An Age-Related Deficit in Preserving the Benefits of Attention in Working Memory

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The pre-registration, materials, data, and analysis scripts for the experiment are available at the Open Science Framework (OSF): https://osf.io/h3sdb/

Abstract

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Deficits in the use of attention to refresh representations are argued to underlie age-related decline in working memory (WM). Retro-cues guide attention to WM contents, enabling the direct assessment of refreshing in WM. This preregistered study investigated aging deficits in refreshing via retro-cues and the preservation of refreshing boosts after distraction incurred by a secondary task. The distractor task is assumed to impede refreshing by engaging attention away from the memoranda. Any free time available before or after distractor processing, however, can be used to resume refreshing thereby ameliorating distractor-related interference. Accordingly, by varying the time available to complete the distractor task, one can vary refreshing opportunities, an effect known as cognitive load. Using an individually calibrated task that controlled for WM capacity and speed of processing, we demonstrate that focusing attention on WM representations is similarly efficient in younger and older adults. However, younger adults were able to retain this retro-cue benefit despite increasing cognitive load, whereas increasing cognitive load reduced the retro-cue benefit in older adults, suggesting that they are less able to protect focused representations from distractor-interference. This shows that aging impacts specific subcomponents of refreshing, such that the benefit of focusing attention is relatively intact in older age, but older adults struggle to preserve the refreshing benefit against distraction.

Keywords: working memory; attention; refreshing; retro-cues

Working memory (WM) is the capacity-limited system that keeps information accessible in mind for ongoing processing. It is well-documented that older adults show reduced WM capacity in comparison to their younger counterparts (Bopp & Verhaeghen, 2005). A great deal of research has focused on the locus of this age-related reduction in WM to uncover the basic factors that limit WM capacity across the lifespan and how they may contribute to broader cognitive changes that accompany normal aging (e.g., McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010; Park et al., 1996; Verhaeghen & Salthouse, 1997).

Among several theoretical accounts that have been proposed (see Loaiza & Oberauer, 2016 for a review), one competitive view suggests that, relative to younger adults, older adults are impaired in their ability to use attention to manage information in WM. One function attention is assumed to serve for WM maintenance is that of refreshing: the attentional focusing of recently active but no longer perceptually-present representations in order to sustain their availability for ongoing cognition (Johnson, 1992). Refreshing is thought to function by bringing a representation into the focus of attention in WM, thereby augmenting its accessibility, although there is still considerable debate concerning how this manifests (see Camos et al., 2018 for a review). In our past work (Loaiza & McCabe, 2012; Loaiza & Souza, 2018; Souza, 2016; Souza, Rerko, & Oberauer, 2015), we have argued that refreshing operates by strengthening the binding between the verbal or visuospatial WM representation and its spatial-temporal context (e.g., its relative spatial position in a memory array), thereby improving WM capacity. According to the *refreshing deficit hypothesis*, WM deficits in older age may be due to a reduced ability to use attention to refresh WM contents (Hoareau, Lemaire, Portrat, & Plancher, 2016; Johnson, Reeder, Raye, & Mitchell, 2002; Loaiza & McCabe, 2013;

Plancher, Boyer, Lemaire, & Portrat, 2017). Thus, age deficits in using attention to keep contents active via refreshing may contribute to developmental differences in WM.

Retro-cues provide one tool to address this question: a retro-cue presented during the retention interval of a WM task guides attention to one WM item, thereby arguably refreshing it and increasing its accessibility. Indeed, the *retro-cue effect* or *retro-cue benefit* refers to the well-replicated finding that visual WM performance is greater for retro-cued items compared to a no-cue or neutral-cue baseline, suggesting that directing attention to WM representations increases their accessibility (see Souza & Oberauer, 2016 for a review). If older adults do indeed have a refreshing deficit, this could manifest as a null or reduced retro-cue benefit relative to younger adults. So far, there is inconsistent evidence regarding the refreshing deficit hypothesis even within the same research groups, with some studies showing intact retro-cue benefits in older adults (Gilchrist, Duarte, & Verhaeghen, 2016; Loaiza & Souza, 2018; Mok, Myers, Wallis, & Nobre, 2016; Souza, 2016; Strunk, Morgan, Reaves, Verhaeghen, & Duarte, 2018) and other work showing a retro-cue deficit for older adults compared to younger adults (Duarte et al., 2013; Newsome et al., 2015; Yi & Friedman, 2014). Thus, further work is required in order to determine whether older adults do indeed exhibit a refreshing deficit that contributes to the frequently observed age-related impairments in WM.

Although an age-invariant retro-cue benefit would suggest that focusing attention is relative intact, it would not unequivocally indicate that refreshing is fully functional in older age. Most of the aforementioned studies assessing the retro-cue benefit in older age employed the typical retro-cue paradigm that only requires focusing on a single representation. Although focusing attention is considered an important component of refreshing, most theoretical accounts assume that refreshing operates sequentially on multiple representations, yielding cumulative boosts according to how often the items are refreshed. This requires (1) shifting the focus of attention among representations in WM, and (2) that the boost achieved through refreshing persists after the focus moves away. Retro-cue studies with younger adults have demonstrated evidence consistent with both effects: younger adults benefit from the presentation of multiple retro-cues (Landman, Spekreijse, & Lamme, 2003; Li & Saiki, 2014; Rerko & Oberauer, 2013; Souza & Oberauer, 2017; Souza et al., 2015; Souza, Vergauwe, & Oberauer, 2018) and retro-cue benefits are resilient to different types of distraction (Hollingworth & Maxcey-Richard, 2013; Janczyk & Berryhill, 2014; Makovski & Pertzov, 2015; Rerko, Souza, & Oberauer, 2014). No work has yet addressed whether older adults can flexibly switch attention between representations and whether the retro-cue benefit is maintained in the face of distractions. Deficits in any of these functions would lend support to the view that refreshing is impaired in older age.

In a previous study (Loaiza & Souza, 2018), we addressed the first question of whether older adults can flexibly switch attention among WM representations. We presented a sequence of up to two retro-cues in a subset of the trials and no-cue in the remaining trials. A second retro-cue following the first retro-cue required shifting attention to the second item in WM because only this item was relevant for the memory test. Similar retro-cue benefits were observed both in single and double retro-cue trials between age groups. These results contradicted the refreshing deficit hypothesis, instead suggesting a preserved ability to focus attention on a single representation and to switch attention among representations in WM.

In the present study we aimed to address the second question, namely, whether the retro-cue benefits observed in older adults are resilient to distraction. Distraction was implemented by requiring participants to perform a secondary task during the retention interval. WM recall is impaired as a direct function of the amount of time attention is engaged in a secondary task during the retention interval, known as the *cognitive load effect* (Barrouillet, Bernardin, & Camos, 2004; Barrouillet & Camos, 2012). It is assumed that engaging attention during the secondary task prevents refreshing from taking place concurrently, and that any free time after distraction is used for refreshing. Studies with younger adults have shown that items retro-cued before the distraction period retain their focusing boost (Hollingworth & Maxcey-Richard, 2013; Janczyk & Berryhill, 2014; Makovski & Pertzov, 2015; Rerko et al., 2014). For example, although performing a two-choice reaction time (RT) task while retaining a set of colored dots in mind for a memory test hampered WM performance, retro-cued items retained their privileged status after distraction compared to the no-cue condition (Rerko et al., 2014). It is worth noting, however, that these studies have not imposed a high cognitive load for distractor processing. Under low cognitive load, there is still free time after the distraction to switch attention back to the cued item in order to continue refreshing it. Hence, it is still unclear whether focused items retain their increased accessibility even in face of distraction, or whether it was the time after the distraction that was used for reestablishing the focusing boost. To assess for these possibilities, one needs not only to compare conditions with or without distraction, but also to vary cognitive load to limit free time after distractor processing. If the focusing boost is maintained relatively intact even under high cognitive load, this would lend further support to the notion that focused items remain resistant to interference.

In sum, it remains an open question whether older adults can maintain the focusing boost applied to an item after distraction similarly to what has been observed for younger adults, and whether the pattern of distractor resilience in either age group depends on the cognitive load of the distractor task.

Research Questions and Predictions

The current study examined age differences in visual WM using a continuous color reproduction task. Participants saw an array of colored dots, and following a brief retention interval, they were asked to recall one of the dots using a continuous color wheel. The events occurring within the retention interval varied according to our overarching goal to assess whether distraction (i.e., responding to digits) impairs visual WM as a direct function of cognitive load (no, low, or high load). We further tested for retro-cue benefits by varying whether a retro-cue was presented or not (retro-cue vs. no-cue conditions) prior to the onset of the distraction. Importantly, the novelty of this design was furthered by the fact that the task was individually calibrated, such that participants first completed a perceptual matching task as well as digit and memory load calibration tasks before beginning the critical task. The calibration tasks allowed us to determine the speed with which to present the digits to individually tailor the levels of cognitive load, and to determine the memory load (i.e., number of colored dots) yielding similar performance between age groups in a baseline with no-cues and with no distraction (hereafter a no-cue, no load condition). Given that age differences are commonly found for WM capacity, calibrating memory performance allows unambiguous interpretation of any interactions between age and key variables, such as cue and cognitive load (Loftus, 1978; Wagenmakers, Krypotos, Criss, & Iverson, 2012).

In sum, this design allowed us to investigate four principal research questions and predictions that we pre-registered on the Open Science Framework (OSF, https://osf.io/h3sdb/). Our research questions concerned age differences in (1) perceptual/motor ability, (2) the retro-cue effect in the conditions without distraction, (3) time-based forgetting, and, most importantly, (4) the persistence of the retro-cue effect after distraction.

First, the perceptual color matching task allowed us to assess age differences in perceptual/motor changes associated with aging. In our previous work (Loaiza & Souza, 2018; Souza, 2016), we observed some evidence for age impairments in color matching, but they were smaller than in the WM task. Hence, we expected to replicate an age difference in the perceptual matching task. We note, however, that by equating performance through our memory calibration procedure, we could measure effects related to the efficiency of attentional focusing that were unconfounded from changes in perceptual, motor, and even WM capacity.

Second, we examined whether there was an age difference in the retro-cue effect in the absence of distraction. As explained previously, it is still unclear whether the basic retro-cue effect is intact or impaired in older adults (e.g., Duarte et al., 2013; Souza, 2016). Our no cognitive load conditions (with and without a retro-cue) reproduces the design of previous work, but with a novel advantage that younger and older adults' performance was calibrated to a similar level in the no-cue condition. Thus, our study allows for a replication and extension of previous work by ensuring that any age differences in the retro-cue effect are not confounded with age differences in memory performance. Accordingly, we first predicted that our calibration procedure would be successful in yielding similar performance in the no-cue, no-load condition between age groups. If so, we would be able to determine whether or not an age difference emerges in the retro-cue, no-load condition by examining the interaction between age and cue condition. We expected to replicate our previous work showing a similar retro-cue effect between younger and older adults (Loaiza & Souza, 2018; Souza, 2016). This would indicate that focusing attention to refresh information in WM is unimpaired in older age.

Third, the nature of our design also allows us to consider whether time-based forgetting occurs for either age group. As more thoroughly explained in the Method section, the no-cue, no-load condition intermixed short and long retention intervals in order to match the timing of the fast and slow pace trials that involved distraction. Given that some work emphasizes that the role of refreshing is to protect representations from decay-based forgetting (e.g., Barrouillet et al., 2004), it may be the case that older adults show relatively greater forgetting as retention interval increases compared to younger adults. Such a finding would emerge as an interaction between age and retention interval, such that older adults' time-based forgetting is greater than that of younger adults.

Finally, and most importantly, the current study was designed specifically to address the novel research question regarding whether the retro-cue benefit is reduced for older adults as a function of distraction and cognitive load. Our pre-registered analysis concerned the "focus boost", i.e., the performance advantage conferred by retro-cues compared to no-cue trials, as a function of age and cognitive load. We predicted that an interaction between age and cognitive load would suggest that older adults are less capable of maintaining the focus boost after having been distracted compared to younger adults. However, previously unconsidered drawbacks of this analysis plan include the possibility that such an interaction could arise as an artifact of using difference scores (e.g., Cerella, 1985; Verhaeghen, 2000), and that it does not indicate whether the observed changes are related to the retro-cue trials (as we predicted) or also to changes in performance in no-cue trials. Thus, we also carried out and report a full analysis considering data in all design cells that included as predictors age, cue, and cognitive load. To foreshadow, after first having established some evidence for a three-way interaction, we moved on to assess the evidence for age x cognitive load interactions in each cue condition separately. This allowed us to examine the predicted two-way interaction between age and cognitive load in the retro-cue condition: given previous work (e.g., Rerko et al., 2014), younger adults may sustain the retro-cue benefit exhibited in no-load condition even after their attention has been distracted, whereas older adults may lose (completely or partially) the retro-cue benefit they exhibited in the no-load condition as function of distraction. In our pre-registration we remained open regarding the precise impact of cognitive load (i.e., the contrast between low vs. high cognitive load) given that previous retro-cue studies have not varied cognitive load. Furthermore, we had no strong prediction regarding the interaction between age and cognitive load in the no-cue condition, but in general we expected cognitive load to impair recall.

In summary, an interaction between age and cognitive load for the retro-cue benefit would provide evidence for a more specific refreshing deficit hypothesis, namely that older adults struggle to recover from distracted attention. This would further indicate that the refreshing deficit is not absolute, and instead specific sub-functions of focusing and switching attention are intact whereas the resilience of the refreshing boost is susceptible to normal age decline.

Method

Participants

In line with our pre-registration, we aimed to collect between 24 to 40 participants per age group. The minimum sample size was determined based on our previous experience with these tasks and effects. We monitored the evidence for our hypothesis after the initial 24 data-sets per group were available and increased the sample size accordingly. Given that the initial analyses did not provide clear evidence regarding our predictions (i.e., a Bayes Factor, BF, greater than 3 for or against the null hypothesis), we continued sampling participants until we acquired 40 valid data-sets. Bayesian inference is considered immune to problems related to changes in sampling plan (Rouder, 2014).

In total, 49 younger adults and 47 older adults took part in the experiment. Younger adults were students from the University of Essex who were compensated with course credit and older adults were individuals from the surrounding community and received £15 for participation. Eight and seven participants of the respective age groups were excluded due to failure to meet a criterion of 70% accuracy[1] on the critical distractor task described in the next section (*n* = 7 and 6, respectively) or failure to complete the experiment (*n* = 1 and 1, respectively). Our final sample included 41 younger adults and 40 older adults, and the older adults self-reported no medical history of memory or cognitive impairment (see Table 1 for sample characteristics). All participants passed a brief test for color blindness and provided

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[1] Note that we had originally pre-registered an 80% accuracy criterion, but after observing that the task was very difficult for most participants, we adjusted the criterion to 70% to retain as many participants as possible.

informed consent prior to starting the experiment. The study was approved by the Department of Psychology Ethics Committee at the University of Essex.

Materials and Procedure

Participants were tested individually in quiet booths; an experimenter was present in the booth during the initial instructions, and thereafter monitored several participants from outside their booths. The entire session lasted about 2 hours, with opportunities for breaks provided. The experiment was programmed in Matlab using the Psychtoolbox (Brainard, 1997; Kleiner et al., 2007), the materials and scripts for which can be found on the OSF (https://osf.io/h3sdb/). Participants first completed a color vision test and older adults additionally completed the MMSE. Participants then completed the critical phases of the task.

Perceptual Matching Task. First, participants completed a perceptual matching task wherein a target-color disk and a grey-probe disk were presented to the left and right of the center of the screen, respectively. A continuous color wheel (comprising 360 colors sampled from a circle in the CIELAB color space, with L = 70, a = 20, b = 38, and radius = 60) was shown around the two disks. Participants matched the color of the probe to the color of the target using the color wheel. The target colors were randomly sampled from the color wheel in each trial. The probe disk changed colors as the participants moved the mouse along the color wheel. When participants were satisfied with the color of the probe, they pressed the left-mouse button to confirm their answer. The dependent variable in this task was the absolute distance in the color wheel between the true color of the target and the response of the participant (hereafter, reproduction error).

For this task, as well as the memory load calibration task and the retro-cue task (explained below), participants completed four practice trials and 50 test trials. After the practice trials and every 10 test trials, participants received feedback about their average accuracy, which was expressed as a percentage based on their mean reproduction error (i.e., 100 – 100*mean error/180).

Digit Task. Second, participants completed a digit two-choice RT task. A digit (from 1-9) was displayed in the middle of the screen and participants classified its parity: if the digit was odd, they pressed the left mouse-button; if the digit was even, they pressed the right mouse-button. After responding to the digit, feedback regarding their response accuracy was displayed for 500 ms. After another 500-ms blank interval, a new digit was displayed. Digits were randomly sampled from 1-9, with the constraint that digits did not repeat across two successive trials. Every 20 trials, participants received feedback regarding their overall accuracy and speed. Participants completed a minimum of 80 trials. If accuracy in the last 20 trials exceeded 80%, the median RT in these trials was used for computing the cognitive load for the distraction phase implemented during the main WM task. If accuracy was below that threshold, an additional 20 trials were completed, and this process was repeated until the 80% accuracy criterion was reached.

The median RT in this task was used to compute the time to process the digit (D_{Time}) in the dual-task conditions (WM task + distraction) described in detail later. We used this value to generate two levels of cognitive load. For setting a low level of cognitive load, the D_{Time} was set to 2.5 x median RT. For setting a high level of cognitive load, D_{Time} was set to 1.5 x median RT. For example, if the median RT in the digit task was 0.6 s, D_{Time} = 1.5 s and 0.9 s under the low and high cognitive load conditions, respectively. The logic of this manipulation is that attention is engaged by the digit task for a given amount of time and any free time available afterwards can be used to refresh the memoranda, thereby counteracting any forgetting that may have occurred during processing of the secondary task.

Memory Load Calibration Task. Third, participants completed a visual WM task in which the memory load was gradually adjusted to achieve a criterion level of performance of 40° of recall error. In this task, a fixation cross was shown for 500 ms alerting participants to the start of the trial. Next, a set of *n* colored dots (dot radius = 32 pixels) was presented for 1 s. The dots were evenly spaced on an imaginary circle (radius = 150 pixels) centered on the middle of the screen. After a brief retention interval, memory for one of the colored dots was tested by presenting a dark-grey disk at the location of one of the dots (probe), a color wheel around the locations of all dots, and the mouse cursor in the center of the screen (see Figure 1B). Participants moved the mouse around the color wheel to adjust the color of the probe disk to the color they remembered in that location. When they were satisfied with their answer, they pressed the left mouse-button to confirm their response. The retention interval in the task was computed as 1.65 s + D_{Time} under the two cognitive load levels computed in the previous step. Half the trials used the low cognitive load D_{Time} (e.g., 1.65 + 1.5 = 3.15 s) and half used the high cognitive load D_{Time} (e.g., 1.65 + 0.9 = 2.55 s) to determine the length of the retention interval, and short and long trials were randomly intermixed. The initial *n* was 6 items for younger adults and 4 items for older adults. Based on their ongoing performance in the last 4 trials, the *n* for the subsequent trial was adjusted. If the mean recall error was below 40°, *n* increased by 1; if above, *n* decreased by 1. The average *n* in the last 20 trials was used to determine the memory load used in the main experimental task. For example, if the average *n* = 5.3 items, 70% of the trials in the main task contained a memory array with 5 items, and 30% of the trials contained 6 items. The distribution of *n*s was used in each block of the main task.

Retro-Cue Task. After completing these three phases, participants then completed the main experimental task. The task comprised trials similar to that of the memory load calibration task. The experimental phase was divided into 6 blocks that differed regarding (1) whether a retro-cue was presented or not, (2) the presence or not of the secondary digit task, and (3) the cognitive load of the digit task. In the *No-Cue, No-Load Baseline* block, participants completed trials exactly as described for the memory load calibration task, with the only difference that the number of items in the memory array was within the range individually calibrated to yield a mean recall error of 40°. The retention interval was again determined by the low and high cognitive load D_{Time} for half the trials, respectively, and randomly intermixed within the block (see first row of Figure 1A). In the *Retro-Cue, No-Load* block, the only difference to the No-Cue block was that 0.7 s after the offset of the memory array, a retro-cue (white arrow) was displayed indicating which item is relevant for the memory test (see second row of Figure 1A). In the No-Cue + Distraction blocks, 1.65 s after the offset of the memory array, a digit appeared in the middle of the screen and participants classified it as odd or even as fast and accurately as possible. D_{Time} in this task was varied across two separate blocks. In one block, participants were informed that they had a relatively long time to process the digit task (low cognitive load block), and in the other block they were informed that they had a relatively short time to process the digit (high cognitive load block). In the Retro-Cue + Distraction blocks, the retro-cue (duration = 0.25 s) appeared 0.7 s after the offset of the memory array, and 0.7 s after the offset of the retro-cue, the digit task was presented. As in the No-Cue Distraction blocks, there was one low cognitive-load block and a high cognitive-load block which differed only regarding the D_{Time}. All experimental blocks comprised 4 practice trials and 50 test trials. The order of the 6 blocks was counterbalanced across participants: we created 60 unique orders which were used once for each individual in each age group.

Data Analysis

Observed recall. For all tasks, practice trials were excluded from analysis. We used Bayesian inferential statistics implemented in R (R core team, 2017) for each analysis. Bayesian inference considers the ratio of the likelihood of different models (e.g., an age effect vs. a null effect) given the observed data, with this ratio (which is the Bayes Factor, BF) in turn serving to update prior beliefs. Importantly, Bayesian analysis allows the assessment of the evidence for or against the null hypothesis, and is thus advantageous over traditional frequentist statistics which disallow any interpretation of a null effect. Given our specific predictions that sometimes comprised, for example, null age differences in a particular outcome, Bayesian inferential statistics were most appropriate for addressing our research questions and corresponding predictions. In particular, we used the BayesFactor package (Morey & Rouder, 2015) in order to compare performance between age groups (i.e., Bayesian t-tests, see Tables 1 and 2) as well as mixed effects models of observed recall error that included fixed effects of the independent variables (i.e., age group, cue condition, and cognitive load) as well as by-participant random effects and slopes for each of the within-subjects factors.

These mixed effects models were implemented using (1) the lmBF function in the BayesFactor package, and (2) the R package rstanarm (Stan Development Team, 2018). The decision to use these respective analysis methods was due to their relative benefits for drawing inferences: (1) by quantifying the relative evidence (BF) for a given model (e.g., a model including an interaction between age and cognitive load) compared to alternative models (e.g., a model including only main effects of age and cognitive load), with BFs greater than 3 and 10 suggesting substantial and strong evidence, respectively; and (2) by obtaining a posterior effect size for each fixed effect that included a range of credible values (i.e., the highest density region, HDR), with credible effects being those that exclude 0. Thus, rather than a single-point estimate, a credible posterior allows an estimation of uncertainty, with relatively more pointed distributions suggesting a narrower, more precise range of credible values. For both methods, we used weakly informative priors by (1) using the default settings of the BayesFactor package (Rouder, Morey, Speckman, & Province, 2012), and (2) specifying Cauchy priors with location 0 and scale 5 and correlation matrices with shape parameter 1 (Gelman et al., 2013; Stan Development Team, 2018). All the models estimated with rstanarm showed that the four independent Markov chains converged to the same posterior distribution, evident in Rhat statistics (i.e., the ratio of between-chain to within-chain variance) close to 1, i.e., less than 1.026 (Gelman et al., 2013). Finally, it should be noted that the analysis with rstanarm required cognitive load to be dummy-coded given the three levels of the variable, and thus the posterior effects reported refer to the impact of a given cognitive load compared to the no-load condition.

Mixture Modeling. Finally, we also applied a hierarchical Bayesian three-parameter mixture model (Oberauer, Stoneking, Wabersich, & Lin, 2017) in order to examine the underlying latent cognitive parameters of observed recall error, i.e., the probability of a recalled item is in memory, memory precision, probability of a binding error, and probability of guessing. Although we did not pre-register this analysis, it is in line with our prior work (Loaiza & Souza, 2018; Souza, 2016). Given that we did not have any pre-registered predictions, we simply fitted a three-parameter model to each cell of the design. We report here the estimated parameters and posterior predictive checks to assess the extent to which the mixture model accurately captures the data.

Results

Before reporting the results to address our pre-registered research questions, we first examined potential age differences in the calibration and secondary task measures. Table 1 presents average group performance in these tasks and the evidence for age differences. During the digit calibration task, there was strong evidence (BF_{10}s > 9) that younger adults were slightly less accurate but faster than older adults. During the critical memory task, younger adults showed slightly higher digit task accuracy than older adults, but there was not enough evidence in the data to support this difference ($BF_{10} = 1.17$). Older adults were still overwhelmingly slower to respond to the digits ($BF_{10} = 1.38e+10$) during the critical memory task. Note that this would be expected given that that the task was calibrated to allow older adults more time to respond. Finally, as a result of the memory calibration phase, the memory load established for the critical task was substantially larger for younger than older adults ($BF_{10} = 24.80$). As planned, performance of both age groups during the last 20 trials of the memory load calibration phase was in the region of 40° error, with ambiguous evidence for an age difference in memory performance ($BF_{10} = 2.02$).

Perceptual Matching Task

Our first pre-registered research question and prediction concerned age differences in perceptual/motor ability (see Table 2). Similar to our previous studies, there was some evidence for an age difference in color matching (BF_{10} = 2.72). When excluding three older adults whose performance was outlying by 3 standard deviations of the group mean, however, there was ambiguous evidence in favor of a null age difference (BF_{10} = 0.76). Overall, these results are in line with the assumption that age-related impairment in perceptual/motor processes is smaller than the one in WM.

Retro-Cue Effect (no distraction)

Our second pre-registered research question concerned whether there was an age difference in the retro-cue effect during the no cognitive load condition. By calibrating memory load for each individual during the calibration phase, we were able to create a baseline condition (no-cue, no-load) that yielded similar performance between age groups (BF_{10} = 0.24, see Table 2), with both age groups' performance in the region of 40° error for which we aimed. To our knowledge, this has not been achieved in previous work using the retro-cue paradigm, but is especially important to ensuring that any potential interaction between age and retro-cue is disordinal and thus interpretable (Loftus, 1978).

In fact, performance in retro-cue, no-load trials tended to be similar between age groups, and there was ambiguous evidence in favor of the null in a t-test comparing these conditions (BF_{10} = 0.43, see Table 2). When the full data pattern was analyzed with a linear mixed effects model having cue and age as predictors, the model that excluded the two-way interaction between age and cue (BF_{10} = 5.35e+18) was only weakly preferred (BF = 1.33) to the full model including the interaction (BF_{10} = 4.02e+18). Table 3 presents the results of the posterior estimation for each model when using rstanarm. As shown in Table 3, the cue effect was large (it reduced recall error by more than 21°), and the posterior HDR did not include 0, indicating that this effect was credible. The age effect and the age x cue interaction were small and the HDR included 0, indicating that these parameters were not credibly different from 0. Thus, overall, these results replicate our prior work that focusing attention in the standard retro-cue paradigm is relatively unimpaired in older age (Loaiza & Souza, 2016; Souza, 2018).

Time-Based Forgetting

Our third pre-registered question concerned whether there was evidence for time-based forgetting in the no-cue baseline condition for either age group. As is evident in Table 2, there was substantial evidence against age differences in either retention interval (BF_{10}s $\leq$ 0.29). The evidence against worse performance over time was in the ambiguous range in younger adults (BF_{10} = 0.47) but substantial in older adults (BF_{10} = 0.24). When examining the evidence for a full mixed effects model relative to reduced models, the best model was the null model (i.e., a model including only a random effect of participants; BF_{10} = 1.5e+9). This model was weakly preferred (BF = 2.63) to the next best model including an effect of retention interval (BF_{10} = 5.7e+8). The posterior of the effect of retention interval presented in Table 3, however, shows a credible increase in recall error over time, but no credible age or age x retention interval interactions. Overall, these results suggest some evidence for time-based forgetting, but there was no evidence that this time-based forgetting is larger for older adults than younger adults.

Retro-Cue Effects after Distraction

Finally, the main goal of the present study was to determine whether retro-cue effects persist in face of distraction in both age groups, and whether cognitive load impacts this persistency. As described previously, our pre-registered plan was to consider the potential age x cognitive load interaction on the focus boost, that is, the performance difference between the no-cue and retro-cue conditions. However, upon further consideration, we realized it would be more proper to analyze recall error as a function of age, cue condition, and cognitive load (i.e., the full design), and then zoom-in on the interaction of age and cognitive load in the retro-cue condition. This is because our prediction of assessing the resilience of the retro-cue effect to distraction pertains to changes in performance in retro-cue trials (and not the effects of distraction on the no-cue conditions). These analyses showed a consistent pattern of results.

Focus Boost. The focus boost reflects how much performance improved as a function of the retro-cue compared to the no-cue condition. The focus boost for each cognitive load condition and age group is presented in Figure 2A. The focus boost was substantial in all conditions and groups, indicating that focusing attention in the cued item was always beneficial. Next, we assessed whether the focus boost varied as a function of age and cognitive load by entering these variables as predictors in a Bayesian linear mixed effects model. The full model including an interaction between age and cognitive load (BF_{10} = 3.74e+16) fitted the data better than the main effects only model (BF_{10} = 1.55e+16), but the full-model was only better than the main-effects model by a ratio of 2.41. The weak evidence for the interaction could have resulted due to the ambiguous evidence against an age difference in the retro-cue boost in the no-load condition (BF_{10} = 0.61). Conversely, evidence was substantial for an age difference in the low-load boost (BF_{10} = 7.60), and it was decisive for an age difference in the high-load boost (BF_{10} = 244.51).

The analysis of the posterior effects estimated with rstanarm presented in Table 3 suggests that the two-way interaction was evident for the age x (high vs. no) cognitive load contrast but not for the age x (low vs. no) cognitive load contrast. This also likely reduced the overall evidence for the two-way interaction described previously. Still, the overall results suggest that younger adults increasingly profit from having focused the cued item because this remains protected from interference, whereas older adults do not show the same pattern.

Overall Recall. To gain further insight into how this interaction came about, we present the full data in each experimental condition in Figure 2B. This figure shows that young and older adults did not differ in terms of their performance in any of the no-cue conditions or in the retro-cue, no-load condition. Only when the retro-cue is followed by varying levels of distraction, the two age groups grow apart, consistent with our prediction that older adults' focus boost is more susceptible to distraction than the one of younger adults. Although we were most interested in the same age x cognitive load interaction in the retro-cue condition, we first report on the full three-way analysis for thoroughness. Similar to the focus boost analysis, the full model including the three-way interaction (BF_{10} = 6.88e+134) was preferred to the model excluding the three-way interaction (BF_{10} = 2.74e+134), but only by a factor of 2.5. Once again, as is evident in Table 3, this appears to be largely driven by a lack of a credible age x cue x cognitive load interaction when contrasting the no-load vs. low-load conditions. Conversely, the same interaction term when contrasting the no-load vs. high-load conditions showed credible evidence for a three-way interaction.

Given our specific research question about the age differences in the retro-cue effect under distraction, we further conducted two separate age x cognitive load analyses splitting by cue condition. As is evident in Figure 2B, when considering the no-cue conditions only, the model excluding the age x cognitive load interaction (BF_{10} = 5.03e+34) was substantially preferred (BF = 5.88) to the model that included the two-way interaction (BF_{10} = 8.71e+33). Conversely, when considering only the retro-cue conditions, the model including the predicted age x cognitive load interaction (BF_{10} = 5.97+e35) was strongly preferred (BF = 87) to a model excluding the two-way interaction (BF_{10} = 6.78e+33).

As a further suggested analysis, we considered whether the age x cognitive load (low-load and high-load) interaction occurs for the retro-cue trials when excluding the no-load condition. This analysis showed ambiguous evidence (BF = 1.39) in favor of excluding the two-way interaction (BF_{10} = 1.43e+14) compared to a model that included it (BF_{10} = 1.03e+14). Furthermore, when modeled with rstanarm, the posterior effect of this interaction included 0 (*M* = 3.06, [-1.38, 7.42]). As is clear in Figure 2B, there was only ambiguous evidence for worse recall error as cognitive load increased in younger adults (BF_{10} = 1.31) whereas the difference was substantial in older adults (BF_{10} = 58.63).

Mixture Modeling. First of all, we assessed the fit of the model with a posterior predictive check. We sampled 1000 values from the posterior distribution of the model parameters and generated simulated data (i.e., model predictions). These predictions were then plotted against the distribution of the data. The predictions captured the data well (see results in the OSF). Next, we assessed the posterior of the parameters estimated by the model. Figure 3 presents the mean of the parameter posteriors, estimated at the group-level, with the error bars reflecting the 95% highest density intervals (HDIs) of the posterior. Comparison of the overlap in the HDIs between conditions is informative regarding the credibility of differences between these conditions. As shown in Figure 3, retro-cues improved memory precision (Figure 3A) and the probability of recalling the target (Figure 3B), congruent with previous retro-cue studies (Mok et al., 2016; Murray, Nobre, Clark, Cravo, & Stokes, 2013; Souza, 2016; Souza, Rerko, Lin, & Oberauer, 2014; Souza, Rerko, & Oberauer, 2016). The increase in target recall as a function of a retro-cue was due to a reduction in binding errors (Figure 3C) and random guessing (Figure 3D). Cognitive load mainly impacted the accessibility of the representations by increasing the probability of guessing (Figure 3D), which is consistent with prior work (Hardman, Vergauwe, & Ricker, 2017; Souza & Oberauer, 2017). The effect of cognitive load on guessing was attenuated in retro-cue trials for the young adults, but not for older adults. In summary, the results of the mixture modeling suggest that older adults struggle to keep the accessibility of the retro-cued item in face of distraction.

Discussion

The source of the age-related deficit in WM has been a profound issue for the field especially because of the wider implications for WM as a construct that constrains cognition across the lifespan. The current study investigated the *refreshing deficit hypothesis* that an attentional deficit is a major contributing factor to this general impairment in WM (e.g., Hoareau et al., 2016). Our novel adaptation of the retro-cue paradigm that equated performance between younger and older adults on baseline measures revealed three main findings regarding the refreshing deficit in older age: First, older adults were able to focus their attention as well as younger adults, replicating prior work that has not used such an adaptation (e.g., Loaiza & Souza, 2018; Souza, 2016). Second, recall error increased similarly between age groups as cognitive load increased in the no-cue condition. Although we predicted an overall effect of cognitive load, it is interesting that this effect did not interact with age, as some work has suggested that older adults are less sensitive to cognitive load effects due to their impaired refreshing ability (Jarjat, Portrat, & Hot, in press; Plancher et al., 2017; but see Baumans, Adam, & Seron, 2012). Critically, this difference may relate to our improved cognitive load calibration relative to previous work. We controlled for cognitive load by adjusting not only the time to respond to the digit, but also the time available for refreshing afterwards. This adjustment takes into consideration that age-related slowing probably affects decision making as well as refreshing speed.

Most importantly to our question, an attenuated retro-cue effect with increasing cognitive load in older adults suggests that preserving the refreshing boost when the focus switches to another unrelated task is impaired in older age. These findings are thus in line with a more nuanced refreshing deficit hypothesis. That is, rather than a kind of cognitive primitive (Raye, Johnson, Mitchell, Greene, & Johnson, 2007), refreshing may be better characterized by several sub-functions that may be differentially susceptible to age-related impairment. In particular, focusing attention on single representations and switching attention between different representations in WM may be relatively preserved with age (e.g., Loaiza & Souza, 2018; Souza, 2016), whereas this study suggests that older adults are relatively impaired at retaining the benefits of focused attention when faced with distraction. In general, the findings emphasize that refreshing in the face of distraction is an underlying factor of WM deficits in older age.

An alternative account of the current results instead suggests that the age deficit exhibited in the retro-cue condition may occur due to an overall cost of mixing different tasks. Indeed, in the cognitive load conditions the participants had to switch between the WM task and the distractor digit task. Thus, the fact that the age difference in the retro-cue effect in the no-load condition was not credible, but became substantial in the cognitive load conditions, suggests that older adults may have experienced disproportionate switch costs that account for the pattern of results. Indeed, the exploratory analysis showed a null age x cognitive load interaction when the no-load condition was excluded. However, there are two points that speak against this account. First, the low-load and high-load no-cue conditions also mixed different tasks of remembering and recalling colors while responding to digits. The task switch deficit should thus predict an age x cognitive load interaction in the no-cue condition, which we did not observe. Second, the results suggested that the age x cognitive load interaction, both with regard to the focus boost and performance in the retro-cue condition, was largely driven by the substantial age difference in the high-load compared to the no-load condition. If the mere presence of an additional task caused an age-related deficit, then one should expect the interaction to be as strong in the low vs. no load condition contrast as in the high vs. no-load condition contrast. Thus, it is unlikely that a task switch deficit explains the pattern of results.

Finally, the results also speak to our research questions regarding perceptual/motor abilities in older age and temporal-based forgetting. The results suggested that there was ambiguous evidence for a null age difference in perceptual/motor ability. For temporal-based forgetting, the evidence generally suggested a small overall effect of retention interval. It is worth nothing that the older adults had relatively longer retention intervals in general because the retention interval depended on the calibration phases that allowed for their slower response speeds compared to younger adults. Still, there was substantial evidence against an age difference in either short or long retention intervals. The fact that the results generally indicate a small impact of retention interval is particularly interesting given WM models that posit a strong role of refreshing to protect representations against temporal-based decay (Barrouillet et al., 2014; Barrouillet & Camos, 2012). Such a finding begs the question: if there is little evidence of temporal-based forgetting in the current paradigm, how then is refreshing operating on representations in WM to boost their recall? As we have asserted in our previous work (Loaiza & McCabe, 2013; Loaiza & Souza, 2018; Souza, 2016), refreshing may operate to strengthen the bindings between WM representations and their relative spatial-temporal context. Indeed, the results of the mixture modeling suggested that retro-cues improved memory precision and target recall due to reducing binding errors as well as guessing. This is consistent with the notion that focused attention strengthens the binding of the cued item to its location (thereby reducing inter-item competition) and increases its accessibility. In contrast, distraction reduces the accessibility of memory representations, with little change in inter-item interference. Whereas young adults can keep refreshed items protected from distraction and hence accessible in mind, older adults were equally susceptible to distraction in no-cue and retro-cue trials showing increased guessing rates in both conditions.

In summary, using a novel adaptation of the retro-cue paradigm that calibrated younger and older adults’ performance at baseline, the current study replicated the finding that older adults are able to focus attention on no-longer perceptually available representations in WM, a critical component of refreshing. Notwithstanding, we observed that focused representations were susceptible to distractor interference in older adults, but younger adults were able to maintain these representations intact. This indicates that one component of refreshing, that is, the ability to preserve the benefits of focused attention after the focus moves away is subjected to age-related decline.

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Table 1. Sample characteristics and means (and standard deviations) and comparisons (Bayes Factor, BF) of performance on calibration and secondary task measures.

Measure	Younger adults	Older adults	BF_{10}
Age in years	19.44 (1.43)	68.58 (4.28)	-
Sex (males/females)	6/35	18/22	-
Mini-mental status exam (MMSE)	-	28.85 (1.00)	-
Calibration Digit Task: Accuracy	0.96 (0.05)	0.98 (0.03)	9.12
Calibration Digit Task: RTs (s)	0.55 (0.09)	0.70 (0.15)	31,445
Calibration Memory Phase (° reproduction error)	42.10 (5.74)	45.62 (8.18)	2.02
Memory Load	5.82 (1.19)	4.89 (1.32)	24.80
Critical Digit Task: Accuracy	0.88 (0.06)	0.85 (0.08)	1.17
Critical Digit Task: RTs (s)	0.63 (0.10)	0.88 (0.16)	1.38×10^{10}

Note. RTs = response times.

Table 2. Means (and standard deviations) and comparisons (Bayes factors, BF) regarding the first three research questions.

Research Question	Measure	Younger adults	Older adults	BF_{10}
1. Is there an age difference in the perceptual matching task?	Perceptual Matching Task (° reproduction error)	3.02 (0.66)	4.03 (2.63)	2.72
	Perceptual Matching Task: Outliers Excluded	3.02 (0.66)	3.41 (1.36)	0.76
2. Is there an age difference in the retro-cue effect in the no-load condition?	No-Cue, No-Load Block (° reproduction error)	45.62 (14.11)	44.70 (14.91)	0.24
	Retro-Cue, No-Load Block (° reproduction error)	23.78 (11.77)	26.99 (12.32)	0.43
3. Is there evidence of time-based forgetting in either age group?	No-Cue Baseline Block: Short RI (° reproduction error)	43.44 (13.98)	44.26 (16.63)	0.24
	No-Cue Baseline Block: Long RI (° reproduction error)	47.81 (16.88)	45.14 (15.85)	0.29

Note. RTs = response times, RI = retention interval

Table 3. Posterior effect estimates (and their 95% HDRs).

	Research Question 2	Research Question 3	Research Question 4	
Variable	Retro-Cue Effect (no load)	Time-Based Forgetting	Focus Boost	Overall Recall
Intercept	**45.68 (41.19, 49.91)**	**43.43 (38.68, 48.14)**	**21.86 (18.16, 25.73)**	**45.75 (41.52, 50.18)**
Age group	-0.89 (-7.14, 5.21)	0.82 (-5.90, 7.50)	-4.08 (-9.66, 1.13)	-1.08 (-7.27, 5.08)
Cue	**-21.81 (-25.80, -17.80)**	-	-	**-21.85 (-25.78, -18.10)**
Retention interval	-	**4.38 (0.20, 8.45)**	-	-
Cognitive load - low	-	-	**10.54 (6.48, 14.52)**	**10.63 (7.48, 13.83)**
Cognitive load - high	-	-	**12.87 (8.67, 16.82)**	**16.10 (13.09, 19.09)**
Age x Cue	4.13 (-1.63, 9.70)	-	-	4.14 (-1.43, 9.71)
Age x Retention interval	-	-3.53 (-9.33, 2.38)	-	-
Age x Cognitive load - low	-	-	-4.11 (-9.53, 1.51)	0.91 (-3.57, 5.48)
Age x Cognitive load - high	-	-	**-8.25 (-13.89, -2.05)**	-0.23 (-4.63, 4.37)
Cue x Cognitive load - low	-	-	-	**-10.61 (-14.58, -6.34)**
Cue x Cognitive load - high	-	-	-	**-12.89 (-17.00, -8.73)**
Age x Cue x Cognitive load - low	-	-	-	4.21 (-1.65, 9.88)
Age x Cue x Cognitive load - high	-	-	-	**8.21 (2.33, 14.17)**

Note. Credible effects (i.e., HDRs that exclude zero) are printed in boldface. HDR = highest density region.

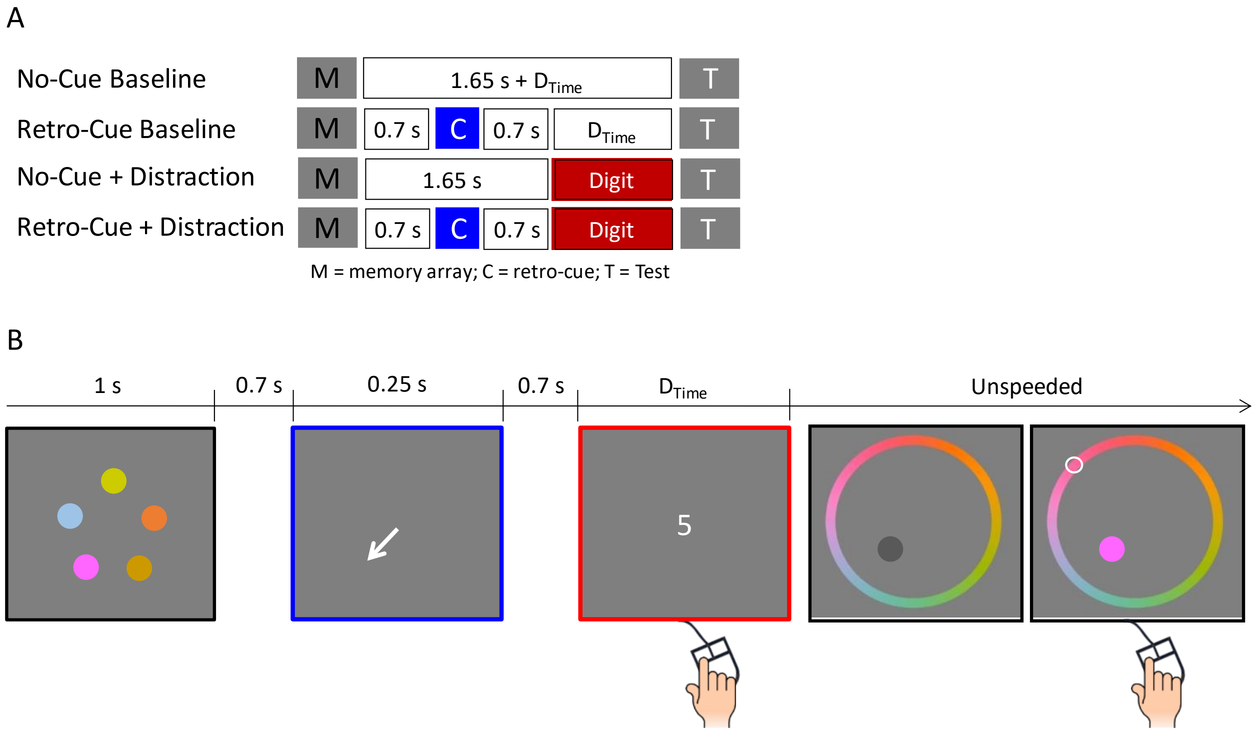

Figure 1. Panel A: Schematic illustration of the events in the structurally different experimental blocks implemented in the main WM task. D$_{Time}$ = the time available to process the digit task which was varied between two levels: low cognitive load and high cognitive load. Panel B: Examples of the displays presented during the main task. In order of appearance: memory array, retro-cue, digit task, and memory test. See the online version of the article for a color version of this figure.

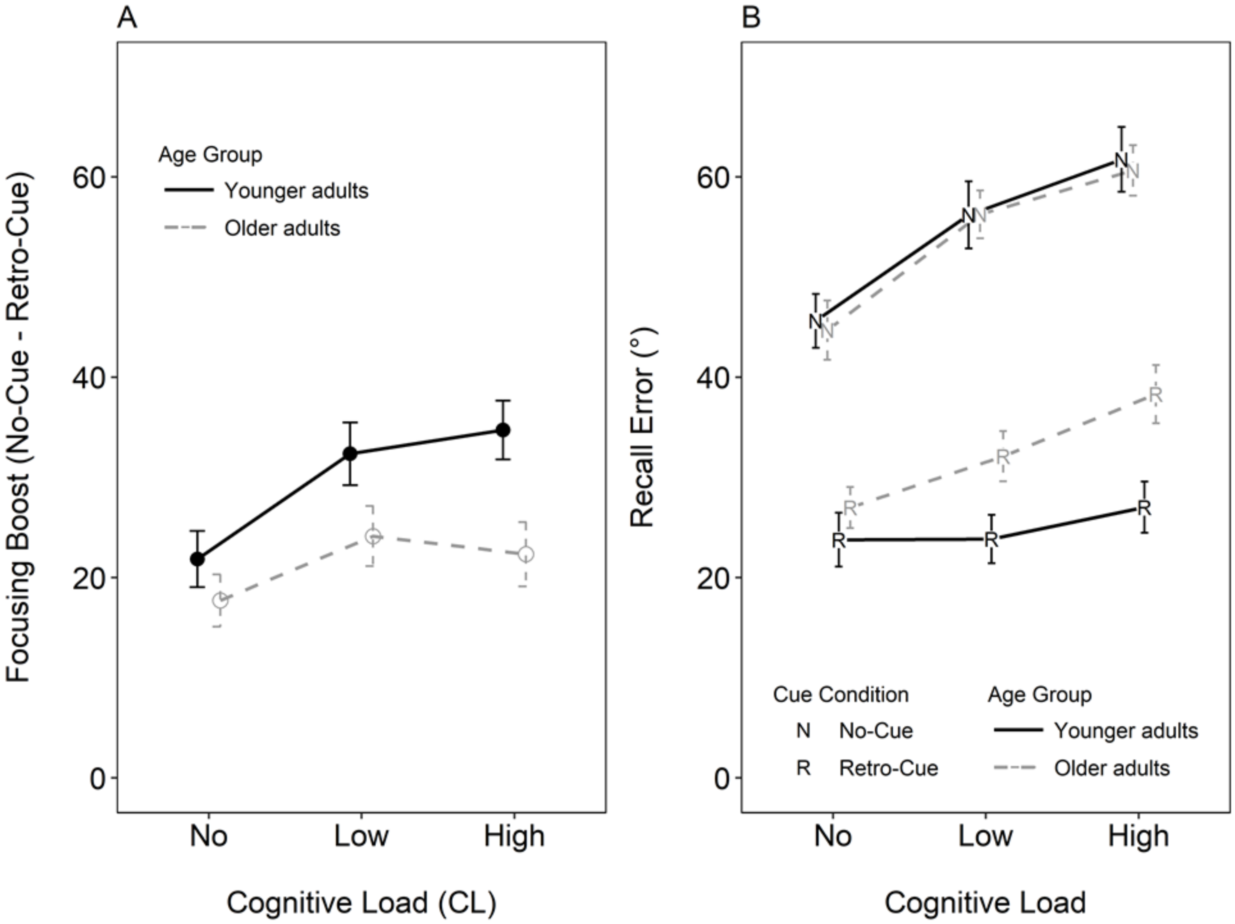

Figure 2. Panel A: Focus boost (i.e., no cue – retro-cue recall error) as a function of age group and cognitive load. Panel B: Recall error as a function of age group, cue condition, and cognitive load. Error bars show 95% within-subjects confidence intervals.

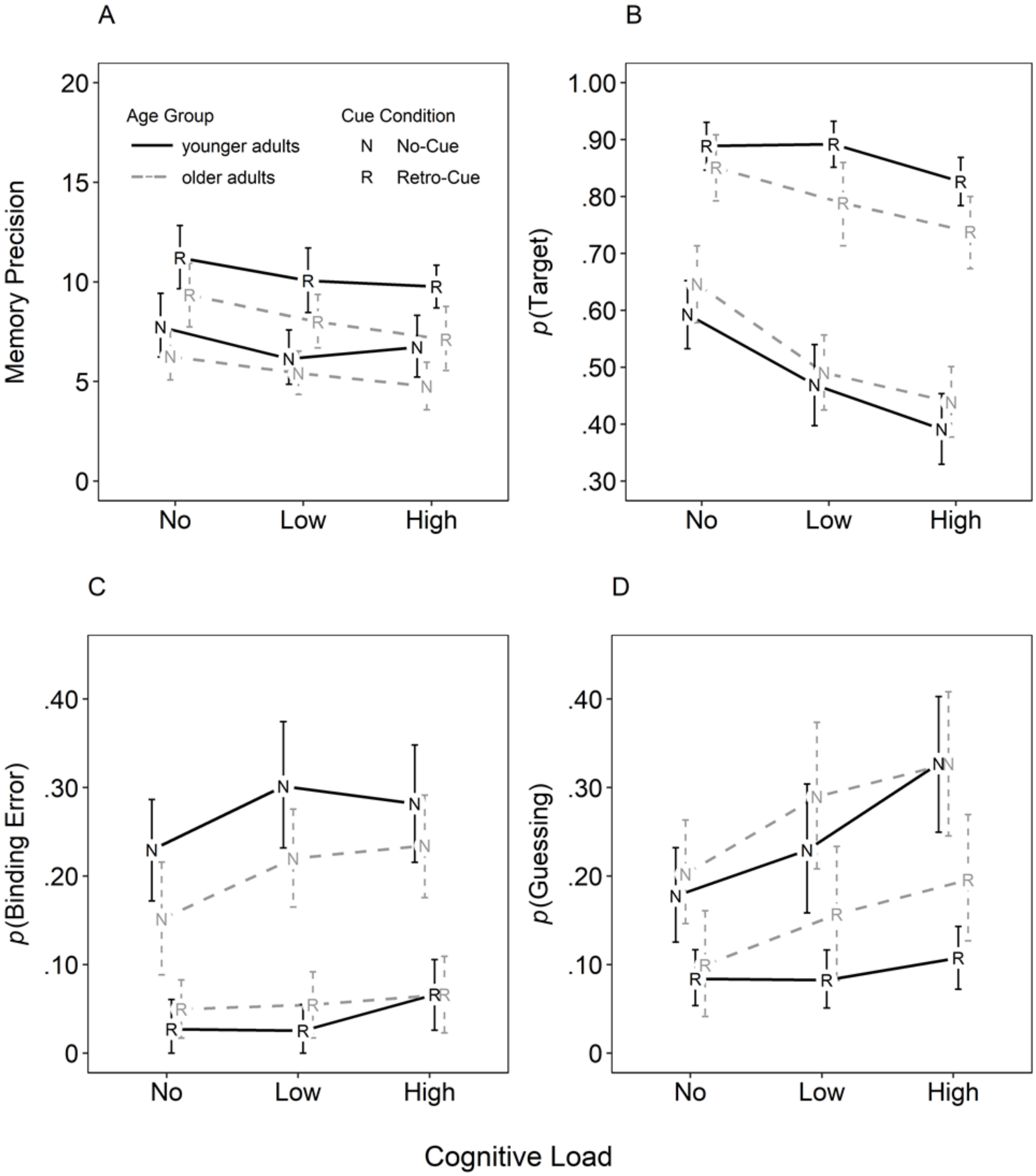

Figure 3. Posterior parameter estimates of the Bayesian hierarchical mixture model for memory precision (Panel A; parameter Kappa), probability of recalling the target (Panel B), probability of a binding error (Panel C), and probability of guessing (Panel D). The dots show the mean and the error bars show the 95% HDIs of the posterior.