Age Differences in Working Memory Filtering of Distracting Information

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Abstract

Previous research has demonstrated that as people age, cognitive processes such as visual working memory (VWM) performance decline. One potential explanation for this age-related decline in VWM is that older adults have decreased inhibitory control relative to younger adults. This impairs older adults' ability to ignore irrelevant information, which contributes to VWM filtering ability deficits. While most research investigating filtering ability deficits in older adults has tended to use *positive* cues, it is unclear whether older adults can also effectively use *negative cues* to ignore irrelevant information. The current study tested whether older adults can filter out irrelevant information from their VWM using negative cues. Across two experiments, young and older adults were presented with 2 (Experiment 1) or 4 (Experiment 2) display items. Participants were given three different cue types: neutral, negative, or positive. After a delay, participants reported the target's orientation in a continuous-response task. Our results demonstrate that both age groups' VWM performance benefitted from being provided a cue (positive or negative) as opposed to no cue (i.e., the neutral condition). However, for both age groups, negative cues were less effective at improving VWM filtering (i.e., more non-target errors) compared to positive cues. Thus, although negative cues aid in filtering of VWM contents, they are less efficient than positive cues. Additionally, older adults are similarly efficient to young adults at inhibiting negatively cued information, resulting in a reduction of distractor intrusions into VWM when using the negative cue, although this benefit is reduced (for both age groups) at higher set sizes.

Keywords: working memory, filtering, negative cue, aging, cognitive control

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Introduction

To perform everyday tasks such as remembering someone's name, deciding what to eat for dinner, and deciding which task to complete first from a to-do list, requires cognitive processes such as memory, decision making, and problem solving**.** Specifically, amongst these cognitive processes, working memory is responsible for information integration and maintenance to enable decision making as well as other higher order processes. Unfortunately, research 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 abilities with age (Gazzaley et al., 2005; 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). There are three main proposed ways in which inhibition functions to limit irrelevant information (Lustig et al., 2007). One way (the access explanation) suggests that inhibition limits the focus of attention, which suggests that only the relevant stimuli at hand are initially activated or accessed, and irrelevant stimuli are suppressed. According to this view, attentional filtering is applied as soon as distractors appear, before they are fully attended, and it has been supported in settings with salient stimuli (Sawaki & Luck, 2010). However, our inhibitory mechanism may not affect attentional filtering ability immediately upon exposure to distractor items. An alternative is that all stimuli (relevant and irrelevant) are initially attended, and the irrelevant information is either a) suppressed, meaning the information is still in our minds but not activated when it is irrelevant to the task at hand but can be activated again when it seems relevant (Gaspelin et al., 2015; Hasher et al., 1999) or b) deleted, meaning the irrelevant information is completely removed from our minds and returns to baseline levels of activation (Hasher et al., 1999).

Several studies suggest that age differences in working memory are not due to age-related impairments in activation, but rather inhibition differences between young and older adults. 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 they were told to either attend to or ignore one category at a time, or to view the image categories passively. It was found that young and older adults engaged in 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 versus when they passively viewed the scenes without trying to remember 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.

Additionally, a behavioural study by Carlson et al. (1995) found a difference in reading speed between young and older adults when irrelevant words were included in the text at random locations (making the irrelevant words more unpredictable and thus more difficult to ignore). However, these reading speed differences decreased when the irrelevant words were presented at more predictable locations**.** This decrease in reading speeds when the location of the irrelevant words is predictable suggests that young and older adults have similar activation capabilities for the predictable locations and may instead differ in their ability to suppress or delete irrelevant information (showed by the inability to ignore text at random locations). A similar pattern was found in a study by Lustig et al. (2001) where young and older adults performed a reading-span task that required participants to remember the last word of each sentence. Sentences were divided unevenly into three bulks: five sets of two, five set of three, and five sets of four sentences in a row. Half of the participants were assigned to an ascending reading-span task (starting at the lowest set size and increasing) while the other half were assigned to a descending version. The authors suggested participants would experience less proactive interference during the descending condition overall due to the larger set sizes being presented first. Because no other items were presented before the larger set sizes, which were also expected to be the most difficult, there would be less proactive interference for those particular trials. Participants were also given a story to read, which they had to recall later. Overall, older adults' working memory performance was higher during the descending condition than the ascending condition, while there was no difference in young adults' working memory performance between conditions. This suggests that older adults were less affected by proactive interference during the descending trials compared to ascending trials, thus leading to better performance as the set sizes decrease. Older adults' working memory span – a typical measure of working memory capacity – also correlated with their recall performance during the standard ascending task but this correlation was not found for older adults in the descending task. The same overall trend was also observed for young adults. These results suggest that inhibition and thus interference plays a critical role in determining the span of participants. Thus, the correlation between reading-span and recall obtained for the ascending condition was mostly a result of interference.

Thus, according to the inhibitory deficit theory, older adults struggle to limit their attention to target-relevant information and ignore irrelevant distractors (Lustig et al., 2007). Older adults' inability to inhibit irrelevant information can also affect their speed, as they tend to respond more slowly to target information when distracting information is also present compared to young adults (Connelly et al., 1991; Lustig et al., 2006).

This inhibitory deficit also extends to visual working memory (VWM), which is the active maintenance and manipulation of visual information. For instance, older adults showed delayed filtering of distracting information from VWM, as indexed by contralateral delay activity (CDA; an electroencephalograhy [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), which used an antisaccade task and a Simon task to test the role of inhibition in working memory across age groups. Through regression analyses and path models, they found that the effect of age on VWM was mediated by inhibition. This demonstrates that changes in inhibition (interference suppression) throughout the lifespan plays a major role in explaining the VWM differences seen with age.

Previous VWM filtering research has tended to use *positive cues*, which means participants are shown a cue of a feature (e.g., color, shape, etc.) 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 which indicated whether they should engage in distractor filtering or not during a delayed-estimation VWM task. After the study display, the target item was presented, and participants had to estimate its original color or orientation. They found that when given negative cues, young adults reported the target information more often and more precisely compared to their performance in the neutral cue condition.

While young adults can efficiently filter irrelevant information using positive and negative cues, it is unclear 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 towards 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 (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 2 (Experiment 1) or 4 (Experiment 2) items at a time and were directed to alter their encoding strategy based on which of the three kinds of cue they were given. When presented with a positive cue, participants had to encode items of one color (e.g., blue), when presented with a negative cue, they had to ignore items of another 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. Although the model fit was checked for, it was important to include the raw error in addition to the mixture model output as an additional method to overcome a potential model mismatch. That is, if there was a model mismatch, the raw error measure was still available to conduct the necessary comparisons between the cue conditions we are investigating (Ma, 2018).

We predicted that older adults would be able to use negative cues to a lesser extent compared to positive cues due to their difficulty disengaging attention from the negatively cued colour, resulting in higher non-target errors for the negative cue condition versus the positive cue condition. This may also be reflected by greater raw error (and lower precision) following negative cues relative to positive cues. Meanwhile, young adults should show a similar pattern of better performance for positive than negative cues, but this difference should be less pronounced than in the older group. We did not expect any effect of condition on guess rate. Finally, for both age groups, filtering performance would improve when provided 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 most 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 OSF (https://osf.io/kpemz/?view_only=775cd12b83954c558af18d88ac0e617c). 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 colour 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 to 30; *M* = 23.50, *SD* = 3.40) and 43 older adults (ages 60 to 80; *M* = 64.3, *SD* = 3.18). The number of participants needed was determined via a statistical power analysis using G*Power, providing a 95% power to detect a small-to-medium sized effect (partial $\eta^2 = 0.03$) for the 2 age (young, old) x 3 conditions (positive, negative, neutral) interaction. 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 a non-target error greater than 50% (as determined by the mixture model; 2 younger adults, 6 older adults), or being more than 3 SDs away from the mean (this final criterium was not part of our initial preregistration; 2 younger adults, 1 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). The task included a pre-cue and it was programmed in PsychoPy (**Figure 1)**. 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 inches. At the start of each trial, a fixation cross appeared for 1000ms (with dimensions of 0.5° x 0.5°). This was followed by a square pre-cue (1.7° x 1.7°) at fixation for 1000ms. The pre-cue indicated whether participants should pay attention to an item of a specific colour (positive cue), ignore an item of a specific colour (negative cue) or no colour information at all (neutral cue, meaning they would have to pay attention to all items), with cue type manipulated across blocks. The colour of the pre-cue was randomized on each trial for the positive and negative cue conditions. After a delay (900ms), participants were presented with sample display consisting of two rectangles (0.6°x1.7°), one 3.38° to the left and the other 3.38° to the right of the center of the screen. Each rectangle was of a different colour and orientation, with one of the two rectangles matching the color of the cue (for the positive and negative cue conditions). The colours of the rectangles were randomly generated from a 360°degree colour wheel (CIE L*a*b color space, [L =70, a =-6, b=14, radius = 49]). The two colours presented at once had to be at least 30° apart from each other in the colour wheel. The orientations of the rectangles were also randomly generated from a 1 - 180° and the two orientations presented at once had to be at least 20° apart.

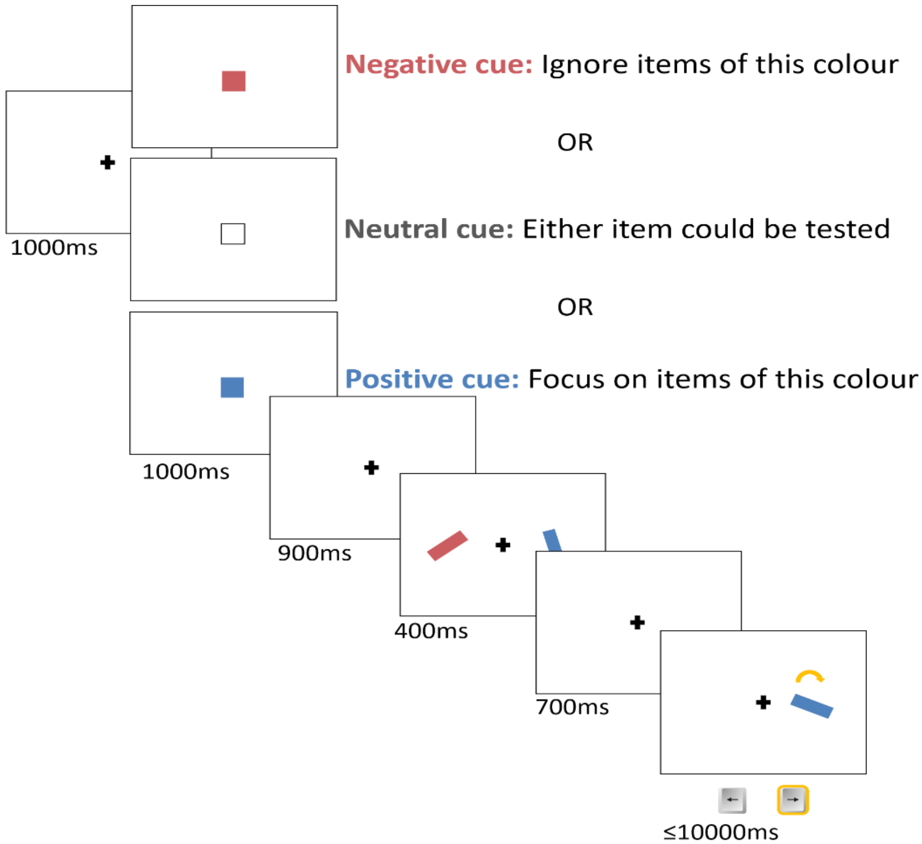

Figure 1. Schematic of the visual working memory task with three different kinds of pre-cues. A negative, neutral, or positive cue is followed by a display screen with one target (for negative and positive cue trials) and two targets (for neutral cue trials). The test screen presented only the target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

Following the sample display, a fixation cross appeared again (700ms). Finally, a test screen was presented with one 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 rectangle's orientation with the left and right arrow keys to replicate its original orientation from the display screen. Once participants were done reorienting the rectangle, they could advance to the next trial by pressing enter (they had up to 10 seconds 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 (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 was exposed to each counterbalance order.

Anxiety Questionnaires

After completing the visual working memory task, participants completed the state and trait anxiety inventories (STAI; Spielberger, 1983). Each questionnaire includes 20 questions which participants respond to using a 4-point Likert scale, though a “Prefer not to answer” option was added. Assuming all questions are answered (i.e., the “Prefer not to answer” option is not used), the questionnaire has a minimum score of 20 points and a maximum score of 80 points, with higher scores corresponding to higher anxiety. In the current sample, young adults reported slightly higher trait (M = 48.40, SD = 10.98) and state (M = 41.93, SD = 9.61) anxiety scores compared to historical undergraduate samples (Spielberger, 1983). Whereas, older adults reported typical trait (M = 34.86, SD = 12.03) and state (M = 33.07, SD = 8.36) anxiety scores for their age group (Kvaal et al., 2005). Overall, older adults reported much lower state, t (81) = 4.49, $p < 0.001$ and trait anxiety scores compared to young adults, t (81) = 5.34, $p < 0.001$.

Data Analysis

All **s**tatistical analysis were completed using custom scripts in MATLAB R2021a and JASP version 0.14.1.0. To analyze the data, the raw error (the circular standard deviation centered around the target) was calculated by determining the difference between the participants’ reported orientation and the shown target orientation. The raw error was also analyzed using the three-component mixture model (Bays, Catalao & Husain, 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). Any participant with a guess rate higher than 30%, a non-target error greater than 50%, or accuracy 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 Figure 2A, these condition differences were more pronounced in the older group (hence the age x 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. This means that when older adults were given a positive cue, they remembered the target more precisely compared to when they were presented with a negative cue. Therefore, older (and young) adults can use more 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 x cue type interaction, F (2,166) = 7.50, p < 0.001. Thus, the effect of cue type differed between age groups (see Figure 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 as 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 were less accurate in the negative than 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 x age interaction, *F* (2, 166) =1.65, *p* = 0.195 (see Figure 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.

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

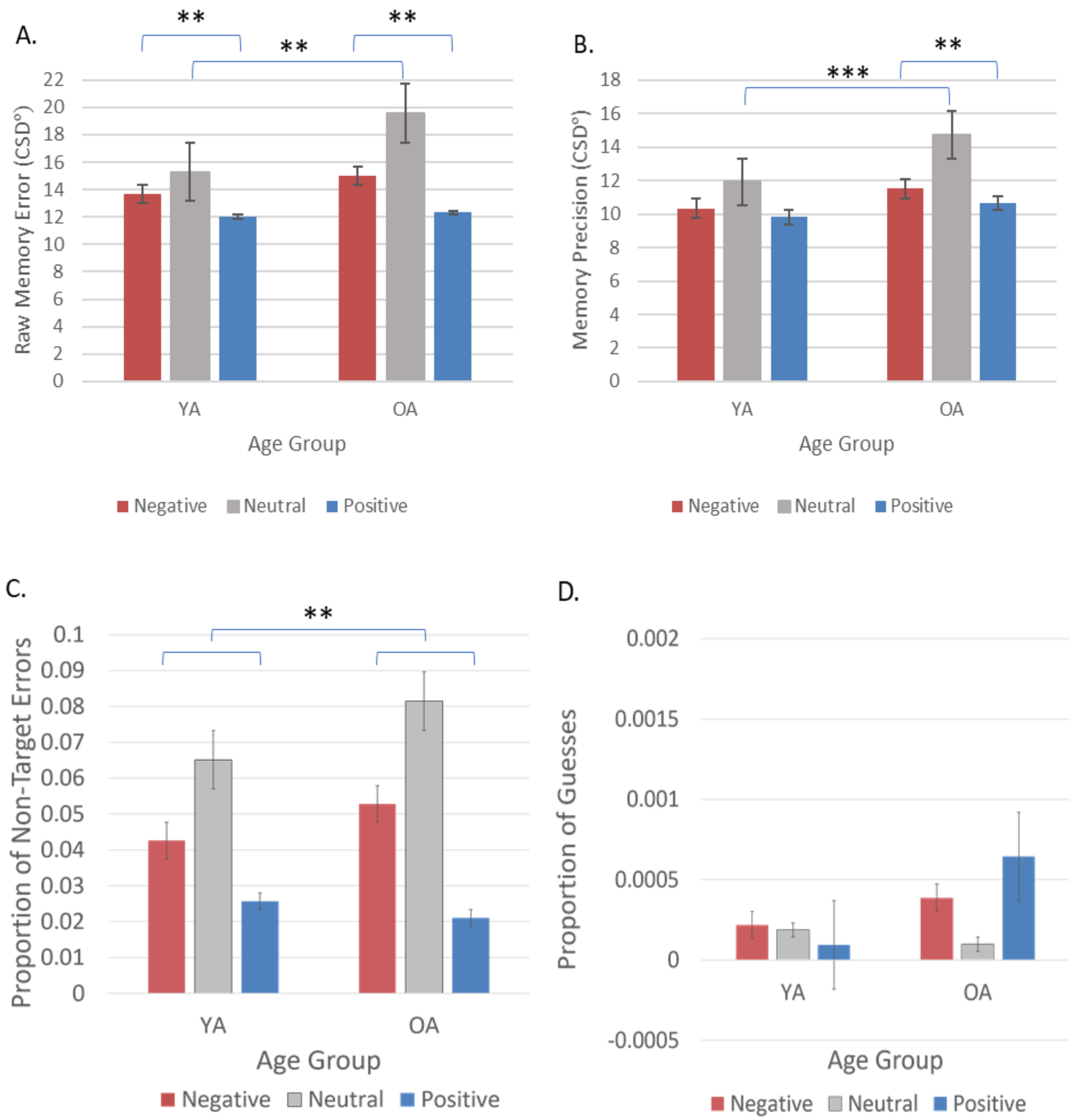

Figure 2. Circular standard deviation of the raw memory error and memory precision measures, and the proportion of non-target errors and guesses of Experiment 1. Negative (red bars), neutral (grey bars), and positive (blue bars) cue condition data for each age group (YA: young adults, OA: older adults) A) Raw memory error measured via circular standard deviation of target responses B) Memory error, from the Mixture Model output, measured by circular standard deviation of target responses C) Proportion of non-target errors D) Guess rate. **p < .01, ***p < 0.001

Discussion

In Experiment 1, I 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 the raw memory error performance. However, only older adults also showed this greater benefit form 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. That is, both younger and older adults 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 may need to be attended 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. This expected age difference may not be present 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, examining the filtering abilities of older and young adults using a higher set size (i.e., 4 items instead of 2) may reveal an age difference in non-target error rates that was masked at a lower set size.

Methods

Participants

Eighty-six healthy participants (i.e., normal or corrected-to-normal vision, normal colour 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 43 young adults (ages 18 to 30; *M* = 24.5, *SD* = 4.32) and 36 older adults (ages 60 to 80; *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 8 were rejected and not included in the analysis due to having a non-target error greater than 50% (as determined by the mixture model; 1 younger adult, 5 older adults) or being more than 3 SDs away from the mean (0 younger adults, 2 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 4 stimuli were presented in the memory array instead of 2 stimuli. Therefore, participants now had to pay attention to (positive cue trials) or ignore (negative cue trials) 2 items. Participants were still asked to remember all items during the neutral condition; therefore, they would have to remember 4 items in total in the neutral cue condition. (**Figure 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.

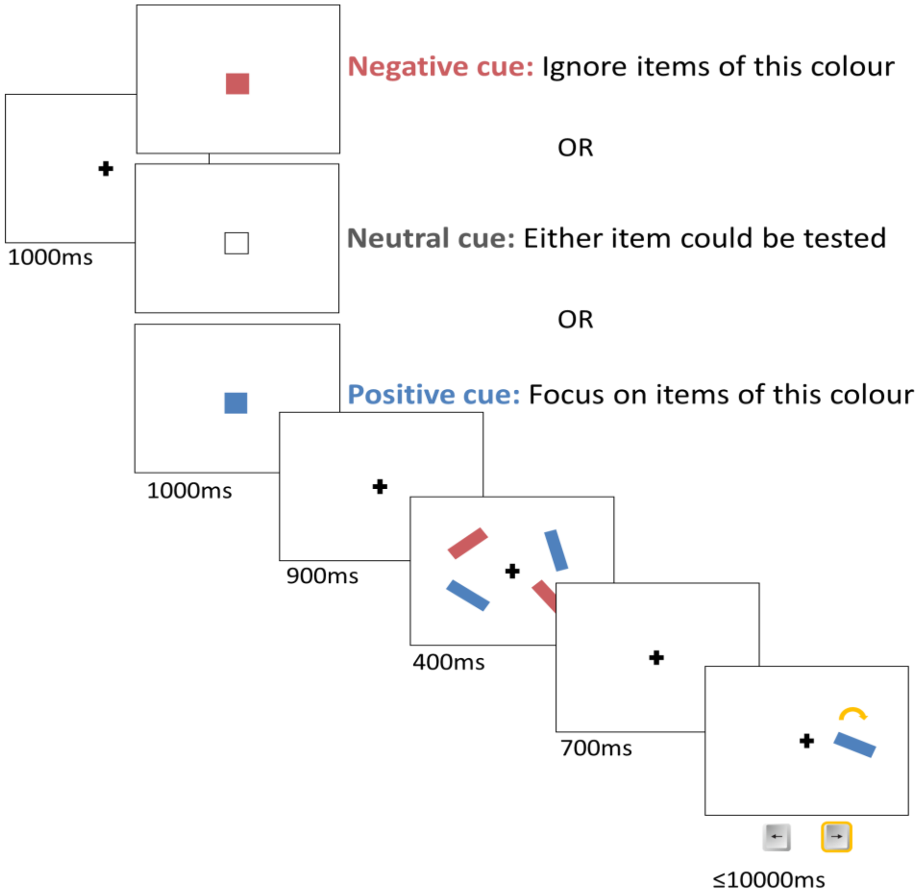

Figure 3. Schematic of the visual working memory task with three different kinds of pre-cues. A negative, neutral, or positive cue is followed by a display screen with two potential targets (for negative and positive cue trials) and four potential targets (for neutral cue trials). The test screen presented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

Anxiety Questionnaires

Participants completed the same anxiety questionnaires described in Experiment 1. In the current sample, young adults reported slightly higher state (M = 38.84, SD = 9.35) and trait (M = 47.19, SD = 12.49) anxiety scores compared to historical undergraduate samples (Spielberger, 1983). Older adults also reported typical state (M = 32.816, SD = 8.52) and trait (M = 35.18, SD = 8.58) anxiety scores for their age group (Kvaal et al., 2005). Overall, older adults reported much lower state, t (73) = 2.92, p = 0.005 and trait anxiety scores compared to young adults, t (73) = 4.86, p < 0.001.

Data Analysis

All **s**tatistical 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 on raw memory error, F (1,76) = 14.62, $p < 0.001$, but no interaction between age and cue type, F (2, 152) = 1.19, $p = 0.308$ (see Figure 4A).

Both young and older adults reported significantly greater error during neutral cue trials (M = 35.65, SD = 8.17) compared to negative cue trials (M = 26.13, SD = 8.42), t (77) = 12.76, $p < 0.001$, and compared to positive cue trials (M = 22.82, SD = 7.28), t (77) = 17.47, $p < 0.001$. Both age groups also reported significantly higher 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, $p < 0.001$. The main effect of age was also significant, F (1,76) = 28.35, $p < 0.001$, and there was a significant age x cue type interaction, F (2,152) = 6.13, $p = 0.003$. Therefore, the effect of cue type differed between age groups (see Figure 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 followed a similar trend compared to young adults. Older adults reported 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 condition (*M* =19.53, *SD* =6.61), *t* (35) =10.48, p < 0.001. However, they 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 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 x age interaction, *F* (2,152) = 0.99, *p* = 0.375 (see Figure 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 cue condition (*M* = 0.11, *SD* = 0.10), *t* (77) = 2.74, p = 0.008, and to the positive cue condition (*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 the positive cue condition, *t* (77) = 2.45, *p* = 0.017.

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 group, F (1,76) = 12.28, $p < 0.001$. The age x cue type condition was also significant, F (2, 152) = 5.82, $p = 0.004$ (see Figure 4D).

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 in guess rate between the neutral cue condition trials and the positive cue condition ($M = 0.02$, $SD = 0.03$), 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 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, $p = 0.301$.

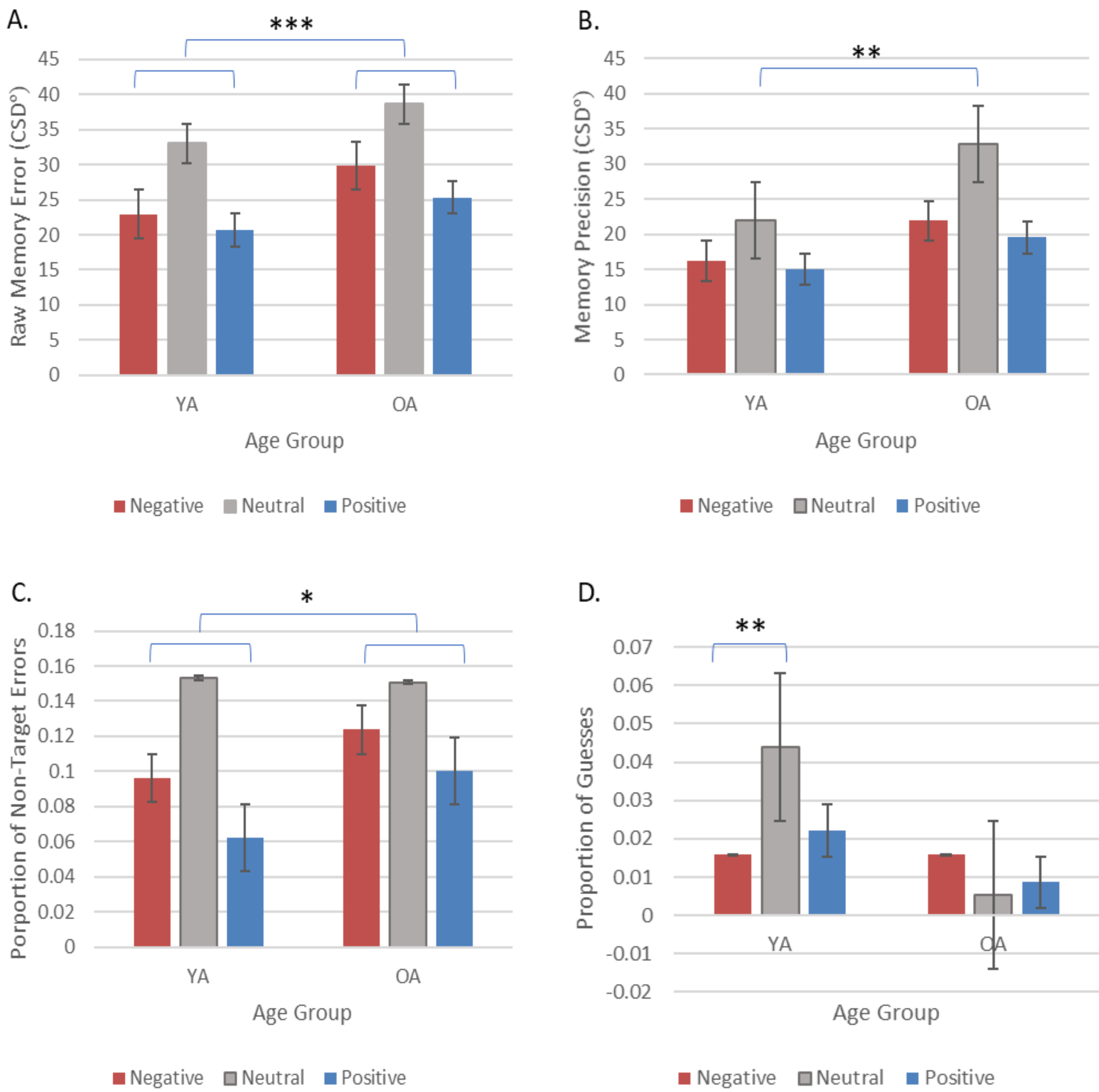

Figure 4. Circular standard deviation of the raw memory error and memory precision measures, and the proportion of non-target errors and guesses of Experiment 2. Negative (red bars), neutral (grey bars), and positive (blue bars) cue condition data for each age group (YA: young adults, OA: older adults) A) Raw memory error measured via circular standard deviation of target responses B) Memory error, from the Mixture Model output, measured by circular standard deviation of target responses C) Proportion of non-target errors D) Guess rate.

Between-Experiment Analyses

In order to examine how a larger set size affected VWM filtering and performance overall, comparisons were made for each memory variable between Experiment 1 and 2. To this end, each measure was entered in a 2 Experiment (Exp 1, Exp 2) x 2 Age (young, old) x 2 Condition (positive, negative) between-subjects ANOVA.

Raw Memory Error

For the raw memory error, the main effects of Experiment, F (1, 159) = 185.84, p < 0.001, Condition, F (1, 159) = 48.59, p < 0.001, and Age, F (1, 159) = 15.37, p < 0.001, were statically significant. Furthermore, the two-way interaction between Condition x Age was nearly significant, F (1, 159) = 3.92, p = 0.050. Meanwhile, there was no Condition x Age x Experiment interaction, F (1, 159) = 0.51, p = 0.477, nor was there any additional significant two-way interactions, *p's* > 0.05. Therefore, older adults made more raw memory errors compared to young adults, especially in the negative cue condition. Additionally, both age groups made more raw memory errors in Experiment 2, with a higher set size to remember.

Mixture Model – Precision

In the case of the memory precision, the main effects of Experiment, F (1, 159) = 156.43, p < 0.001, Condition, F (1, 159) = 9.47, p = 0.002, and Age, F (1, 159) = 25.06, p < 0.001, were statistically significant. There was also a significant two-way interaction between Age x Experiment, F (1, 159) = 11.12, p = 0.001. There was no significant Condition x Age x Experiment interaction, F (1, 159) = 0.30, p = 0.586, nor were there any additional significant two-way interactions, *p's* > 0.05. Thus, older adults reported a lower memory precision compared to young adults, especially in Experiment 2, although both age groups performed more poorly in Experiment 2. Both age groups also performed worse for in the negative cue condition compared to the positive cue condition.

Non-Target Error

For the non-target error measure, the main effects of Experiment, F (1, 159) = 43.39, $p <$ 0.001, and Condition, F (1, 159) = 14.11, $p < 0.001$, were statistically significant. Meanwhile, the main effect of age was not statistically significant, F (1, 159) = 3.75, $p = 0.055$. Furthermore, there was no significant Condition x Age x Experiment interaction, F (1, 159) = 0.79, $p = 0.376$, nor were there any significant two-way interactions, *p's* > 0.05. Thus, participants made more non-target errors in Experiment 2, at a higher set size, but this did not interact with condition or age.

Discussion

In Experiment 2, young and older adults showed higher raw memory error after negative than 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-targets 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. Comparing across Experiments 1 and 2, both groups made more non-target errors in Experiment 2 relative to Experiment 1, suggesting that participants of any age are less efficient at filtering out irrelevant information at higher set sizes. Both age groups also made more raw memory errors and had lower precision in

Experiment 2, suggesting that their overall VWM performance also decreased when participants were given a higher set size. 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

Behavioural studies have suggested that young and older adults can use a variety of positive cue types to guide their attention towards relevant stimuli and 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 their non-target error measures, their overall VWM performance (i.e., raw error) and VWM filtering (i.e., non-target errors) benefits less compared to when they use positive cues to filter VWM, although this effect was similar to younger adults.

Across both experiments, we found that this pre-cuing method with negative cues affected three aspects that contribute to VWM: the degree of raw memory error, how precisely the target information was remembered and how often participants made swap/non-target errors – thus incorrectly reporting distractor information instead of the target.

Overall, we found that for raw memory error, using negative cues showed a benefit in VWM performance in both age groups by reducing the amount of raw memory error during the negative cue condition versus the neutral cue condition. However, both age groups still showed more raw memory error when using the negative cue compared to the positive cue, which suggests that negative cues are used less efficiently to increase VWM performance compared to positive cues, possibly because attention is first deployed towards these items before they are 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 towards this effect). Therefore, older adults appear to benefit similarly to young adults across both experiments.

Contrary to our prediction, older adults did not make a greater proportion of non-target responses. Across both experiments, we found that negative cues reduced the rate of non-target errors for young and older adults to a similar extent, thus improving VWM filtering. The VWM filtering of both groups was less efficient when they used negative cues to filter VWM compared to positive cues, as they made more non-target errors when presented with negative cues. 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 not attended to when participants are provided with a negative cue. 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. Our current findings of greater non-target errors in the negative cue condition lend some support to the search-and-destroy theory as it seems unlikely that participants would be able to report the non-target items if they had not first attended to them prior to suppression (though it is conceivable that participants simply attended to the negatively cued items by mistake on some trials).

More definitive evidence for the search-and-destroy theory could be provided by examining when exactly negative cues aid in the filtering process. This question can be explored behaviourally by varying SOAs between the sample array and the probe, as previous work suggests that older adults may require more time to filter information from working memory (Jost et al., 2011). Related work using retro-cues suggests that information *can* be filtered out even after it has entered visual working memory (Kuo et al., 2012; Lepsien et al., 2005). Additionally, this question could be explored using electroencephalography (EEG) to test neural components such as the N2pc and (Eimer, 1996; Hickey et al., 2006) P_D,(Burra & Kerzel, 2014; Gaspar & McDonald, 2014), which are associated with attentional enhancement of items, and attentional suppression, respectively, as well as the CDA as a measure of the number of items in VWM. These methods could help us address whether the filtering benefit we see with negative cues is more associated with attention or VWM.

While it was expected older adults would make more non-target errors than young adults overall, it should be noted that since our data was collected online, our results may be less representative of the average young and older adult VWM filtering. Recently it has been found that when doing online experiments, the older adults sampled tend to be quite high-achieving. Thus, having high-performing older adults would contribute to our findings of relatively few age differences in filtering efficiency. Therefore, it is possible that if this study was done in person, with a more representative older adult sample, we would find an age difference in VWM filtering (Merz et al., 2022).

In the case of the guess rate measure, the only significant results were found in Experiment 2, where young adults reported more guesses compared to older adults, especially in the neutral cue condition. This trend may be the result of low-performing young adults having difficulty with a higher set size experiment.

The current study was conducted to gain 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' 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).

Research looking at distractor inhibition suggests that older adults are impaired in multiple cognitive functions, such as information retrieval, as a result of their poor inhibitory control (Hasher et al., 1999). Although some recent studies have argued that there is no age difference in distractor inhibition abilities in some cognitive tasks, such as in the pop-out task (Wnuczko et al., 2012), there is still ample evidence suggesting that age differences in distractor inhibition happen overall. However, most of these studies have gathered evidence towards the age difference in distraction inhibition mainly using long-term memory related tests (Zacks et al., 1996), attention-based tasks (Parsons & Barnett, 2019), or language-based working memory tasks (Lustig et al., 2006). As a consequence, our results from Experiment 1 & 2 fill the gap in VWM research regarding age differences in distractor inhibition. Our results indicate that older adults are capable of using negative cues to filter their VWM contents, to a similar extent as young adults, suggesting there are age no differences in the efficiency of distractor inhibition. This pattern of behaviour of young adults from our study is also consistent with the findings obtained by Williams et al. (2020), where young adults were to remember 2 to 4 items when given no cue, and 1 to 3 items when given a negative pre-cue, as the negative cue indicated they should ignore 1 of the items from the display. Williams et al. (2020) found that young adults benefitted from being provided with a negative cue to a degree between what would be expected if they always encoded the distractor items and never encoded them. Specifically, if young adults always filtered out the distractor information (i.e., using the negative cue at its maximum efficiency), then their accuracy and precision performance when given a negative cue was expected to match that of the neutral cue performance of a set size with one less item to remember. This type of VWM filtering is also evident in our results in the form of non-target errors reported when young adults were given a negative cue. Overall, our data in conjunction with the results by Williams et al. (2020) suggest that just like older adults, young adults also initially attend the distractor/irrelevant information and later focus their attention on the target information in order to filter out the irrelevant information.

Since the inhibitory mechanism appears to be a multi-step process, as suggested by the distractor suppression and search-and-destroy view, it is possible that young but especially older adults could benefit from negative cues to a greater extent if they were provided more time to use it in their VWM filtering process. This possibility should be especially considered since a similar pattern has been shown in young adults, where young adults with a lower VWM capacity took longer to implement the information provided by cues in their VWM filtering (Jost et al., 2011). This very same pattern has also been shown with older adults when they were provided with a positive cue to filter out distracting information, where older adults attend irrelevant stimuli in the early VWM filtering stages compared to young adults (Gazzaley et al., 2005, 2008; Jost et al., 2011). If older adults required more time to implement the positive cue for VWM filtering, it follows that it would also take more time – perhaps even more time than positive cues – to apply the negative cue. Understanding whether a time modification would benefit older adults' filtering performance is crucial to determine exactly the similarities and differences between young and older adults VWM abilities.

In summary, 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 no cue, negative cues still resulted in less efficient VWM filtering when compared to positive cues. Taken together, these results suggest that when participants are given negative cues, they initially guide attention towards the task-irrelevant items before shifting to the target information.

Open Practices Statement

All behavioural data will be publicly available on the Open Science Framework at: https://osf.io/kpemz/?view_only=775cd12b83954c558af18d88ac0e617c.

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