for Cognitive Status.

reactive mode of processing. Importantly, these results demonstrate that these (healthy) older adults' ability to engage in proactive control was preserved. Below, we provide a detailed review of the past retrocue studies and how our proposed DMC account can explain the mixed results.

General Discussion

This study assessed the role of proactive control as a source of age-related differences in WM. When PI was low (because all the stimuli were trial unique, except the repeated lures), older adults had worse WM than young adults with FA, particularly with regard to their (a) exaggerated errors to repeated lures, (b) switch costs with reactivating the initially uncued item that was presumably passively retained, and (c) smaller benefits of testing the same item twice with feedback. Collectively, this suggested that older adults relied on a reactive, familiarity-based mode of responding. When young adults' ability to engage in proactive control to prioritize the cued item in focal attention was disrupted, they performed similarly to the older adults, likely because dividing their attention during the delays forced them to rely on a reactive/familiarity-based mode of responding. When PI was high (because the stimuli were repeated across trials, especially on within-trial repeated-lure trials), older adults still had worse WM on the first block of trials (on average), in terms of their repeated-lure error rates and switch costs. By the third and fourth blocks, older adults had eliminated their age deficits relative to young adults with FA; meanwhile, the young adult DA groups' deficits remained. This suggested that older adults were able to engage in proactive control, while young adults with DA were not. Taken together, the results support our DMC account of age differences in WM.

The DMC Account of Age Differences in WM

We suspected that the inconsistent age differences in retrocue effects in the literature may stem from older adults' preference for a reactive, familiarity-based approach to performing WM tasks. In conditions with low PI or when familiarity signals are reliable on most trials (e.g., recognition with unique stimuli), older adults likely rely on a reactive, familiarity-based mode of responding. This would lead to smaller retrocue effects compared to young adults. However, in many (but not all) WM task situations (e.g., on recall tasks), relying on the strength of familiarity signals is ineffective. In such situations, older adults might realize that they should engage in a more proactive, maintenance-focused mode of processing to perform the task. If they do, they should show retrocue effects similar to young adults. This could explain older adults' occasionally observed benefits of retrocuing. Below we show how our DMC account can explain these mixed results.

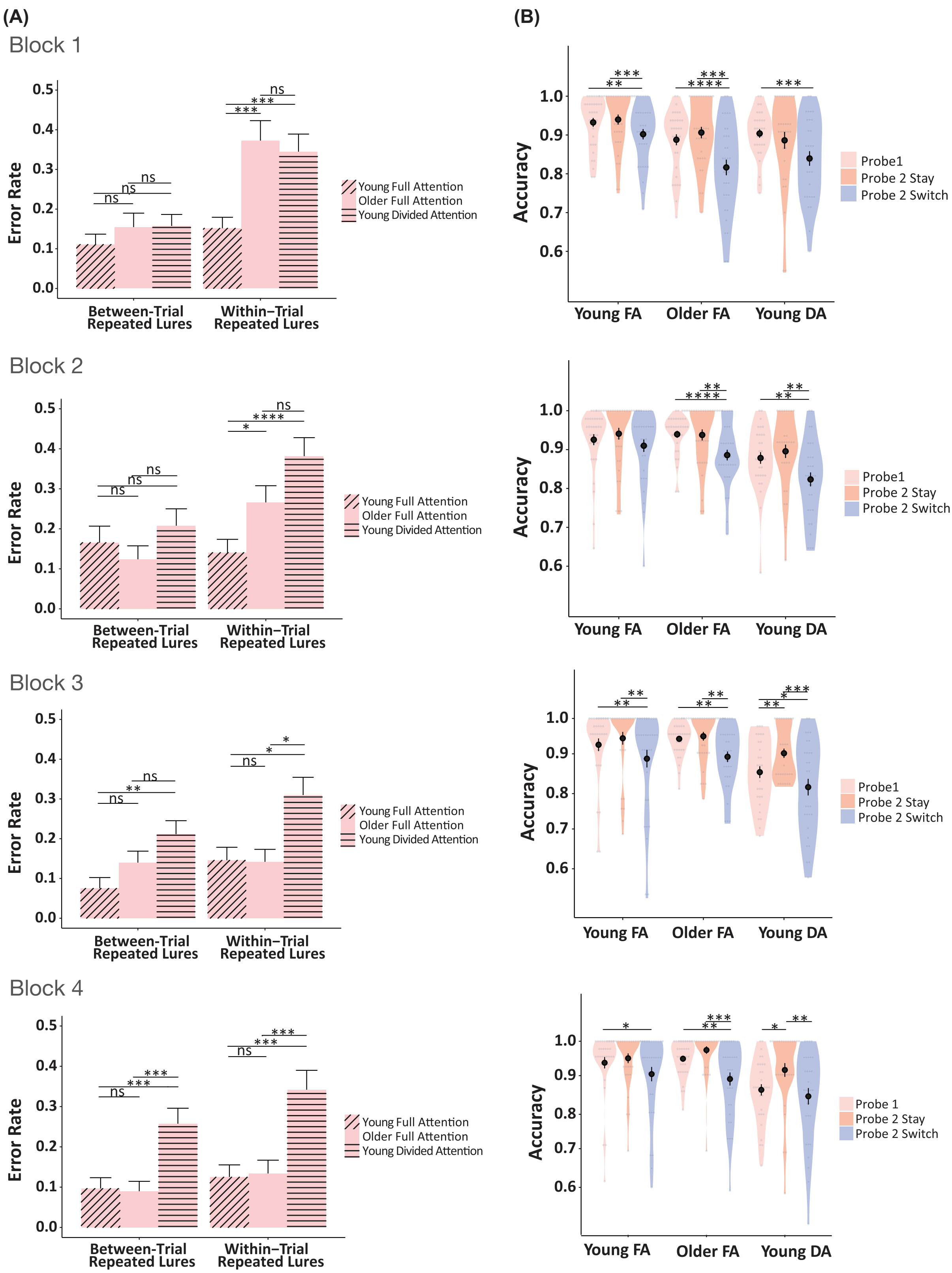
As reviewed earlier in the introduction, several studies showed similar retrocue benefits between young and older adult participants (Gilchrist et al., 2016; Loaiza & Souza, 2018; Mok et al., 2016; Souza, 2016; Yi & Friedman, 2014). Loaiza and Souza (2018, 2019), Souza (2016), and Mok et al. (2016) asked participants to precisely recall the retrocued feature. Such recall tasks would be hard to perform by simply relying on the familiarity of the cued stimulus. Therefore, older participants would be more likely to proactively maintain the cued color or orientation during the delay. Gilchrist et al. (2016) and Yi and Friedman (2014) used high-overlapping or closed-set stimuli across trials; thus, PI was high. Consequently, relying on a passive-maintenance, familiarity-based mode of responding would not support performance because both target and lure probes would be familiar.

These findings collectively support the idea that older adults can engage in proactive control in situations when it is necessary, such as high-PI tasks, which diminishes age-related differences in retrocue benefits.[19] Of the two studies that found age-related deficits in retrocue benefits (Duarte et al., 2013; Newsome et al., 2015), in both tasks, in at least half of the trials, participants were asked to make recognition decisions when the memoranda were within WM capacity for most older adults. In such situations, relying on familiarity signals would likely yield correct responses on most trials. Critically, even though the colors could repeat across trials, as in the study by Loosli et al. (2014) reviewed in the introduction,

[19] This is also consistent with previous findings that showed comparable performance between younger and older adults on tasks that purportedly rely on proactive control (Mutter et al., 2005; West & Baylis, 1998).

Figure 3

High-Proactive Interference Experiment: Mean WM Error Rates on Trials With Between- and Within-Trial Repeated Lures (A) and Accuracy on Probe 1, Probe 2 Stay, and Probe 2 Switch Trials (B) as a Function of Testing Block for the Young FA, Older FA, and Young DA Groups



Note. Error bars indicate the standard error of mean. WM = working memory; FA = full attention; DA = divided attention.
* $p < .05$. ** $p < .01$. *** $p < .001$. **** $p < .0001$, ns means nonsignificant ($p > .05$)

Table 8
High-Proactive Interference Experiment: Two-Way Analysis of Variance Results and Bayes Factors Comparing the Young FA, Older FA, and Young DA Groups' Error Rates on Repeated Versus Nonrepeated Lure Trials as a Function of Block

Block	Main effect of group	Main effect of lure type	Group × Lure Type Interaction
Block 1	$F(2, 91) = 4.36$, $p = .015$, $\eta_p^2 = 0.09$, $BF_{10} = 2.44$	$F(1, 93) = 36.59$, $p < .001$, $\eta_p^2 = 0.28$, $BF_{10} = 261{,}003$	$F(2, 93) = 3.28$, $p = .042$, $\eta_p^2 = 0.07$, $BF_{10} = 2.72$
Block 2	$F(2, 91) = 6.17$, $p = .003$, $\eta_p^2 = 0.12$, $BF_{10} = 5.82$	$F(1, 93) = 13.30$, $p = .004$, $\eta_p^2 = 0.12$, $BF_{10} = 5.82$	$F(2, 93) = 3.96$, $p = .022$, $\eta_p^2 = 0.08$, $BF_{10} = 6.48$
Block 3	$F(2, 91) = 7.48$, $p = .001$, $\eta_p^2 = 0.14$, $BF_{10} = 34.21$	$F(1, 93) = 6.07$, $p = .016$, $\eta_p^2 = 0.06$, $BF_{10} = 2.26$	$F(2, 93) = 1.71$, $p = .19$, $\eta_p^2 = 0.04$, $BF_{01} = 1.31$
Block 4	$F(2, 91) = 17.01$, $p < .001$, $\eta_p^2 = 0.27$, $BF_{10} = 18{,}307$	$F(1, 93) = 2.75$, $p = .101$, $\eta_p^2 = 0.03$, $BF_{10} = 1.77$	$F(2, 93) = 0.05$, $p = .953$, $\eta_p^2 = 0.00$, $BF_{01} = 4.70$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} = favors the alternative; FA = full attention; DA = divided attention.

feedback was not provided, so it is unclear if participants even knew when their recognition decisions were erroneous. Therefore, the variability in age differences in retrocue effects can be explained by our proposed DMC account.[20] Older adults demonstrate age-related deficits in retrocue benefits when they engage in a more reactive than proactive mode of processing. In the following sections, we consider several alternative or complementary explanations of the pattern of results.

Complementary Explanation: Verbal Labeling of Stimuli

A complementary account of the change in age differences over testing blocks is that, as the stimuli were repeated, participants came up with verbal labels to help them remember and rehearse each specific face and scene (Forsberg et al., 2019, 2020; Nicholls & English, 2020). Anecdotal evidence from postexperiment debriefing suggests that most older adults reported creating verbal labels for the stimuli. For example, participants reported labels such as "dweeb" and "ROTC guy" for faces and "river going across" and "two rivers" for scene stimuli. This suggests that older adults maintained and rehearsed their WM by generating and using verbal labels of the stimuli. This would be consistent with the literature on memory and aging, which shows that older adults tend to rely more heavily on verbal strategies than young adults (e.g., Hedden et al., 2005). If this were true, there should be a difference in the pattern of results between familiar verbal stimuli (the names) and unfamiliar visual stimuli (the faces and places) that became associated with verbal labels (e.g., "messy hair"). Specifically, if labeling the stimuli contributed to both the age difference and the change in age differences across blocks, then there would be less change across blocks for names compared to face and scene stimuli. We tested this by rerunning an ANOVA comparing accuracy and error rates of the older and young FA groups with stimulus category as a within-subjects factor. If verbal labeling affected WM performance, there should be an interaction with stimulus category, especially on early blocks. If the faces and scenes had associated verbal labels on later blocks, then there should be minimal difference compared to names. Results showed a significant interaction between stimulus category, block, and group, $F(1, 64) = 10.61$, $p = .002$, because the interaction between block and stimulus category was significant for the older FA group, $F(1, 64) = 12.34$, $p = 8.18\text{e}{-04}$, but not the young FA group, $F(1, 60) = 0.513$, $p = .48$. The older FA group's performance for nonverbal stimuli improved as a function of block, suggesting that they eliminated the age-related difference in part by associating verbal labels with each stimulus (see Supplemental Figures 4 and 5 and Tables 7 and 8).

Alternative Explanation: Shift in Response Criterion

An alternative account of the change in error rates is that there may not have been a change in the nature of the maintenance processes that were engaged during the delays; it may have resulted from older adults adopting a more conservative response criterion when making their match/nonmatch recognition decisions. If this were true, then there would be a corresponding shift in hit rates or RTs, somewhat consistent with a speed–accuracy tradeoff. We tested whether older adults showed reduced hit rates or increased RTs on repeated-lure trials as a function of block. As shown in Figure 3A, older adults did not show reduced hit rates for any probe type across blocks. Additionally, the older FA group's mean RTs to within-trial repeated lures on the last two blocks of the High-PI Experiment were not slower than either their mean RT on the first

[20] Note that this DMC account may be able to account for age differences in WM in other contexts and paradigms beyond the retrocue paradigm. For example, the DMC account can probably also account for the findings of Allen et al. (2021), that is, that older adults are as efficient as young adults in (proactively) prioritizing specific items in WM. Additionally, the DMC account might also be able to account for findings in the precue literature. Two of the articles that we reviewed in the general discussion (Duarte et al., 2013; Souza, 2016) also included precue trials in their study. In Duarte et al. (2013), a precue and a retrocue were provided in all trials for contralateral delay activity tasks. The result demonstrated a contralateral delay activity attenuation prior to the onset of a retrocue in only older adults. This suggested that older adults likely were not maintaining items in WM in the same way that young adults did, which is consistent with their finding that only young adults showed a retrocue benefit. If the tasks had high PI and feedback was provided, we predict that older adults might have performed the task more similar to young adults and shown similar contralateral delay activity. In Souza (2016), their study had a separate precue condition. The only difference between the precue and postcue condition was the timing when the cue was provided. Results showed that the precue condition yielded a similar result as in the retrocue condition. We thank an anonymous reviewer for raising this point. See also Cowan et al. (2006), who found that older adults had particular difficulties with binding information when item- and binding-change detection trials were mixed together and suggested that older adults were lulled into relying on familiarity signals for the easier item-change detection trials, making them susceptible to errors on binding-change detection trials.

Table 9

High-Proactive Interference Experiment: Mean (SE) Error Rates, t Tests, and Bayes Factors Comparing Each Age Group on Within-Trial (Top) and Between-Trial (Bottom) Repeated Lures on Each Block

	Error rate mean (*SE*)			*t*-Test result and Bayes factors		
Block	Young FA	Older FA	Young DA	Young FA versus older FA	Young FA versus young DA	Older FA versus young DA
Within-trial repeated lures						
Block 1	0.15 (0.03)	0.37 (0.05)	0.35 (0.04)	$t(60) = -3.52$, $p = .002$, $BF_{10} = 36.88$	$t(61) = -3.11$, $p = .006$, $BF_{10} = 13.33$	$t(61) = 0.34$, $p = .736$, $BF_{01} = 3.73$
Block 2	0.14 (0.03)	0.27 (0.04)	0.38 (0.05)	$t(60) = -2.39$, $p = .04$, $BF_{10} = 2.71$	$t(61) = -4.56$, $p < .001$, $BF_{10} = 743.49$	$t(61) = -1.98$, $p = .05$, $BF_{10} = 1.28$
Block 3	0.15 (0.03)	0.14 (0.03)	0.31 (0.05)	$t(60) = 0.13$, $p = .895$, $BF_{01} = 3.94$	$t(61) = -2.74$, $p = .017$, $BF_{10} = 5.68$	$t(61) = -2.85$, $p = .017$, $BF_{10} = 7.43$
Block 4	0.13 (0.03)	0.13 (0.03)	0.34 (0.05)	$t(60) = -0.01$, $p = .99$, $BF_{01} = 3.97$	$t(61) = -3.85$, $p < .001$, $BF_{10} = 93.98$	$t(61) = -3.74$, $p < .001$, $BF_{10} = 67.84$
Between-trial repeated lures						
Block 1	0.11 (0.03)	0.15 (0.04)	0.16 (0.03)	$t(60) = -0.67$, $p = 1$, $BF_{01} = 3.28$	$t(61) = -1.30$, $p = .597$, $BF_{01} = 2.84$	$t(61) = -0.55$, $p = 1$, $BF_{01} = 3.44$
Block 2	0.17 (0.04)	0.12 (0.03)	0.21 (0.04)	$t(60) = 0.78$, $p = .76$, $BF_{01} = 3.06$	$t(61) = -0.88$, $p = .760$, $BF_{01} = 2.71$	$t(61) = -1.68$, $p = .29$, $BF_{01} = 1.19$
Block 3	0.08 (0.03)	0.14 (0.03)	0.21 (0.03)	$t(60) = -1.84$, $p = .14$, $BF_{10} = 1.05$	$t(61) = -3.72$, $p = .001$, $BF_{10} = 65.39$	$t(61) = -1.76$, $p = .14$, $BF_{01} = 1.07$
Block 4	0.10 (0.03)	0.09 (0.02)	0.26 (0.04)	$t(60) = 0.09$, $p = .93$, $BF_{01} = 3.95$	$t(61) = -3.77$, $p < .001$, $BF_{10} = 72.90$	$t(61) = -3.92$, $p < .001$, $BF_{10} = 113.03$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} = favors the alternative. SE = standard error; FA = full attention; DA = divided attention.

two blocks or the older adults' mean repeated-lure RT on the Low-PI Experiment, $t(58) < 1.47$, $p > .062$. In fact, their mean RT on the last two blocks was significantly faster than that on Block 1, $t(32) > 3.63$, $p < .006$. Therefore, there was no evidence that the reduction in older adults' error rates was because of a shift in response criterion or a speed–accuracy tradeoff. See Supplemental Materials for details.

Alternative Explanation: Long-Term Memory Account of Age Differences in WM

An LTM account suggests that switching attention away from an item, and passively retaining and reactivating such latent items back into the focus of attention, involves episodic LTM retrieval processes, even for small amounts of information maintained over delays of only a few seconds (Beukers et al., 2021; Foster et al., 2024; Greene et al., 2020; Hale et al., 2011; Rose, 2020). If that was the case for this WM task, an alternative explanation for the current findings could be attributed to older adults' deficiencies with episodic LTM, such as deficient feature-binding or source-monitoring abilities (Henkel et al., 1998). We (Chao et al., 2023) tested this account by having participants in the Low-PI Experiment complete subsequent item, location, and associative LTM tests for the items from the WM task, after they completed the WM task. Results showed that the effects of reactivating latent items did not interact with or systematically affect subsequent LTM for reactivated versus control items on any of the recognition memory judgments. This suggests that the WM items on this task were likely not retained and reactivated with episodic LTM processes. Therefore, the age differences on this WM task are likely not attributable to age differences in episodic LTM processes (Chao et al., 2023).

Relation to Theories of Cognitive Aging

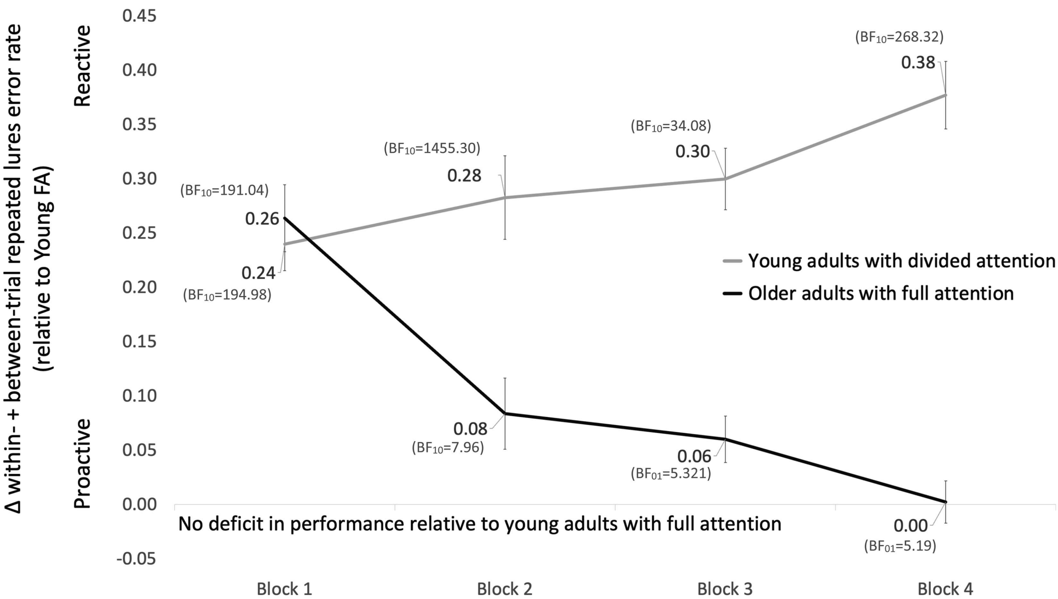
While the present study focused on our DMC account of age differences in WM, it is important to acknowledge other potential sources of age-related variation in WM. Next, we briefly relate our proposed account with prevailing theories of cognitive aging, including hypotheses about perceptual effort, processing speed, cognitive dedifferentiation, inhibitory control, and metacognitive deficits.

Our proposed account of older adults' preference for a familiarity-based/reactive mode of processing aligns with the perceptual effort hypothesis (e.g., Pichora-Fuller, 2006; Verhaegen et al., 2014) and processing speed theory (e.g., Salthouse, 1996) because older adults' impoverished sensory/perceptual input likely requires additional effort to process degraded stimuli, which takes up cognitive resources that would otherwise be involved in encoding and rehearsal (Rabbitt, 1991). This likely contributes to older adults' encoding of less distinct/differentiable memory representations (Baltes & Lindenberger, 1997; Ghisletta & Lindenberger, 2003) and also slows their ability to rapidly switch attention between to-be-remembered items, which likely contributes to their slowed information processing speed (Salthouse, 1996). We argue that older adults' preference for the less-demanding, reactive/familiarity-based mode of processing is an adaptive attempt by older adults to compensate for these limitations brought on by aging.

Relatedly, the inhibitory deficit theory posits that aging is associated with a decreased ability to inhibit irrelevant information in WM (Hasher & Zacks, 1988; Lustig et al., 2007). Specifically, a

Figure 4

The Reactive-Proactive Mode of Responding Index



Note. The reactive–proactive mode of responding index captures the summed differences on within- and between-trial repeated-lure error rates relative to young adults with full attention (FA) for the older adults with FA and young adults with divided attention (DA) during the cueing and delay periods over the four testing blocks of the two-item double-retrocue WM task. Zero means no difference from young adults with FA. Older adults started out on Block 1 with a 26% deficit in error rates relative to young adults, likely due to their reactive/familiarity-based mode of responding; by Block 3, as the stimuli were repeated and proactive interference accumulated over trials on the task, older adults eliminated their large age difference in error rates, presumably by adopting a more proactive mode of processing. Young adults with DA during the delays did not. Error bars = standard error of mean; BF_{01} = Bayes factors favoring the null hypothesis of no difference from 0; BF_{10} = favors the alternative; WM = working memory; BF = Bayes factors.

consequence of older adults' reduced ability to inhibit irrelevant information would be difficulties with attending to task-relevant information in an active, sustained manner (Braver, 2012). This could explain both our older adults' susceptibility to making errors on repeated-lure probes when PI was low and also their elimination of this deficit when PI was high. Encouragingly, this suggests that most older adults could override inhibition deficiencies by engaging in proactive control and also that most older adults failed to spontaneously engage in proactive control—they relied on a reactive/familiarity-based mode of responding when they could, and their WM suffered—but, when it became more apparent that this mode of processing was ineffective (when PI was high),

Table 10

High-Proactive Interference Experiment: Two-Way Analysis of Variance and Bayes Factor Results Comparing the Young FA, Older FA, and Young DA Groups' Accuracy on Probe 1, Probe 2 Stay, and Probe 2 Switch Trials on Each Block

Block	Main effect of group	Main effect of probe type	Group × Probe Type Interaction
Block 1	$F(2, 91) = 5.38$, $p = .006$, $\eta_p^2 = 0.10$, $BF_{10} = 6.66$	$F(2, 184) = 25.81$ $p < .001$, $\eta_p^2 = 0.22$, $BF_{10} = 45536478$	$F(4, 184) = 2.43$, $p = .06$, $\eta_p^2 = 0.05$, $BF_{01} = 1.38$
Block 2	$F(2, 91) = 6.58$, $p = .002$, $\eta_p^2 = 0.12$, $BF_{10} = 17.6$	$F(2, 184) = 24.89$, $p < .001$, $\eta_p^2 = 0.21$, $BF_{10} = 18719774$	$F(4,184) = 2.02$, $p = .104$, $\eta_p^2 = 0.04$, $BF_{01} = 2.56$
Block 3	$F(2, 91) = 7.42$, $p < .001$, $\eta_p^2 = 0.14$, $BF_{10} = 32.64$	$F(2, 184) = 30.79$, $p < .001$, $\eta_p^2 = 0.25$, $BF_{10} = 1710034391$	$F(4, 184) = 1.55$, $p = .11$, $\eta_p^2 = 0.03$, $BF_{01} = 5.39$
Block 4	$F(2, 91) = 5.06$, $p = .008$, $\eta_p^2 = 0.10$, $BF_{10} = 5.37$	$F(2, 184) = 18.65$, $p < .001$, $\eta_p^2 = 0.17$, $BF_{10} = 182,366$	$F(2, 114) = 2.25$, $p = .078$, $\eta_p^2 = 0.05$, $BF_{01} = 1.85$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} = favors the alternative; FA = full attention; DA = divided attention.

Table 11

High-Proactive Interference Experiment: t-Test Comparisons Between Groups for Probe 1 (Top), Probe 2 Stay (Middle), and Probe 2 Switch (Bottom)

Block	Young FA versus older FA	Young FA versus young DA	Young DA versus older FA
Probe 1			
Block 1	$t(64) = 2.45$, $p = .05$, $BF_{10} = 3.11$	$t(62) = 1.76$, $p = .25$, $BF_{01} = 1.02$	$t(62) = -0.93$, $p = 1.00$, $BF_{01} = 2.79$
Block 2	$t(64) = -0.86$, $p = 1.00$, $BF_{01} = 2.97$	$t(62) = 2.20$, $p = .096$, $BF_{10} = 2.25$	$t(62) = 3.42$, $p = .004$, $BF_{10} = 38.26$
Block 3	$t(64) = -0.92$, $p = .36$, $BF_{01} = 2.91$	$t(62) = 3.05$, $p = .003$, $BF_{10} = 14.88$	$t(62) = 5.07$, $p \leq .001$, $BF_{10} = 5983.14$
Block 4	$t(64) = -0.68$, $p = .498$, $BF_{01} = 3.33$	$t(62) = 3.23$, $p = .002$, $BF_{10} = 24.98$	$t(62) = 4.78$, $p \leq .001$, $BF_{10} = 2423.9$
Probe 2 stay			
Block 1	$t(64) = 1.70$, $p = .284$, $BF_{01} = 1.17$	$t(62) = 2.11$, $p = .12$, $BF_{10} = 1.73$	$t(62) = 0.82$, $p = .42$, $BF_{01} = 3.04$
Block 2	$t(64) = 0.14$, $p = 1.000$, $BF_{01} = 3.93$	$t(62) = 1.94$, $p = .171$, $BF_{10} = 1.33$	$t(62) = 1.86$, $p = .202$, $BF_{10} = 1.15$
Block 3	$t(64) = -0.32$, $p = .749$, $BF_{01} = 3.85$	$t(62) = 1.79$, $p = .079$, $BF_{10} = 1.11$	$t(62) = 2.66$, $p = .01$, $BF_{10} = 4.84$
Block 4	$t(64) = -1.65$, $p = .106$, $BF_{01} = 1.2$	$t(62) = 0.54$, $p = .593$, $BF_{01} = 3.33$	$t(62) = 2.49$, $p = .017$, $BF_{10} = 4.05$
Probe 2 switch			
Block 1	$t(64) = 3.54$, $p = .002$, $BF_{10} = 39.36$	$t(62) = 2.72$, $p = .026$, $BF_{10} = 5.45$	$t(62) = -0.85$, $p = 1.00$, $BF_{01} = 2.91$
Block 2	$t(64) = 1.08$, $p = .855$, $BF_{01} = 2.27$	$t(62) = 3.54$, $p = .002$, $BF_{10} = 48.34$	$t(62) = 2.79$, $p = .022$, $BF_{10} = 6.27$
Block 3	$t(64) = -0.31$, $p = .759$, $BF_{01} = 3.91$	$t(62) = 2.24$, $p = .029$, $BF_{10} = 2.51$	$t(62) = 3.11$, $p = .003$, $BF_{10} = 13.49$
Block 4	$t(64) = 0.46$, $p = .648$, $BF_{01} = 3.57$	$t(62) = 1.97$, $p = .053$, $BF_{10} = 1.44$	$t(62) = 1.64$, $p = .107$, $BF_{01} = 1.23$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} = favors the alternative; FA = full attention; DA = divided attention.

they were able to engage in proactive control and eliminate their sizable age differences in WM. This is consistent with the notion that older adults have preserved metacognitive monitoring of memory selectivity (Siegel & Castel, 2019). Because feedback was provided, older adults were aware of their errors, and most appeared to be able to engage in proactive control, but some needed more practice than young adults with FA to do so.

Post hoc individual difference analyses of the reactive–proactive response mode index within the older FA group revealed some interesting differences between individuals in the extent to which proactive control was engaged and the timing at which it appeared to be engaged. There was individual variability in the trends over the blocks of trials, suggesting individual differences in the extent to which an older adult both started to operate in a more proactive mode and could eliminate their age difference relative to the younger adults with full attention (Supplemental Figure 6). We summed the reactive–proactive index over all four blocks for each older adult and correlated it with each individual's WM accuracy on the trials without repeated lures, their retrocue effect, their age, and their cognitive ability as measured by the TICS. Those with the highest values showed an age deficit throughout the experiment; the lowest values showed either no or minimal age deficits. The summed reactive–proactive index was negatively correlated with older adults' WM accuracy for each probe type ($r < -0.71$, $p < .001$). Moreover, it was positively correlated with the retrocue effect measured as the difference in accuracy between Probe 1 and Probe 2 switch trials ($r = 0.48$, $p = .004$) and age ($r = 0.48$, $p = .005$) and negatively correlated with immediate recall on the TICS ($r = -0.48$, $p = .005$). These individual difference analyses and results provide further support for our DMC account of age differences in WM. See Supplemental Material for further details.

Limitations and Future Directions

The present study included a memory set size of two items per trial to ensure that WM capacity was not exceeded for all participants. One potential concern is that some participants may have kept both items active in focal attention throughout some trials, which potentially obscures the retrocue effects. Extensive prior evidence from behavioral, neuroimaging, and neurostimulation research using the same task paradigm suggests that this is unlikely to be the case. For example, previous studies with almost identical paradigms (Lewis-Peacock et al., 2012; LaRocque et al., 2015; Rose et al., 2016) have shown a return-to-baseline level of brain decoding evidence for uncued items with only two memory items per trial. This suggests that participants do not maintain both items in WM in an active, sustained manner. This is especially true for the DA group when they processed the secondary task; the items were likely dropped from continuous maintenance in focal attention due to the demanding nature of the DA task. Nonetheless, we note that future studies could include neutral cue, no cue or invalid cue conditions to gauge the size of retrocue benefits similar to previous studies with single retrocues (e.g., Loaiza & Souza, 2018, 2019). Including those conditions will allow the assessment of both the baseline level of performance and the benefit of engaging in proactive control. Additionally, a postexperiment questionnaire to assess self-reported strategies could also shed light on group differences in the use of reactive versus proactive control. Future studies with neuroimaging and neuromodulation could also be informative regarding the neurocognitive bases of the DMC account of age differences in WM.[21]

Conclusion

The present study showed that, whereas young adults with FA engaged in proactive control to outperform older adults (and young adults with DA), who tended to rely on a reactive/familiarity-based mode of processing when PI was low, most older adults were able to engage in proactive control and use retrocues to optimize their WM performance and eliminate their large age deficit in repeated lure error rates when PI was high and feedback was provided (while young adults with DA could not). Moreover, our DMC account of

[21] Also note that the power analysis determined the sample sizes required to detect large effect sizes; larger sample sizes may be necessary to detect small-to-moderate effect sizes. We thank Louise Brown Nicholls for this suggestion.

Table 12

High-Proactive Interference Experiment: Mean (SE) Accuracy (Top) and Comparisons Between the Conditions (Probe 1, Probe 2 Stay, and Probe 2 Switch Trials) Within Each Group (Young FA, Older FA, and Young DA) (Bottom)

Condition	Young full attention				Old full attention				Young divided attention			
	Block 1	Block 2	Block 3	Block 4	Block 1	Block 2	Block 3	Block 4	Block 1	Block 2	Block 3	Block 4
Probe 1	0.93 (0.01)	0.93 (0.01)	0.93 (0.02)	0.94 (0.02)	0.89 (0.01)	0.94 (0.01)	0.95 (0.01)	0.95 (0.01)	0.90 (0.01)	0.88 (0.02)	0.86 (0.02)	0.87 (0.02)
Probe 2 stay	0.94 (0.01)	0.94 (0.02)	0.95 (0.02)	0.94 (0.02)	0.91 (0.02)	0.94 (0.01)	0.95 (0.01)	0.98 (0.01)	0.89 (0.02)	0.90(0.02)	0.91 (0.01)	0.92 (0.02)
Probe 2 switch	0.90 (0.01)	0.91 (0.02)	0.89 (0.02)	0.91 (0.02)	0.82 (0.02)	0.89 (0.01)	0.90 (0.01)	0.90 (0.02)	0.84 (0.02)	0.82 (0.02)	0.82 (0.02)	0.85 (0.02)
Probe 1 versus Probe 2 stay	$t(32) = -0.71$, $p = .484$, $BF_{01} = 4.13$	$t(32) = -1.57$, $p = .24$, $BF_{01} = 1.58$	$t(32) = -1.37$, $p = .18$, $BF_{01} = 2.09$	$t(32) = 0.35$, $p = .73$, $BF_{01} = 5.26$	$t(32) = -1.28$, $p = .21$, $BF_{01} = 2.46$	$t(32) = 0.23$, $p = .819$, $BF_{01} = 5.32$	$t(32) = -0.46$, $p = .65$, $BF_{01} = 4.73$	$t(32) = -1.87$, $p = .07$, $BF_{01} = 1.04$	$t(30) = 1.1$, $p = .28$, $BF_{01} = 3.31$	$t(30) = -1.27$, $p = .215$, $BF_{01} = 2.33$	$t(30) = -3.45$, $p = .003$, $BF_{10} = 19.27$	$t(30) = -2.97$, $p = .01$, $BF_{10} = 10.79$
Probe 1 versus Probe 2 switch	$t(32) = 3.14$, $p = .007$, $BF_{10} = 11.17$	$t(32) = 1.6$, $p = .24$, $BF_{01} = 1.69$	$t(32) = 3.59$, $p = .003$, $BF_{10} = 28.38$	$t(32) = 2.74$, $p = .03$, $BF_{10} = 4.65$	$t(32) = 4.83$, $p \leq .001$, $BF_{10} = 7.93 \times 10^2$	$t(32) = 5.00$, $p \leq .001$, $BF_{10} = 1.03 \times 10^3$	$t(32) = 3.98$, $p = .001$, $BF_{10} = 75.35$	$t(32) = 3.80$, $p = .001$, $BF_{10} = 52.32$	$t(30) = 4.15$, $p \leq .001$, $BF_{10} = 107.40$	$t(30) = 3.20$, $p = .007$, $BF_{10} = 12.32$	$t(30) = 2.33$, $p = .026$, $BF_{01} = 1.80$	$t(30) = 1.02$, $p = .316$, $BF_{01} = 3.57$
Probe 2 stay versus Probe 2 switch	$t(32) = 4.28$, $p \leq .001$, $BF_{10} = 193.17$	$t(32) = 2.25$, $p = .094$, $BF_{10} = 1.99$	$t(32) = 3.51$, $p = .003$, $BF_{10} = 33.37$	$t(32) = 1.36$, $p = .37$, $BF_{01} = 1.99$	$t(32) = 4.16$, $p \leq .001$, $BF_{10} = 141.96$	$t(32) = 3.48$, $p = .003$, $BF_{10} = 27.21$	$t(32) = 3.71$, $p = .002$, $BF_{10} = 43.72$	$t(32) = 4.03$, $p \leq .001$, $BF_{10} = 124.61$	$t(30) = 1.94$, $p = .124$, $BF_{10} = 1.29$	$t(30) = 3.93$, $p = .001$, $BF_{10} = 78.97$	$t(30) = 4.16$, $p \leq .001$, $BF_{10} = 117.72$	$t(30) = 3.33$, $p = .007$, $BF_{10} = 18.36$

Note. BF_{01} = Bayes Factors favoring the null hypothesis; BF_{10} = favors the alternative; *SE* = standard error; FA = full attention; DA = divided attention.

these age differences also provides a unifying account for the mixed findings in the literature regarding age differences in retrocue effects on WM and possibly age differences in WM more generally. This approach and theoretical account help elucidate the source of age-related declines in WM and should be incorporated into theories and future studies of age differences in WM.

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