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Age differences in the use of positive and negative cues to filter distracting information from working memory

Rosa E. Torres[1] · Stephen M. Emrich[1] · Karen L. Campbell[1]

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Abstract
Previous research has demonstrated that as people age, visual working memory (VWM) declines. One potential explanation for this decline is that older adults are less able to ignore irrelevant information, which contributes to VWM filtering deficits. Most research examining age differences in filtering ability has used *positive* cues (indicating which items to pay attention to), but *negative cues* (indicating which items to ignore) may be even harder for older adults to implement as some work suggests that negatively cued items are first paid attention to before they are suppressed. The current study aimed to test whether older adults can use negative cues to filter irrelevant information from VWM. Across two experiments, young and older adults were presented with two (Experiment 1) or four (Experiment 2) display items, preceded by a neutral, negative, or positive cue. After a delay, participants reported the target's orientation in a continuous-response task. Results show that both groups benefitted from being provided with a cue (positive or negative) compared to no cue (i.e., neutral condition), but the benefit was smaller for negative cues. Thus, although negative cues aid in filtering of VWM, they are less effective than positive cues, possibly due to residual attention being directed towards distractor items.

Keywords Working memory · Filtering · Negative cue · Aging · Cognitive control

Introduction

A long line of work shows that as people age, working memory abilities decline (Brockmole & Logie, 2013; Park & Reuter-Lorenz, 2009), which is thought to in turn affect other cognitive abilities such as executive function and fluid intelligence (Fukuda et al., 2010; Johnson et al., 2013; Miyake et al., 2001). One possible explanation for this age-related working memory decline may be a decrease in inhibitory control (Hasher & Zacks, 1988). Inhibitory control allows people to limit their attention to the most relevant information to complete their goals and it has been shown to predict working memory abilities (Emrich & Busseri, 2015; Lustig et al., 2007). Specifically, several studies suggest that age differences in working memory are not due to age-related impairments in the ability to attend to/activate relevant information, but rather impairments in the ability to (1) prevent irrelevant information from entering the focus of attention and (2) suppress previously attended information that is no longer relevant (for a recent review, see Campbell et al., 2020). For instance, in a functional magnetic resonance imaging study by Gazzaley et al. (2005)**,** older and younger adults were presented with a series of faces and scenes and asked to either attend to or ignore one category at a time, or to view the image categories passively. They found that both young and older adults showed equivalent levels of activation for the relevant category, meaning that both groups were able to increase their activation in the parahippocampal place area (a scene-selective region) when told to attend to scenes relative to passively viewing them. However, when participants actively tried to ignore scenes and remember the faces, young adults showed reduced activation in the parahippocampal place area relative to passive viewing (i.e., suppression) while older adults exhibited no significant suppression in this region. Thus, activation of relevant information seems to remain intact with age, while suppression of irrelevant information is impaired.

This inhibitory deficit also extends to visual working memory (VWM), which is the active maintenance and

✉ Rosa E. Torres
rt18dk@brocku.ca

Stephen M. Emrich
semrich@brocku.ca

Karen L. Campbell
karen.campbell@brocku.ca

[1] Department of Psychology, Brock University, 1812 Sir Isaac Brock Way, St. Catharines, ON L2S 3A1, Canada

manipulation of visual information. For instance, older adults show delayed filtering of distracting information from VWM, as indexed by contralateral delay activity (CDA, an electroencephalography (EEG) component that tracks the number of items stored in VWM; Jost et al., 2011). This was also shown in a recent study by Zuber and colleagues (2019), who used an antisaccade task and a Simon task to determine whether individual differences in inhibitory control contribute to age-related declines in VWM performance. Through regression analyses and path models, they found that the effect of age on VWM was mediated by inhibition. These findings suggest that changes in inhibition throughout the lifespan play a major role in age-related declines in VWM.

Previous VWM filtering research has tended to use *positive cues*, which means participants are shown a cue of a feature (e.g., color, shape) of the target item to be tested later (e.g., Zhang et al., 2020), which allows participants to selectively pay attention to relevant to-be-tested items and ignore distractors (i.e., non-targets). However, recent studies have demonstrated that young adults can also use *negative cues* – providing information on distractor features that should be ignored – to filter out irrelevant information (Williams et al., 2020; Zhang et al., 2020). For instance, Williams et al. (2020) gave participants negative and neutral pre-cues that indicated whether they should engage in distractor filtering or not during a delayed-estimation VWM task. After a delay, the target item was tested, and participants had to estimate its original color or orientation. They found that when given negative cues, young adults were more accurate in their reports of the target information than in the neutral cue condition, suggesting that people can use negative cues to filter irrelevant information from VWM.

While young adults can efficiently filter irrelevant information using positive and negative cues, it has yet to be determined whether older adults can effectively use negative cues to ignore irrelevant information. There is ample evidence to suggest that older adults can use positive cues to direct their attention in space (Hartley, 1993) or towards relevant features (Quigley et al., 2010). However, since some work suggests that negative cues first direct attention toward to-be-ignored items prior to those items being suppressed (i.e., the search-and-destroy hypothesis; Moher & Egeth, 2012), and older adults have trouble disengaging their attention once it is captured (e.g., Weeks et al., 2020), we may expect older adults to have trouble using negative cues.

In the current study, we aimed to test whether older adults can filter out irrelevant information as effectively as young adults when presented with a negative cue. Across two experiments, older and younger adults were presented with two (Experiment 1) or four (Experiment 2) items at a time and were directed to alter their encoding strategy based on cue type. When presented with a positive cue, participants had to encode items of that color (e.g., blue); when presented with a negative cue, they had to ignore items of that color (e.g., red); and when given a neutral cue, they had to encode all items on the screen. After a delay, participants were probed to report the orientation of the target item. To measure filtering ability, we used participants' raw error (i.e., how far their response was from the correct orientation) as well as a three-component mixture model (Bays et al., 2009) to derive estimates of memory precision, non-target error rate (how often they reported the orientation of the irrelevant item(s) instead of the target), and guess rate.

We predicted that older adults would be less able to use negative cues relative to positive cues due to their difficulty in suppressing information once it has entered the focus of attention (e.g., Jost et al., 2011; Weeks et al., 2020) and evidence suggesting that negatively cued items are first attended prior to being suppressed (Moher & Egeth, 2012). Thus, older adults should show greater error and higher non-target error rates in the negative cue condition than in the positive cue condition. This may also be reflected by lower precision following negative cues relative to positive cues. We also expected younger adults to show better performance for positive than negative cues, based on past literature (Zhang et al., 2020), but this difference should be less pronounced than in the older group. We did not expect any effect of condition on the guess rate. Finally, for both age groups, we expected filtering performance to be improved when provided with any kind of cue (whether positive or negative) compared to when no cue was provided, and this should be reflected in their raw error, memory precision, and non-target errors.

Experiment 1

Experiment 1 was designed to determine whether older adults can use negative cues to filter out irrelevant information as efficiently as young adults at a low memory load (i.e., two items). Since older adults' VWM deficits tend to be more pronounced at higher loads, a low memory load was chosen to optimize performance in this initial test.

Methods

Participants

This study was approved by and performed in line with the Brock University Social Science Research Ethics Board and preregistered on the Open Science Framework (https://osf.io/kpemz/). Participants were recruited to the study through the Prolific online participant pool and were based in the United Kingdom. We collected data from 85 healthy participants (i.e., normal or corrected-to-normal vision, normal color vision, and no psychological disorders) in total. All participants were fluent in English. The sample was split evenly between age groups, containing 42 young adults (ages 18–30 years; *M* = 23.50, *SD* = 3.40) and 43 older adults (ages 60–80 years; *M* = 64.3, *SD* = 3.18). The number of participants needed was determined via a statistical power analysis using G*Power, aiming for 95% power to detect a small-to-medium sized effect (partial $\eta^2 = 0.03$) for the 2 age (young, old) × 3 conditions (positive, negative, neutral) interaction (the small-to-medium effect size was not based on previous work, as there were no similar studies on which to draw). An additional 49 participants were tested and needed to be replaced (criteria set out in the preregistration): 38 due to failing the attention checks (10 younger adults, 28 older adults), and 11 due to having a non-target error greater than 50% (as determined by the mixture model; two younger adults, six older adults), or being more than 3 SDs away from the mean memory precision (this final criterium was not part of our initial pre-registration; two younger adults, one older adult).

Materials and procedure

Visual working memory task Participants completed a visual working memory task that was modified from Experiment 3 of Williams et al. (2020) and programmed in PsychoPy. At the beginning of the task, each participant's screen was calibrated to make the stimulus dimensions consistent across participants; similar methods were used by Yao et al. (2022). Despite each participant's screen being calibrated, since this study was performed online, there was no way to control the participants' distance from the screen, and thus all measurements are approximate. However, participants were instructed to view the monitor from a distance of approximately 10 in. At the start of each trial (see Fig. 1), a fixation cross appeared for 1,000 ms (with dimensions of 0.5° × 0.5°). This was followed by a square pre-cue (1.7° × 1.7°) at fixation for 1,000 ms. The pre-cue indicated whether participants should pay attention to an item of a specific color (positive cue), ignore an item of a specific color (negative cue), or have no color information at all (neutral cue, meaning they would have to pay attention to all items), with cue type manipulated across blocks. The color of the pre-cue was randomized on each trial for the positive and negative cue conditions. After a delay (900 ms), participants were presented with a sample display consisting of two rectangles (0.6° × 1.7°), one 3.38° to the left and the other 3.38° to the right of center. Each rectangle was of a different color and orientation, with one of the two rectangles matching the color of the cue (for the positive and negative cue conditions). The colors of the rectangles were randomly generated from a 360° color wheel (CIE L*a*b color space (L = 70, a = -6, b = 14, radius = 49)). The two colors presented at once had to be at least 30° apart from each other in the color wheel. The orientations of the rectangles were also randomly

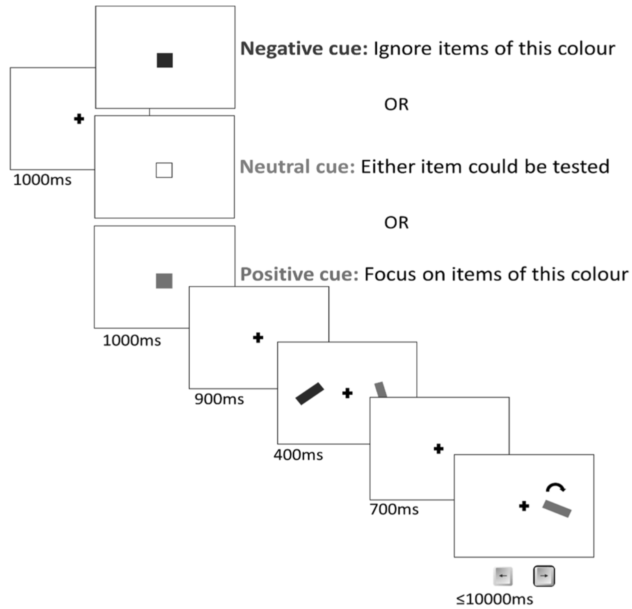

Fig. 1 Schematic of the visual working memory task with three different kinds of pre-cues. A negative, neutral, or positive cue is followed by a display screen with one target (for negative and positive cue trials) and two targets (for neutral cue trials). The test screen presented only the target item from the display and was present until a response key was pressed, or 10 s passed. An example of a positive cue trial is depicted above

generated from 1°–180° and the two orientations presented at once had to be at least 20° apart.

Following the sample display, a fixation cross appeared again (700 ms). Finally, a test screen was presented with one (the target) of the two rectangles from the display at its original location; however, the orientation of the probe item was randomized. Participants were instructed to rotate the target rectangle's orientation with the left and right arrow keys to replicate its original orientation of the one target from the display screen. Once participants were done reorienting the target rectangle, they could advance to the next trial by pressing enter (they had up to 10 s to respond before a new trial began). The task consisted of 360 trials in total and was divided into three blocks with 120 trials each (including 20 practice trials at the beginning of each block). Each block consisted of trials of one condition only (positive, negative, or neutral) and the order of the conditions was fully counterbalanced. Therefore, the same number of subjects were exposed to each counterbalance order.

Data analysis

All statistical analyses were completed using custom scripts in MATLAB R2021a and JASP version 0.14.1.0. To analyze the data, the raw error was calculated by determining the difference between the participants' reported orientation and the shown target orientation, and then analyzed using the three-component mixture model (Bays et al., 2009). The model breaks down the general raw error distribution into the maximum likelihood of the guess rate (the proportion of random responses), non-target errors (the proportion of responses centered around the non-target items), and memory precision (the circular standard deviation centered around the target; see Bays et al., 2009, for model details). While the mixture model allows us to examine responses specific to our hypotheses (in particular, non-target responses), raw error was also examined as raw error provides a model-free measure of performance (Ma, 2018). Any participant with a guess rate higher than 30%, a non-target error greater than 50%, or memory precision higher or lower than 3 SDs from the mean in any cue condition was replaced.

Mixed ANOVAs are reported for each parameter estimate from the model (guess rate, memory precision, and non-target error) in addition to the raw memory error using cue type as a within-subjects factor and age (young vs. older adults) as a between-subjects factor. Additionally, paired-samples t-tests were used for follow-up comparisons.

Results

Raw memory error

A mixed ANOVA of raw memory error demonstrated a significant main effect of cue type, F (2, 166) = 43.57, $p <$ 0.001. There was also a significant main effect of age on raw memory error, F (1,83) = 7.11, p = 0.009, and an interaction between age and cue type, F (2, 168) = 3.59, p = 0.030.

Follow-up t-tests were conducted within each age group. Young adults exhibited greater error (measured in circular standard deviation, where a higher score means a less precise answer) in the neutral condition (M = 15.29, SD = 5.36) compared to the negative (M = 13.70, SD = 4.10), t (41) = 2.19, p = 0.034, and positive cue conditions (M = 12.00, SD = 3.70), t (41) = 4.44, p < 0.001. Young adults also displayed lower memory error on positive cue trials compared to negative cue trials, t (41) = 2.89, p = 0.006.

As can be seen in Fig. 2A, these condition differences were more pronounced in the older group (hence the age × cue type interaction). Older adults' memory error was highest in the neutral condition (M = 19.58, SD = 5.05), followed by the negative cue condition (M = 15.03, SD = 5.61), t (42) = 4.63, p < 0.001, and they performed best on positive cue trials (M = 12.31, SD = 2.98), t (42) = 8.65, p < 0.001. Additionally, older adults' memory error was significantly lower on positive cue trials compared to negative cue trials, t (42) = 3.14, p = 0.003. Thus, both older and younger adults appear to use direct cues, such as the positive cue, more efficiently compared to indirect cues (i.e., the negative cue).

Mixture model – precision

A mixed ANOVA of memory precision revealed a significant main effect of cue type, F (2, 166) = 71.85, p < 0.001. The main effect of age was also significant, F (1, 83) = 12.50, p < 0.001, and there was a significant age × cue type interaction, F (2,166) = 7.50, p < 0.001. Thus, the effect of cue type differed between age groups (see Fig. 2B).

Looking within each age group separately, for young adults, the neutral cue condition (M = 11.92, SD = 3.04) resulted in significantly lower memory precision compared to the negative cue condition (M = 10.33, SD = 2.25), t (41) = 4.07, p < 0.001, as well as to the positive cue condition (M = 9.81, SD = 2.28), t (41) = 4.89, p < 0.001. There was no significant difference in memory precision between trials with a positive and negative cue, t (41) = 1.72, p = 0.092.

Older adults exhibited a similar trend to young adults, with memory precision of the neutral cue condition (M = 14.74, SD = 2.94) being significantly lower compared to that of the negative (M =11.52, SD = 2.45), t (42) = 7.69, p < 0.001 and positive cue conditions (M = 10.66, SD = 2.20), t (42) = 10.01, p < 0.001. Unlike younger adults, older adults also showed lower precision in the negative cue condition compared to the positive cue condition, t (42) = 2.58, p = 0.013. Thus, older adults had higher memory precision when using positive cues, followed by negative cues, and had the lowest memory precision in the neutral cue condition.

Non-target errors

A mixed ANOVA of the non-target errors showed a significant main effect of cue type, F (2, 166) = 11.36, p < 0.001. However, there was no main effect of age, F (1,83) = 1.46, p = 0.231, and no cue type × age interaction, F (2, 166) =1.65, p = 0.195 (see Fig. 2C).

When collapsing across age groups, participants reported significantly more non-target errors during the neutral cue trials (M = 0.07, SD = 0.08) compared to the positive cue condition (M = 0.02, SD = 0.03), t (84) = 4.759, p < 0.001, and no significant difference in non-target errors between the neutral cue condition and the negative cue condition (M = 0.05, SD = 0.07); t (84) = 1.87, p = 0.064. Additionally, participants showed a significantly higher proportion of non-target errors on the negative cue condition compared to the positive cue condition t (84) = 3.09, p = 0.003, suggesting that both groups reported the wrong item more often following negative than following positive cues.

Guess rate

A mixed ANOVA of guess rate showed no significant difference in guess rate between cue conditions, F (2, 166) = 0.44, p = 0.646, nor between age groups, F (1,83) = 0.89, p

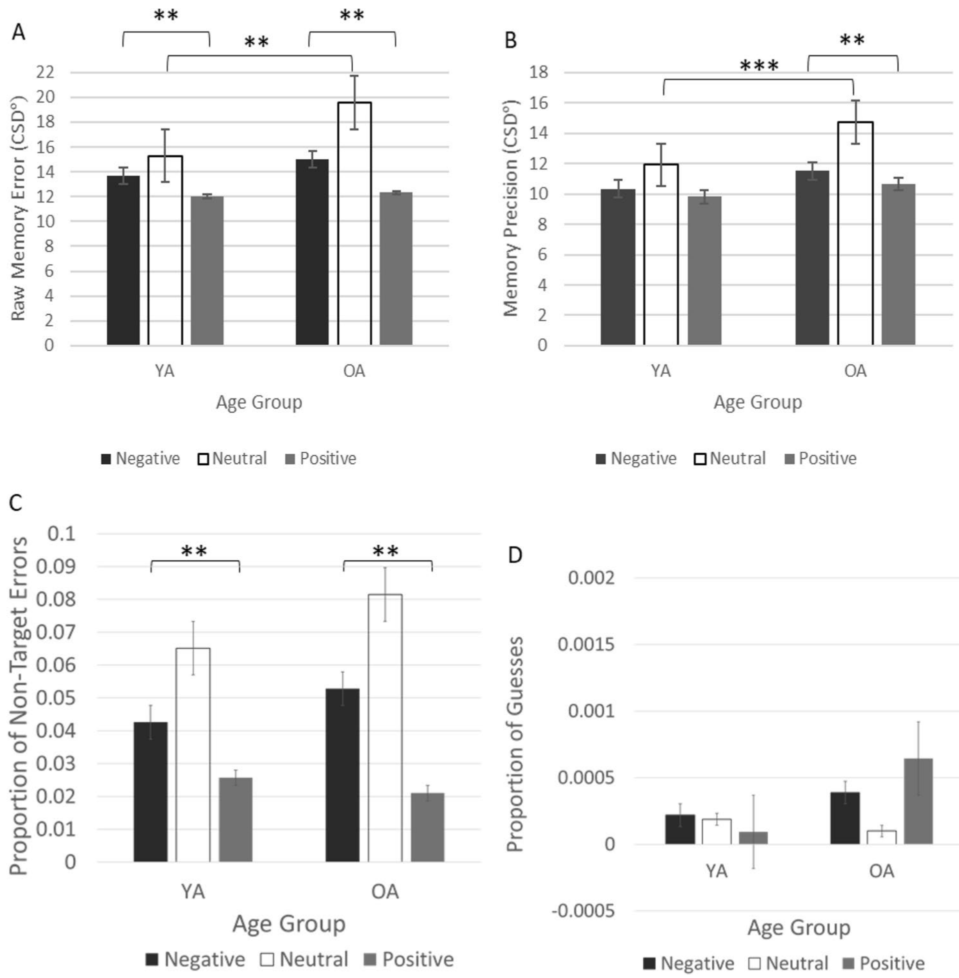

Fig. 2 Circular standard deviation of the raw memory error (**A**) and memory precision (**B**) measures, and the proportion of non-target errors (**C**) and guesses (**D**) of Experiment 1. Negative (dark grey bars), neutral (white bars), and positive (light grey bars) cue condition data for each age group (YA: young adults, OA: older adults; CSD: circular standard deviation) are presented. $^{**}p < .01$, $^{***}p < .001$

= 0.349. The age × cue type condition was also not significant, F (2, 166) = 0.85, p = 0.428 (see Fig. 2D).

Discussion

In Experiment 1, we used three cueing conditions (positive, neutral, and negative) to indicate to which stimulus participants should direct their attention. Older adults demonstrated that they can use negative cues to improve the precision of VWM, in that their memory precision was higher (and their raw error lower) in the negative cue condition relative to the neutral cue condition. It should be noted, however, that young and older adults also saw a greater benefit from positive cues compared to negative cues in raw memory error. However, only older adults also showed this greater benefit from positive cues compared to negative cues in their memory precision. Contrary to our prediction, there was no age difference in terms of the rate of non-target errors, but both groups erroneously reported more non-target information when they were given a negative cue compared to when they were presented with a positive cue. Therefore, all participants filtered out irrelevant non-target information less efficiently when presented with the negative cues compared to when they used positive cues, which is in line with the hypothesis that negatively cued items are first attended to prior to being suppressed (Beck & Hollingworth, 2015; Geng, 2014; Moher & Egeth, 2012). Taken together, these findings suggest that older adults can benefit from negative cues to nearly the same extent as younger adults.

Experiment 2

In Experiment 1, both age groups used negative cues less effectively compared to positive cues. However, contrary to our prediction that older adults would make more non-target errors, both age groups made more non-target errors in the negative cue condition relative to the positive cue condition. We may not have observed the expected age difference in non-target errors because we used the lowest possible set size in Experiment 1. Previous work suggests that older adults' inhibitory abilities may be more pronounced as tasks become more challenging (i.e., by having more items to remember; Luck & Vogel, 1997). Thus, Experiment 2 used a higher set size (i.e., four items instead of two) to examine age differences in the ability to employ negative cues when attentional demands are increased.

Methods

Participants

Seventy-eight healthy participants (i.e., normal or corrected-to-normal vision, normal color vision, and no psychological disorders) completed the study via Prolific. All participants were fluent in English and were from the United Kingdom. The sample was split between age groups, with 42 young adults (ages 18–30 years; M = 24.5, SD = 4.32) and 36 older adults (ages 60–80 years; M = 65.97, SD = 5.36). An extra 55 participants were replaced or rejected based on the same rejection criteria as Experiment 1: 47 were replaced due to failing the attention checks (15 younger adults, 32 older adults), and eight were rejected and not included in the analysis due to having a non-target error greater than 50% (as determined by the mixture model; one younger adult, five older adults) or being more than 3 SDs away from the mean memory precision (no younger adults, two older adults).

Materials and procedure

Visual working memory task Participants completed a visual memory task identical to that of Experiment 1, with the exception that four stimuli were presented in the memory array instead of two stimuli. Therefore, participants now had to pay attention to (positive cue trials) or ignore (negative cue trials) two items, to eventually report the orientation of only one item of the target color at test. Participants were still asked to remember all items during the neutral condition; therefore, they would have to remember four items in total in the neutral cue condition (see Fig. 3). On the display screen, a rectangle was presented at each of the following locations: 3.38° to the left and 3.38° to the top, 3.38° to the left and 3.38° to the bottom, 3.38° to the right and 3.38° to the top, and 3.38° to the right and 3.38° to the bottom of the center of the screen. Two different colors were used on each trial, meaning that two pairs of rectangles shared the same color. The two rectangles of the same color were placed diagonally from each other to avoid cueing only one side of the screen when participants were presented with the color cue.

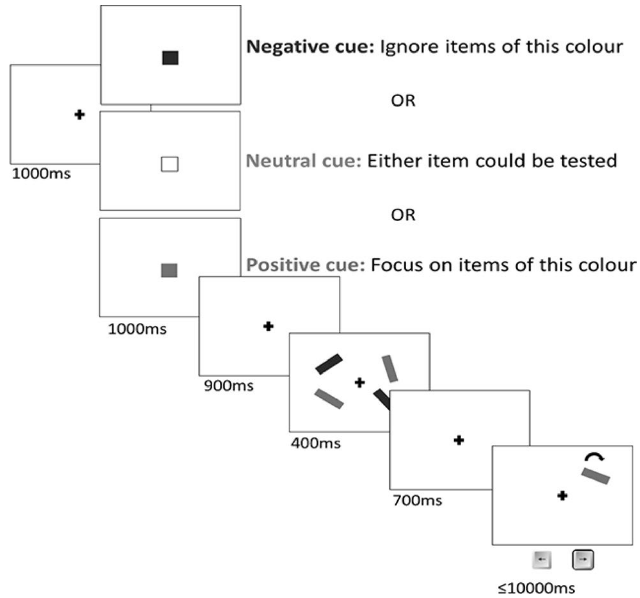

Fig. 3 Schematic representation of the visual working memory task with three different kinds of pre-cues. A negative, neutral, or positive cue is followed by a display screen with two potential targets (for negative and positive cue trials) and four potential targets (for neutral cue trials). The test screen presented only one item from the display and was present until a response key was pressed, or 10 s passed. An example of a positive cue trial is depicted above

Data analysis

All statistical analyses were identical to those described in Experiment 1.

Results

Raw memory error

A mixed ANOVA of raw memory error indicated a significant main effect of cue type, F (2, 152) = 179.71, $p < 0.001$. There was also a significant main effect of age, F (1,76) = 14.62, $p < 0.001$, due to greater error in the older group, but no interaction between age and cue type, F (2, 152) = 1.19, p = 0.308 (see Fig. 4A).

Both young and older adults exhibited significantly more error during neutral cue trials (M = 35.65, SD = 8.17) than during negative (M = 26.13, SD = 8.42), t (77) = 12.76, $p <$ 0.001, and positive cue trials (M = 22.82, SD = 7.28), t (77) = 17.47, $p < 0.001$. Both age groups also showed greater memory error in trials with a negative cue compared to trials with a positive cue, t (77) = 5.34, $p < 0.001$.

Mixture model – precision

A mixed ANOVA of memory precision revealed a significant main effect of cue type, F (2, 152) = 60.92, $p < 0.001$.

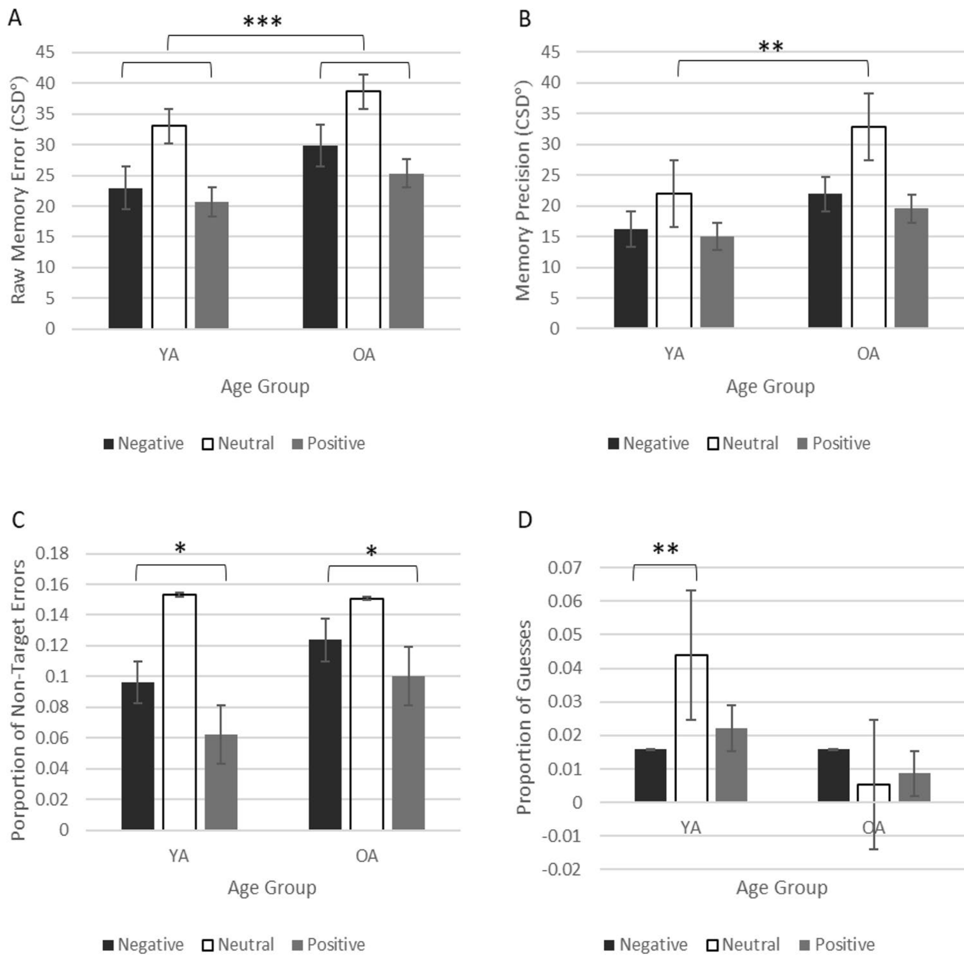

Fig. 4 Circular standard deviation of the raw memory error (**A**) and memory precision (**B**) measures, and the proportion of non-target errors (**C**) and guesses (**D**) of Experiment 2. Negative (dark grey bars), neutral (white bars), and positive (light grey bars) cue condition data for each age group (YA: young adults, OA: older adults; CSD: circular standard deviation) are presented. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

The main effect of age was also significant, F (1,76) = 28.35, $p < 0.001$, and there was a significant age × cue type interaction, F (2,152) = 6.13, $p = 0.003$. Older adults were less precise in their responses and the effect of age differed across cue types (see Fig. 4B).

When breaking the results down by age group, young adults had significantly higher memory error (i.e., lower memory precision) for trials with a neutral cue ($M = 21.94$, $SD = 11.06$) compared to negative ($M = 16.24$, $SD = 6.03$), t (41) = 3.75, $p < 0.001$, and positive cue trials ($M = 15.06$, $SD = 4.67$), t (41) = 4.87, $p < 0.001$. However, young adults showed no difference in memory precision between negative and positive cue trials, t (41) = 1.35, $p = 0.184$.

Older adults showed a similar pattern to young adults, with significantly lower memory precision for the neutral condition ($M = 32.83$, $SD = 8.09$) compared to the negative ($M = 21.92$, $SD = 7.67$), t (35) = 6.47, $p < 0.001$, and positive cue conditions ($M = 19.53$, $SD = 6.61$), t (35) = 10.48, $p < 0.001$. They also showed no difference in memory precision between negative cue trials and positive cue trials, t (35) =1.70, $p = 0.098$. Notably, this contrasts with the results from Experiment 1, where older adults were less precise for negative than for positive cue trials.

Non-target errors

A mixed ANOVA of the non-target errors showed a significant main effect of cue type, F (2,152) = 11.30, $p < 0.001$. However, there was no main effect of age, F (1,76) = 1.56, $p = 0.216$, nor was there a cue type × age interaction, F (2,152) = 0.99, $p = 0.375$ (see Fig. 4C).

Both young and older adults reported significantly more non-target errors during the neutral cue trials ($M = 0.15$, $SD = 0.13$) compared to the negative ($M = 0.11$, $SD = 0.10$), t (77) = 2.74, $p = 0.008$, and positive cue conditions ($M = 0.08$, $SD = 0.08$), t (77) = 4.33, $p < 0.001$. Additionally, both young and older adults made significantly more non-target errors in the negative cue condition than in the positive cue condition, t (77) = 2.45, p = 0.017.

One issue with this non-target analysis for Experiment 2 is that it collapses across two types of non-target error: responses that resemble the untested item in the target color (from now on referred to as "matching non-targets") and responses that resemble the two distractor items ("non-matching non-targets"). Both types of response contribute to the overall non-target error rate reported above, but may differ in important ways between older and younger adults. Specifically, if older adults attended to the distractor items more following a negative cue (as this item might be initially attended to), we might expect more non-target responses to the "cued" distractor items than the items matching the color of the target. Therefore, we ran a follow-up analysis that decomposed the non-target error rate into separate measures of matching and non-matching error. To this end, we reran the three-component mixture model using the orientation of the target-matching non-target and again using the orientation of the non-matching non-targets. Since the non-matching analysis contained two possible non-target answers (i.e., the two distractors), the non-target error rate from this analysis was divided by two to obtain an estimate of the number of responses made proportionate to each distractor item present. These separated non-target error rates were submitted to a mixed ANOVA with non-target error type (matching, non-matching) and cue type (positive, negative, neutral) as within-subjects factors and age (young, old) as a between-subjects factor. This revealed a main effect of cue type, F (2, 152) = 7.80, p < 0.001, and a main effect of non-target error type, F (1, 76) = 7.98, p = 0.006. The main effect of age was not significant, F (1,76) = 1.72, p = 0.194, but there was a significant non-target error type × age interaction, F (1,76) = 4.95, p = 0.029. As shown in Fig. 5, this appears to be due to older adults reporting the orientation of the non-target that matches the target's color more often than they report the non-matching non-targets, F (1,35) = 8.99, p = 0. 005, while young adults show no difference between these two types of non-target, F (1,41) = 0.27, p = 0.608. Finally, there was no significant interaction between cue type and age, F (2,152) = 0.15, p = 0. 861, nor was there a significant three-way non-target type × cue type × age interaction, F (2, 152) = 0. 07, p = 0. 934.

Guess rate

A mixed ANOVA of guess rate showed no significant difference in guess rate between cue conditions, F (2, 152) = 1.59, p = 0.207. However, there was a significant main effect of age, F (1,76) = 12.28, p < 0.001. The age × cue type condition was also significant, F (2, 152) = 5.82, p = 0.004 (see Fig. 4D).

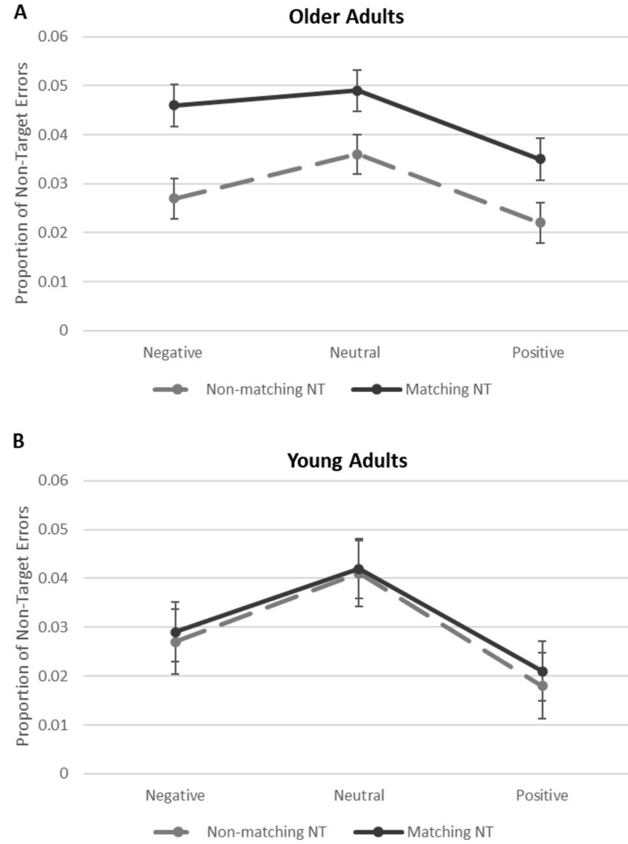

Fig. 5 The proportion of non-target (NT) errors broken down by type of non-target (NTs matching the target color and NTs not matching the color of the target) for older adults (**A**) and younger adults (**B**) across all cue conditions

When looking at young adults, they showed a significantly higher guess rate during the neutral cue condition (M = 0.04, SD = 0.07) compared to the negative cue condition (M = 0.02, SD = 0.02), t (41) = 2.85, p = 0.007, but no significant difference between the neutral and positive cue conditions (M = 0.02, SD = 0.03), t (41) = 1.94, p = 0.060. There was also no significant difference in guess rate between the negative cue condition and the positive cue condition, t (41) = 1.08, p = 0.289.

Older adults, however, reported no significant difference in guess rate between the neutral cue condition (M = 0.01, SD = 0.02) and the negative cue condition (M = 0.02, SD = 0.04), t (35) = 1.49, p = 0.145, nor the positive cue condition (M = 0.01, SD = 0.02), t (35) = -0.93, p = 0.358. There was also no significant difference in guess rate performance between the negative and positive cue conditions, t (35) = 1.05, p = 0.301.

Discussion

In Experiment 2, young and older adults showed higher raw memory error after negative than after positive cues, but this difference was not significant for the mixture model precision measure. For non-target errors, both groups made more non-target errors when given a negative cue versus when they were given a positive cue, but contrary to our predictions, this difference was not larger in the older group. Thus, for both older and younger adults, negative cues provide fewer VWM filtering benefits than positive cues. Nevertheless, both age groups displayed more non-target errors during the neutral condition compared to when they used either the negative or positive cues, suggesting that any kind of cue (whether positive or negative) benefits VWM filtering performance compared to when no cue is provided. When non-target errors were broken down into target-matching and non-matching errors, older adults were more likely to report the non-target that was the same color as the target than either of the non-matching distractor items, but young adults showed no difference between these two error types. Contrary to the prediction that greater attention towards the negatively-cued distractors would result in more responses towards the non-matching items, this suggests that older adults confused the two items that they were holding in mind at test, sometimes reporting the orientation of the unprobed item (possible reasons for this are discussed below). Finally, young adults in Experiment 2 showed a higher guess rate than older adults, particularly in the neutral cue condition when they had to maintain four items in VWM.

General discussion

Behavioral studies have suggested that young and older adults can use a variety of positive cue types to guide their attention toward relevant stimuli to improve their VWM performance (Beck et al., 2012; Woodman & Arita, 2011; Zhang et al., 2020). It has also been shown that when provided with a negative cue, young adults are able to implement the negative cue information to improve their VWM filtering compared to when no cue is provided (Arita et al., 2012; Zhang et al., 2020). In the current study, we examined whether older adults can also benefit from using negative cues to aid their VWM performance. Across two experiments, we showed that older adults' VWM performance benefits from using negative cues; however, based on their raw memory error and non-target error rates, they benefit less from negative cues than positive cues, although this effect was similar to younger adults.

Overall, we found that for raw memory error, using negative cues provided a benefit in VWM performance in both age groups by reducing the amount of raw memory error during the negative cue condition relative to the neutral cue condition, consistent with previous studies with young adults (Williams et al., 2020). However, both age groups still showed more raw memory error when using negative cues compared to positive cues, which suggests that negative cues are used less efficiently. This may be because attention is first deployed towards negatively cued items before they can be suppressed (Moher & Egeth, 2012).

Additionally, negative cues could be used by both age groups, but to different levels of efficiency, to improve VWM precision. That is, although young adults could use negative cues as efficiently as positive cues, shown by their similar levels of memory precision for both cue conditions, older adults exhibited a more limited benefit in VWM performance when compared to their use of positive cues. Specifically, older adults in Experiment 1 reported target information more precisely when they used a positive versus a negative cue at the time of encoding. However, in Experiment 2, older adults no longer showed a memory precision difference between the negative and positive cue conditions (though there was a trend toward this effect). Taken together with the raw error results, these findings suggest that older adults may be less able to use negative cues than positive cues to filter VWM.

Across both experiments, we found that VWM filtering of both groups was less efficient when they used negative cues compared to positive cues, though both cues were better than the neutral condition. Thus, it seems that the information that was cued to be ignored with the negative cues may have been attended to, at least to some extent, by both age groups. According to the search-and-destroy theory of negative cues, people use negative cues by first directing their attention to the negatively cued items before they are suppressed (Moher & Egeth, 2012). An alternative explanation is that distracting items are simply not attended to when participants are provided with a negative cue (Carlisle & Nitka, 2019). That is, attention allocated to items matching the negatively cued information would be actively suppressed instead of being enhanced, supporting the mechanism of active attentional suppression (Arita et al., 2012; Carlisle, 2019; Sawaki & Luck, 2011). Our current findings of greater non-target errors in the negative cue condition lend some support to the search-and-destroy theory as it indicates that providing a negative cue potentially directed participants' attention to non-targets before the irrelevant information could be filtered out.

Contrary to our prediction, older adults did not make more non-target errors on negative cue trials than younger adults. This could be due to the pace of our paradigm, which was relatively slow, giving older adults enough time to suppress distractors to the same extent as younger adults. Recent work suggests that older adults can suppress (or "delete") information once it has been attended to, it just takes longer than in younger adults (e.g., Gazzaley et al., 2008; Jost et al., 2011; Schwarzkopp et al., 2016; Weeks et al., 2020). In a recent study with young adults, Zhang et al. (2020) showed that negatively cued items are only attended to very briefly (i.e., ≤ 100 ms) before being suppressed. In the current study, the encoding display was presented for 400 ms, followed by a 700-ms delay, which was probably enough time for older adults to suppress negatively cued items to the same extent as younger adults (though clearly for both groups, not to the same extent as in the positive cue condition). Future work should use a range of shorter delay periods (similar to Zhang et al., 2020) to examine age differences in the time-course of suppression of negatively cued items.

An additional source of non-target error for older adults was identified in Experiment 2, in that older adults more often reported the orientation of the unprobed item that matched the target color. Young adults, on the other hand, showed no difference in error rate between items that matched and did not match the target color. This finding is contrary to evidence that older adults may have impairments during encoding (McNab et al., 2015), or that they are attending more to the distractor items. Instead, this finding is consistent with a long line of work showing age differences in the ability to overcome interference at retrieval (e.g., Healey et al., 2013; Ikier et al., 2008; Lustig et al., 2001). In Experiment 2, participants were required to maintain two target items in mind during the delay and then report the orientation of one of those items at test. Some would argue that in order to report the probed item's orientation, competing responses must be suppressed at retrieval (Anderson et al., 2000; Hasher & Zacks, 1988), in this case, the unprobed item. Our finding of a greater tendency in older adults to report the target-matching (unprobed) item suggests that they failed to resolve this competition at retrieval, which likely contributed to their poorer VWM performance overall. This failure to suppress unprobed items could help explain why age differences tend to be more pronounced at higher set sizes (e.g., Henderson et al., 2020; Mitchell et al., 2018).

While it was expected that older adults would make more non-target errors and, thus, make less efficient use of negative cues than young adults overall, it should be noted that since our data was collected online, our sample may differ from typical in-lab samples. Recently it has been found that when doing online experiments, the older adults sampled tend to be quite high functioning (Merz et al., 2022). Thus, it is possible that if this study was done in person, with a more representative older adult sample, we would find more pronounced age differences in non-target error rates.[1] Further, it should be noted that a large proportion of participants had to be removed for failing attention checks and not meeting our inclusion criteria (laid out in our preregistration), many of these older adults. If these individuals had been included in the sample, we may have seen a more pronounced age effect. Another issue with online testing was our inability to administer any neuropsychological tests for dementia; thus, we cannot rule out the possibility that some of our participants were starting to exhibit signs of dementia. However, participants were asked in the demographics questionnaire if they had any history of memory impairments or whether they were concerned about their memory, so the current sample is unlikely to include anyone with an official diagnosis of dementia. Nevertheless, these issues emphasize the importance of replicating the current findings using an in-lab sample.

Another limitation of the current study is that participants were not explicitly told to maintain central fixation. It is possible that participants moved their eyes during encoding and that age differences in speed or control of eye movements (e.g., Abrams et al., 1998; Noiret et al., 2017; Wynn et al., 2020) contributed to the observed age effects. One way to address this issue is to compare raw error performance between left- and right-sided targets, under the assumption that most Westerners will direct their attention (and eye movements) toward the left side of the screen first (Rinaldi et al., 2014; Spalek & Hammad, 2005). If age differences are particularly pronounced for targets appearing on the right side of the screen, this would suggest that older adults were slower to move their eyes at encoding and failed to fully encode items located on the right. However, there was no significant interaction between age and side (of screen) of the target for either Experiment 1, $F(1, 83) = 0.132$, $p = 0.717$, or Experiment 2, $F(1, 76) = 3.566$, $p = 0.063$. Even within the older groups alone, raw error was not affected by the side of screen of the target in either Experiment 1, $t(42) = 1.11$, $p = 0.272$, or Experiment 2, $t(35) = 0.93$, $p = 0.360$. Taken together, these findings suggest that age differences in performance were not due to the lack of fixation during encoding.

The current study was conducted to gain a better understanding of how VWM filtering of distracting information differs between age groups. The goal was to determine whether providing distractor information before encoding would lead to automatically attending, and thus prioritizing the distracting information, despite explicitly directing participants to ignore distractors. To date, VWM filtering research has focused on using young adults to look at the filtering mechanism (Beck et al., 2012; Woodman & Arita, 2011; Zhang et al., 2020), and when using older adults, it has been limited to only providing them with positive cues. Thus, not only was there a gap in research because older adults' distractor inhibition was not being researched in the context of VWM, but consequently, there was no knowledge on which kind of cue would be more beneficial to older adults or whether they employed this negative cue type differently. Thus, the information available about older adults'

[1] We also examined whether raw error correlated with age within the older adult group from each study separately, as it is possible that response error became more pronounced in the oldest old. However, there was no significant correlation between age and raw error in either Experiment 1, Spearman's $\rho = 0.221$, $p = 0.155$, or Experiment 2, Spearman's $\rho = 0.159$, $p = 0.354$.

VWM was severely limited as previous studies only examined one kind of VWM filtering or were mostly limited to either attentional or long-term memory tests (Hartley, 1993; Padgaonkar et al., 2017; Quigley et al., 2010).

Our findings suggest that participants of both age groups benefitted from being provided with a negative cue, meaning that older adults can use these negative cues similarly to young adults to prevent non-target errors. Additionally, though both age groups benefitted from the negative cues compared to when provided with no cue, negative cues still resulted in less efficient VWM filtering when compared to positive cues. This may be because attention is initially guided towards task-irrelevant items before shifting to the target information.

Open practices statement The pre-registration of Experiment 1 as well as all behavioral data will be publicly available on the Open Science Framework at: https://osf.io/kpemz/

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Data Availability Behavioral data is available at https://osf.io/kpemz/

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